WESTERN SYDNEY
UNIVERSITY

Centre for
Smart Modern Construction

AUBEA 2022

The 45th Australasian Universities Building Education Association Conference

GLOBAL CHALLENGES IN A DISRUPTED WORLD: Smart, Sustainable and Resilient Approaches in the Built Environment

Conference Proceedings

Editors
Srinath Perera and Mary Hardie

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Proceedings of the 45th AUBEA Conference 2022

DOI: 10.26183/a6pq-mg06

Published by Western Sydney University, Locked Bag 1797, Penrith, New South Wales 2751, Australia

Edited by Srinath Perera and Mary Hardie, Centre for Smart Modern Construction (c4SMC), School of Engineering, Design, and Built Environment, Western Sydney University, Australia.

Citation
Perera, S. and Hardie, M. (2022), 45th AUBEA Conference 2022: Global Challenges in a Disrupted World: Smart, Sustainable and Resilient Approaches in the Built Environment, Australia. [DOI 10.26183/a6pq-mg06]

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Hear from us on 25 November 2022 from 9.45 am to 10.15 am at the plenary session at hall P.1.24

"Working together: An education opportunity"

Professor Gabrielle Wallace *(Group Manager NCC Management and Standards)*
Clare Wright *(Group Manager NCC Education)*

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Welcome Message from the Conference Chair

I am delighted and honoured to welcome you to the 45th Australasian Universities Building Education Association (AUBEA) Conference hosted by the School of Engineering, Design, and Built Environment in collaboration with the Centre for Smart Modern Construction, Western Sydney University.

I am confident that AUBEA 2022 will play an important role in encouraging activities in research and development in construction and built environment sectors. The broad theme of ‘Global Challenges in a Disrupted World: Smart, Sustainable and Resilient Approaches in the Built Environment’ brings together researchers, educators, students, and industry practitioners to share knowledge, collaborate, reflect, and learn from each other. The context created by Western Sydney University being ranked Number One in 2022 in the Times Higher Education (THE) impact rankings, recognising excellence in our commitment to the UN Sustainable Development Goals, provides an opportunity to identify current issues and contribute towards shaping the future of the construction and built environment sectors. Conducting this year’s conference in a hybrid format allows delegates from around the world to attend the sessions on-site and online, enabling wider participation and bringing together a global community.

I thank our distinguished keynote speakers for sharing their knowledge gained through years of experience in industry and academia. I sincerely thank our sponsors for their generosity in supporting the conference. I would also like to express my gratitude to the program committee, scientific committee and all reviewers for their efforts in ensuring a rigorous, double-blind peer review of abstracts and full papers to accept high quality papers for presentation and publication. I gratefully acknowledge the untiring efforts of Professor Srinath Perera, the Chair of the program committee, the AUBEA leadership and membership and all members of the organising committee who contributed towards the success of AUBEA 2022. They have all done an excellent job!

I sincerely hope that all participants at the 45th AUBEA Conference will benefit from the discourse and collaboration and wish you a fruitful and enjoyable experience at Western Sydney University.

Professor Mike Kagioglou
AUBEA 2022 Conference Chair
Dean, School of Engineering, Design, and Built Environment
Western Sydney University

Welcome Message from the President of AUBEA

Throughout its long history from its inception in 1975, AUBEA has gone through positive changes and experienced widening participation in its annual conferences. This means strengthening its presence in the traditional catchment area of Australasia and attracting serious interest from Asia, Africa, and Europe to earn a reputation as a regional association with global reach. True to its mission to promote and improve teaching and research in building/construction through communication, collaboration and scholarly events, AUBEA has become the platform for academics, industry practitioners and students in building to exchange good practices in educating the next generation of building professionals. I genuinely believe in the Triple Helix model of innovation, where government, tertiary education and industry work in unison to drive innovation in a country. Therefore, I am delighted to oversee the direction AUBEA is travelling and confident that AUBEA is on the right track to becoming a truly global phenomenon.

The 45th AUBEA Conference is hosted by Western Sydney University this year. As the entire world is resuming normality from the disruptive global impact of COVID-19, it is great to see that this year's AUBEA Conference is offered in a hybrid mode. This provides opportunities for loyal as well as new AUBEA delegates to attend this annual global gathering despite their different circumstances. I am thankful and would like to commend the hard work of the organising committee to host a successful AUBEA 2022. This strongly signals that AUBEA, as an association, continues to be the platform for exchanging ideas and best practices in building/construction education.

Finally, I would like to take this opportunity to show appreciation to our sponsors and all delegates for attending and supporting this year's 45th AUBEA Conference. I would also like to extend this thankful remark to the scientific reviewers and other relevant parties that have supported AUBEA 2022. Your support is extremely meaningful and instrumental to the success of continuing the tradition of holding AUBEA Conferences. The rest of the AUBEA Council and I envision AUBEA continuing to be the platform for educating the next generation of professionals in our building/construction industry in Australasia and beyond. Therefore, we greatly appreciate your strong support for AUBEA Conferences.

Professor Monty Sutrisna
President of AUBEA 2020-2022

Message from the Program Committee Chair

It is with immense pleasure that I write this message for the 45th AUBEA Conference. The Centre for Smart Modern Construction (c4SMC) is proud to collaborate with the School of Engineering, Design and Built Environment, Western Sydney University to host AUBEA 2022.

This year's conference theme of 'Global Challenges in a Disrupted World: Smart, Sustainable and Resilient Approaches in the Built Environment' aims to explore the state of the art in research and development in the field of built environment in a post-pandemic world. The call for papers attracted over 140 abstract submissions from researchers worldwide. A double-blind review process was followed for all abstracts and full papers, which yielded 96 accepted papers of high quality. These papers are categorised under seven sub-themes: Construction Project Management, Digitalisation of Construction, Industrialisation of Construction, Sustainability in Built Environment, Resilience in Built Environment, Health & Safety in Construction, and Education in Built Environment. We are also pleased to introduce the inaugural event in the CIB Early Career Researcher Workshop Series: the **CIB Doctoral School - AUBEA 2022**. I sincerely thank all authors for disseminating the outputs of their research through this conference. I extend my gratitude towards the scientific committee and reviewers for their timely support in selecting and refining the conference papers. I also thank the session chairs for their assistance in conducting the paper presentation sessions and the expert panel at the AUBEA 2022 Doctoral School for providing valuable feedback for the participating doctoral researchers.

Our keynote speakers, Davina Rooney, David Chandler OAM, and Professor Peter Shergold AC are prominent individuals in their respective fields. I heartily thank our keynote speakers for spending their valuable time to impart their knowledge, vision, and insights at AUBEA 2022.

I am grateful for the generosity of our Gold Sponsor, the Australian Building Codes Board; Bronze Sponsors, AIQS, the MDPI Buildings Journal, and RMIT University; and supporters, CIOB and CQUniversity. I also acknowledge c4SMC industry contributors for their generosity in funding research for public and industry good.

My heartfelt appreciation goes out to the conference organising committee and specifically for the c4SMC researchers for their significant efforts over many months to successfully bring together this conference. Finally, I thank all delegates for their valuable participation to make AUBEA 2022 a success.

Professor Srinath Perera
Char of the Program Committee – AUBEA 2022
Director
Centre for Smart Modern Construction (c4SMC)
Chair Professor of Built Environment & Construction Management
Western Sydney University

Keynote Speakers

Davina Rooney

Chief Executive Officer, Green Building Council of Australia (GBCA)

Presentation Title:

Sustainability Trends and Future Partnerships

A property professional with a passion for sustainability, Davina has led the Green Building Council of Australia since 2019. As a qualified engineer, Davina worked on large-scale construction projects in Sydney and London, and spent nearly a year building an award-winning school in the Himalayas. She devoted a decade to driving sustainability at one of Australia's largest diversified property companies, Stockland, which culminated in Stockland's recognition as the world's most sustainable property company. Now leading a member organisation with 550-plus members with a combined value of $46 billion, Davina brings together practical knowledge, on-the-ground experience and a systematic approach to champion leadership in sustainable design and construction. Davina works with government and industry to advocate for supportive policy and transform complex supply chains. Building on a strong legacy of leadership, Davina is elevating the GBCA's reach and impact into new markets. Davina is on the Board of Evolve Housing and the Australian Sustainable Built Environment Council, as well as Chairing the Sustainable Procurement Roundtable for the Sustainable Built Environment National Research Centre. The property industry has recognised Davina's leadership with multiple awards.

David Chandler OAM

New South Wales Building Commissioner

Presentation Title:

The Journey from Adjunct Professor to Building Commissioner, 2015 – 2022

David Chandler OAM was appointed NSW Building Commissioner in 2019 after an impressive forty-year career in the Australian construction industry. David is improving the quality of construction and restoring trust in the industry through leading the delivery of Construct NSW Reform Strategy in collaboration with the sector.

The NSW Reform Strategy has involved in modernising the Building Regulator, shifting focus from reactive to pro-active, with a core reliance on digital capability. David delivered major infrastructure and urban renewal projects including the new Parliament House in Canberra and Sydney's Quay Apartments. As Adjunct Professor in the School of Computing, Engineering and Mathematics at Western Sydney University, David helped shape the next generation of construction professionals and founded the Centre for Smart Modern Construction, which invests in new academic and research capabilities for the construction sector. David was awarded an Order of Australia Medal in 1989 for his services to the construction industry.

Professor Peter Shergold AC

Chancellor, Western Sydney University

Presentation Title:

Rethinking Tertiary Education: The Role of IATs

The Board of Trustees elected Professor Peter Shergold AC as its chair and the University's Chancellor in 2010. His term began on 1 January 2011 and has been extended until December 2022.

Peter received a B.A. Hons (First Class) in Politics and American Studies from the University of Hull; an M.A. in History at the University of Illinois at Chicago Circle; and a PhD in Economics from London School of Economics. He was awarded a Hon.DLitt from the University of New South Wales in 2017. Peter migrated to Australia in 1972 to take up a lecturing position at the University of New South Wales. In 1987, Peter became a CEO in the Australian Public Service (APS) for two decades, working with Prime Ministers and Ministers from both sides of politics. He wrote a major report on project management of major government programs, *Learning from Failure*, which was handed to the Commonwealth government in 2015. He has also chaired reviews into Health Providers' Access to Medicare Card Numbers in 2017, implementation of the National Construction Code, *Building Confidence* in 2018 and Integration, Employment and Settlement outcome for Refugees, *Investing in Refugees, Investing in Australia,* in 2019. He was also chair the Forum on Western Sydney Airport 2017-20.

Peter was made a Member in the Order of Australia (AM) for public service on Australia Day 1996 and was presented with the Centenary Medal in 2003. In 2007, he received Australia's highest award, the Companion in the Order of Australia (AC) for service to the community.

Program Overview

Wednesday, 23 November	
17:00 - 18:00	**Registration, Coffee and Tea** *Venue: KW-P.1.Foyer*
18:00 - 19:00	**Welcome Reception** *Venue: John Phillips Library Foyer (KW-Building T)*
	Welcome to Country **Mr Nicholas Howie** Dharug Man from the Boorooberongal Clan
Thursday, 24 November	
08:00 - 09:00	**Registration, Coffee and Tea** *Venue: KW-P.1.Foyer*
09:00 - 10:25	**Plenary Session** ***Venue: KW-P.1.24***
09:00 - 09:15	**Welcome to Western Sydney University** **Professor Mike Kagioglou** Pro Vice-Chancellor, Global Development (UK/Europe) Dean, School of Engineering, Design and Built Environment Western Sydney University
09:15 - 09:30	**Address by President of AUBEA** **Professor Monty Sutrisna** Head of School, School of Built Environment, College of Sciences Massey University
09:30 - 09:45	**Address by President of CIB** **Professor Makarand (Mark) Hastak** Dernlan Family Head of Construction Engineering and Management Professor of Civil Engineering Purdue University
09:45 - 10:25	**Keynote** "Sustainability Trends and Future Partnerships" **Ms Davina Rooney** CEO, Green Building Council of Australia **Q&A with Ms Davina Rooney**
10:25 - 10:45	**Morning Tea** *Venue: KW-P.1.60*

10:45 - 12:15	**Parallel Paper Presentation Session 1**				
	Construction Project Management Session Chair: Prof Anthony Mills *KW-P.1.49*	**Education in Built Environment** Session Chair: Dr Amir Ghanbaripour *KW-P.1.29*	**Resilience in Built Environment** Session Chair: Dr Marcus Jefferies *KW-P.1.51*	**CIB TG124 Net Zero Carbon - Panel Discussion** Panel Moderators: A/Prof Sepani Senaratne and Dr Niluka Domingo *KW-P.1.50*	**CIB Doctoral School - AUBEA 2022** Session Chair: Prof Srinath Perera *KW-P.1.33*
12:15 - 13:15	**Lunch** *Venue: KW-P.1.60*				
13:15 - 13:55	**Plenary Session** *Venue: KW-P.1.24*				
	Keynote "The Journey from Adjunct Professor to Building Commissioner, 2015 – 2022" **David Chandler OAM** New South Wales Building Commissioner **Q&A with David Chandler OAM**				
14:00 - 15:30	**Parallel Paper Presentation Session 2**				
	Digitalisation of Construction Session Chair: Dr Leila Naeni *KW-P.1.29*	**Health & Safety in Construction** Session Chair: Prof Imriyas Kamardeen *KW-P.1.49*	**Resilience in Built Environment** Session Chair: Dr Krisanthi Senevirathne *KW-P.1.51*	**Sustainability in Built Environment** Session Chair: A/Prof. Thayaparan Gajendran *KW-P.1.50*	**CIB Doctoral School - AUBEA 2022** Session Chair: A/Prof Yingbin Feng *KW-P.1.33*
15:30 - 16:00	**Afternoon Tea** *Venue: KW-P.1.60*				
16:00 - 17:15	**Parallel Paper Presentation Session 3**				
	Construction Project Management Session Chair: TBC *KW-P.1.49*	**Digitalisation of Construction** Session Chair: Prof Peter SP Wong *KW-P.1.29*	**Industrialisation of Construction** Session Chair: Prof Monty Sutrisna *KW-P.1.51*	**Sustainability in Built Environment** Session Chair: A/Prof. Rameez Rameezdeen *KW-P.1.50*	**CIB Doctoral School - AUBEA 2022** Session Chair: A/Prof. Yingbin Feng *KW-P.1.33*
18:15 - 21:00	**Conference Gala Dinner** *Venue: Panthers Penrith – "Jamison Room", 123 Mulgoa Road, Penrith, NSW 2750*				

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Professor Peter Shergold AC
Chancellor
Western Sydney University

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A/Prof Sepani Senaratne, Dr Robert Osei-Kyei, Dr Sameera Wijesiri Pathirana,
Dr Brendan Kirkland, A/Prof Yingbin Feng</td></tr>
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13:05 - 13:15	**Vote of Thanks** **Prof Srinath Perera** Director, Centre for Smart Modern Construction (c4SMC) Chair Professor of Built Environment & Construction Management Western Sydney University
13:15 - 14:00	**Lunch** *Venue: KW-P.1.60*
14:00 - 16:00	**Site Visit** **Western Sydney International (Nancy-Bird Walton) Airport**

Note: All times are in Australian Eastern Daylight Time (AEDT)

Disclaimer: The information in this program was correct at the time of printing, however is subject to change.

Panel Discussion on "Challenges and Opportunities for Net Zero Carbon Practices in the Construction Industry"

'CIB TG124 Net Zero Carbon' Session at the AUBEA 2022 Conference

Background to CIB TG124

The International Council for Research and Innovation in Building and Construction (CIB) is the worldwide network of building and construction experts who improve their performance through international co-operation and information exchange with their peers to improve the quality and impact of research and innovation activities in the sector. CIB was established in 1953 and has members across 53 countries, including 1351 experts, 35 working commissions and 6 task groups. CIB TG 124 (Net Zero Carbon Building Design and Construction (TG124 Net Zero Carbon Building Design and Construction Practices - CIB (cibworld.org) is established this year with the aim of bring together leading construction industry and other experts internationally to debate, research and reduce global construction emissions targets to support the expectations set out in the Paris Agreement.

CIB TG124 Coordinators

Dr Niluka Domingo is a senior lecturer in the School of Built Environment at Massey University New Zealand. She has over 12 years of experience in sustainable construction research with an excellent track record of publications, awards, and research grants. She is currently leading the Innovation, Resilience and Climate Change research group at Massey University.

Prof. Suzanne Wilkinson is the Associate Dean of Research at the College of Sciences at Massey University, New Zealand. She has extensive research and consulting experience in resilience building, disaster management, disaster recovery, and disaster reconstruction and is currently working on government-funded climate change mitigation projects.

A/Prof. Sepani Senaratne is the Director of Academic Program (DAP) Undergraduate Construction Management at Western Sydney University, Australia. She has over 150 publications, with several awards and grants. Her current sustainability research is focused on circular economy, embodied carbon reductions and lifecycle costing.

Panel Moderator

Prof. Srinath Perera: Professor of Built Environment & Construction Management, Western Sydney University and Director at c4SMC. Srinath has many research specialties, and his sustainability research are in carbon management, whole life costing, low carbon building technologies. Srinath is the mentor for CIB TG124 and the program committee chair for the AUBEA 2022 conference.

Panel Members

Jorge Chapa: Head of market transformation at the Green Building Council of Australia. He is the chair of WorldGBC's Global Commitment for Net Zero Carbon Buildings Taskforce. He is also a member of Climate Bonds Initiative Building Standards working group, the Australian Sustainable Finance Initiative's Technical Advisory Group, and GRESB's Real Estate Standards Committee.

Joe Karten: Head of sustainability and social impact for Built. He is a specialist in Green Star, WELL and NABERS certification and peer review, circular economy, net zero carbon, and LEED certification. With his national and international experience in sustainable design and construction methods, he contributes to the proliferation of sustainability throughout the built environment.

Laszlo Peter: Partner and CEO of KPMG Origins. He has experience working in several countries, managed large and specialist teams, driven business strategies, developed technology platforms and orchestrated the Asia Pacific collaboration effort around investments in emerging technologies. He led the Building Trustworthy Indicator (BTI) with embodied carbon estimating project for the NSW government.

A/Prof. Thayaparan Gajendran: Assistant Dean - Education, College of Engineering, Science and Environment at University of Newcastle. His research focuses on the sociological aspects associated with built environment in the context of construction, project and disaster management and net zero carbon.

Editorial

This marks the 45th Australasian Universities Building Education Association (AUBEA) conference, held in Western Sydney University in collaboration with the Centre for Smart Modern Construction (c4SMC). The call for papers of AUBEA 2022 was under the theme of 'Global Challenges in a Disrupted World: Smart, Sustainable and Resilient Approaches in the Built Environment'. The conference from the onset was organised into eight thematic areas as identified in Table 1. These themes reflect how built environment researchers approach addressing global challenges they face in these respective areas and how they respond to disruptions experienced. A theme lead was appointed to manage the editorial process of the respective theme. These themes include the CIB Doctoral School papers. This is the inaugural doctoral school to be held under the CIB doctoral school series that is managed by the CIB committee for Student Chapters and ECR network. Table 1 lists the themes of the conference, the theme leaders, and the number of papers in each theme.

Table 1. Conference themes

Theme	Theme Leader	Papers
Construction Project Management	Dr. Ali Al-Ashwal	18
Digitalisation of Construction	Dr. Wei Zhou	15
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Total		**95**

A total of 140 abstracts were reviewed and accepted. To maintain and assure the quality of the conference proceedings, each abstract received was reviewed through a double-blind peer review process under the editorship of theme leaders and the proceedings editors (as editors in chief). Authors received anonymous reviewer comments on their abstracts and were invited to submit their initial full papers. All full papers underwent a double-blind review process, with de-identified feedback and suggestions for revisions provided to authors. This process was managed through the EasyChair conference management software. All submissions and revisions were also re-reviewed by the theme leaders before final acceptance was issued. The scientific committee, general academic community and qualified fellow authors were engaged for the peer review process. We gratefully acknowledge the generous work of the reviewers who contributed their time and expertise to provide review commentary, including constructive and valuable feedback for all submissions. All reviewers, scientific committee and theme leaders are duly acknowledged in these proceedings.

The accepted papers are included in the conference presentation programme and the proceedings. Table 2 provides the outcomes of the review process.

Table 2. Outcomes of the review process

Abstracts	
Submitted	140
Reviewed and accepted	140
Full papers	
Submitted	104
Reviewed and conditionally accepted	104
Papers accepted for presentation	95

This book of proceedings would not be possible without the assistance of the c4SMC researchers named below. Their contributions are highly appreciated and acknowledged.

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List of Full Papers

Theme:

Construction Project Management

Insolvency Prediction Models in the Australian Construction Industry: A Proposed Framework

Hewa Dunuwilage Kanchana Nandasena[1*], Samer Skaik[2]

[1*]School of Engineering and Technology, Central Queensland University, Brisbane QLD 4000, AUSTRALIA
[2]School of Engineering and Technology, Central Queensland University Melbourne, VIC 3000, AUSTRALIA

h.nandasena@cqu.edu.au; s.skaik@cqu.edu.au
* Corresponding author

Abstract:
Construction firms have long been very vulnerable to insolvency risk compared to their counterparts in other industries. The severity of insolvency causes has led to the development of numerous prediction models to implement remedies by forecasting the financial status of the company. The effectiveness of these models is usually criticised with regard to the capability of insolvency factors in addressing the dominant causes. This paper aims to develop a framework of factors that can address insolvency causes of the Australian construction industry. A systematic literature review is adopted to identify the factors required to build an effective prediction model. The Australian Securities and Investments Commission Insolvency Statistics Reports' results are triangulated with the systematic review findings to develop the framework. The study reveals that the critical quantitative factors; profitability, liquidity, leverage, management efficiency, cash flow, and capital structure can predict the insolvency causes in Australia. The financial related causes predominantly influence the insolvencies of any country, but the qualitative factors are too inseparable. The positions of financial factors are a result of qualitative factors such as strategic management of the business, macroeconomic conditions, characteristics of the owner, manager, contractor, and company. All those factors are significant, nevertheless, the priority or the ranking may vary depending on insolvency causes relevant to a country or a region. The consideration of integrating the qualitative and quantitative factors to develop an effective insolvency prediction model is thus manifested.

Keywords:
Australian construction industry, Bankruptcy, Insolvency factors, Prediction models, Systematic literature review

1 Introduction

The success or failure of any firm is an extensive concern of the involved stakeholders, and a key index to measure the health and growth of the economy (Dikmen *et al.*, 2010). Business failure has become an attentive research topic in various industries (Lee *et al.*, 2022). The construction industry, in particular, is more vulnerable to insolvency risk and it always marks higher insolvency rates among other industries (Arain 2008). Construction sector holds the second highest failure rate (Mahamid, 2012) due to the uncertainty associated with the unique nature, project durations, and sensitivity to the economic cycles (Choi *et al.*, 2018). The effect of higher insolvencies does not only demoralise the company's internal stakeholders (Alaka *et al.*, 2018), but also the society and the country's economy (Patel *et al.*, 2022).

In Australia, insolvency is a prevalent issue in the construction sector (Coggins *et al.*, 2016), that makes associated businesses face excessively higher risks than their counterparts in other industries (Commonwealth of Australia, 2015). Australian construction firms have to face an inadmissible level of risk of entering into insolvency by themselves or becoming a target of insolvency due to contracting chains (Commonwealth of Australia, 2015). The severity of insolvency causes has led to the development of numerous insolvency prediction models to early foresee the status of the company and implement remedies to reduce the risk of being insolvent (Alaka *et al.*, 2017).

Scholars have developed models to predict the likelihood of a construction firm default based on insolvency causes (Tserng *et al.*, 2015). The early insolvency warning management systems are beneficial for contractors as well as project owners and stakeholders. Those systems can mitigate the damages due to the financial distress during project execution (Choi *et al.*, 2018) and enhance the sustainability of construction businesses (Thomas *et al.*, 2011). Moreover, the systems can reduce the need of performing special assessments on the financial capacity of contractors as a prequalification criterion (Huang *et al.*, 2013). The financial failure prediction tools are either statistical models or artificial intelligence (AI) expert systems (Alaka *et al.*, 2018; Bragoli *et al.*, 2022). As argued by Alaka *et al.* (2017), the effectiveness of a prediction model largely depends on the variables that are chosen to develop it and those variables are used to measure various factors that might cause the insolvency of a construction firm. Most of the research has aimed to determine the causes of bankruptcy by looking at variables beyond those that come from accounting background (Eklund *et al.*, 2020). A deficiency that restrains the development of a highly effective insolvency prediction model for the construction industry is the unavailability of a clear theoretical framework to select insolvency factors and variables (Bragoli *et al.*, 2022). As a result, the previous studies employ variables arbitrarily (Chen, 2012), statistical analysis (Thomas *et al.*, 2011), or common variables from non-construction industry studies (Alaka *et al.*, 2017).

Recently, Alaka *et al.* (2017) conducted a systematic literature review (SLR) to develop a comprehensive theoretical framework with quantitative and qualitative insolvency factors. However, the authors did not identify the best variables for the critical factors described in the prediction models. They proposed that future studies should try to identify more qualitative variables to resolve the lack of availability. The qualitative factors are essential to forecast the financial soundness of a contractor (Tserng *et al.*, 2012) since the industry depends on how smoothly the construction projects run and how profitable they are (Chen, 2012). According to Tserng *et al.* (2011), most of the business failure models primarily focus on financial conditions and ignore management factors, on the basis that these managerial variables are biased and qualitative. Furthermore, these models do not integrate the impact of economic conditions on the contractors' failure (Tserng *et al.*, 2011). This implies that relying merely on the quantitative factors will not contribute to develop a robust prediction model because the corporate performance does not reveal the danger associated with project failure and other environmental factors (Balcaen and Ooghe, 2006). The effectiveness of prediction models, that merely cover quantitative factors, is questionable because the financial ratios or macroeconomic variables are accessible periodically (Hillegeist *et al.*, 2004). Moreover, these models are developed by discriminating the characteristics of default and non-default firms, which is an ad-hoc methodology depending on prior specifications (Gharghori *et al.*, 2006). In addition, the financial factors are a result of qualitative factors such as managerial, strategic, and macroeconomic factors (Alaka *et al.*, 2017). However, practitioners emphasise the importance of integrating both types of factors by suggesting that quantitative models need to adjust periodically with the changes in economic conditions and market trends (Tserng *et al.*, 2011).

This study thus aims to develop a comprehensive framework for the selection of insolvency factors and variables for the Australian construction industry (ACI). The following objectives are framed to achieve this central aim:

1. To identify and evaluate the critical insolvency factors and variables that help to early predict the contractor's insolvency through a SLR.
2. To develop a framework based on the identified factors, that can address insolvency causes of the Australian construction industry.

It is imperative to differentiate between "variables" and "factors", referred to in this study. A variable is a measurable quantity that represents a certain characteristic of a firm, usually in the form of a numeric value such as financial ratios (Alaka *et al.*, 2017). A factor is a characteristic being measured by a variable and usually, there are many variables that can be used to measure one specific factor (Alaka *et al.*, 2017).

The scope of this work is limited to identifying and evaluating the critical factors and variables which emerge from the SLR. This helps to map and assess the gaps in the existing knowledge on a specific subject area to redevelop the knowledge base (Mengist *et al.*, 2020). This procedure allows the study to draw reliable findings and conclusions that could assist decision makers and practitioners in the field to act accordingly.

2 Research Methodology

This study follows two sequential phases: the first phase is a systematic literature review (SLR) of scholarly journal articles that discuss construction insolvency prediction models, and the second phase is an archival analysis of insolvency data in Australia.

The first phase of SLR aims to distil all key variables and factors needed for the development of insolvency prediction models. The included studies are then thoroughly examined in order to identify and tabulate all factors and variables used in prediction models discussed in each study. The occurrence of similar factors and variables in every prediction model is counted to conduct a frequency analysis. By following the approach proposed by Bajaj *et al.* (2018), the Pareto analysis technique is performed to rank the critical factors based on their frequency of occurrences.

The second phase (archival analysis) aims to check whether the identified factors and variable in the SLR are capable of predicting the critical insolvency causes in the ACI. For this purpose, the ASIC Insolvency Statistics Reports from 2004 to 2019 are selected and triangulated with the results from SLR. The triangulation facilitates the use of two or more independent sources for data collection and to collaborate findings within a study (Alaka *et al.*, 2017).

The SLR protocol adapts and integrates followed procedures in previous similar studies (Appiah *et al.*, 2015; Li *et al.*, 2015; Alaka *et al.*, 2018) as follows:

2.1 Scope

The SLR is limited to reviewing the scholarly studies on construction industry insolvency prediction. As stated by Khan *et al.* (2003), the first step of SLR is framing the questions for a review. The study focuses on a single research question which is clearly formulated (Abu *et al.*, 2019), specified and unambiguous to bring new synthetic insights at the end (Khan *et al.*, 2003). The high validity of the reviewed results is ensured since the results from peer-reviewed journals are employed for the SLR process. They are argued to be of high quality and validity in the literature (Schlosser *et al.*, 2007). The study achieves the central aim through the SLR approach, which involves revealing the literature gaps in the process to facilitate future research in the field of contractors' insolvency prediction.

2.2 Query string

The development of a query string is an iterative process, and it typically starts with a pilot study (Usman *et al.*, 2014). The initial string with the Boolean operators such as AND, OR and NOT, is piloted with ProQuest Central, Science Direct and Business Source Ultimate search engines. This process allows to check whether the string can retrieve relevant studies. Accordingly, the final search structure is designed with the following string: ("Insolvency" OR "Bankruptcy" OR "Failure" OR "Default" OR “Distress” OR “Financial” OR “Insolvent”) AND ("Construction" OR "Contractor").

2.3 Database selection

The search string is applied to databases that contain peer-reviewed journal articles relevant to the topic. The databases of Science Direct and Applied Science and Technology Source Ultimate are thus selected due to their wide range of journals relevant to science and technology, AI, and applied mathematics. Furthermore, ProQuest Central and Business Source Ultimate databases are selected as they cover business, justice, and economics subject areas. The search string must be customised and applied to each database accordingly (Usman *et al.* 2014) to obtain the results as shown in Table 1. The studies that only appear from database searches are used for the review to eradicate the database biasness and to ensure reliability, high consistency, and quality (Schlosser *et al.*, 2007).

Table 1. Database search results

Database	Scope and Filters	Number Of Entries	After Removing Duplicates
Science Direct	Title, Review articles, Research articles	77	58
Business Source Ultimate	Title, Find all of my search terms, Scholarly (Peer Reviewed) Journals, Publication Type: Academic Journal, Document Type: Article, Language: English	147	97
ProQuest Central	Document title, Peer-reviewed, Source Type: Scholarly Journals, Document Type: Article, Language: English	159	122
Applied Science and Technology Source Ultimate	Title, Find all of my search terms, Scholarly (Peer Reviewed) Journals, Publication Type: Academic Journal, Document Type: Article, Language: English	77	50
Total		460	327

2.4 Study Selection Criteria

In the next phase of SLR procedure, all identified studies are filtered using specific inclusion exclusion criteria (Abu *et al.*, 2019). The study formulates a list of objective inclusion and exclusion criteria, that helps address the research question by defining the review boundaries. Figure 1 below shows the process flow diagram as adapted from Alaka *et al.* (2017) to search the literature for the study, and it demonstrates how many publications are identified, screened, included, and excluded (Moher *et al.*, 2009).

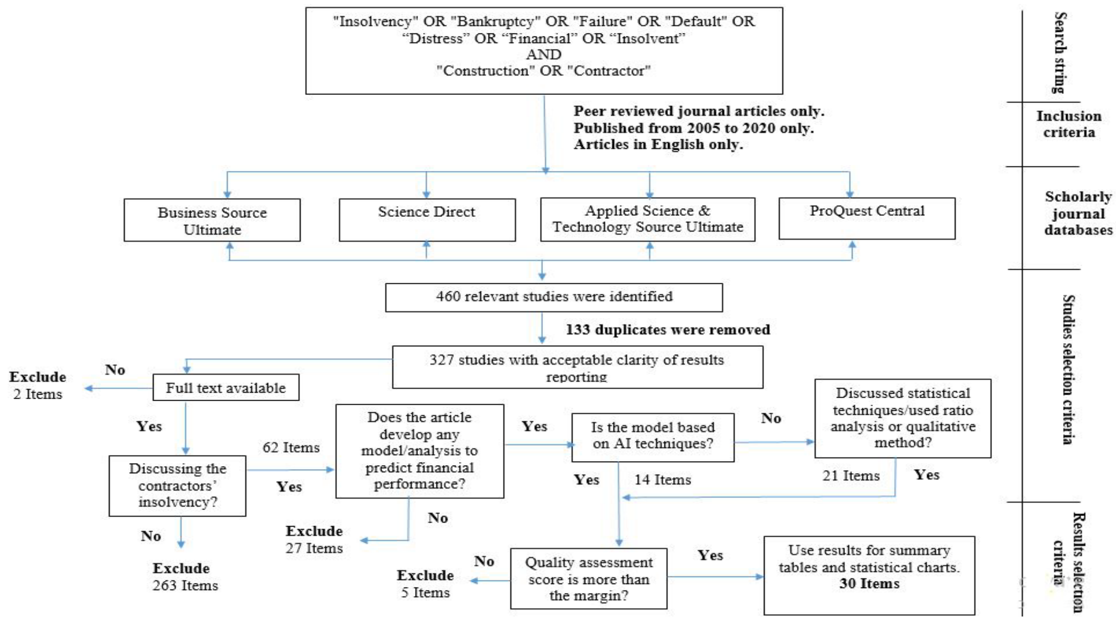

Figure 1. Process flow diagram of SLR approach

2.5 Quality Assessment (QA)

The study QA checklist is customised based on the checklist provided by Li *et al.* (2015) and Appiah *et al.* (2015). The study uses five criteria as shown in Table 2 and each is answered according to a three-point scale. According to the scale shown in Table 2, each article can obtain a range of 0 to 5 points. This study uses the median (5/2=2.5) as the cut-off point to include studies for further analysis. The studies that obtain less than or equal to 2.5 overall score are removed from the final list of included studies.

Table 2. Quality assessment checklist

Criteria	Score
C1 : Articles must have been published in high quality journal.	Y|P|N
C2 : Is the model or analysis validated with a separate sample?	Y|P|N
C3 : More than one technique is used to develop the model.	Y|P|N
C4 : Are statistical techniques used to analyse data and their use justified?	Y|P|N
C5 : Results are not based on a systematic literature review or a literature review.	Y|P|N
‘Y’=Yes (1 Point), ‘N’=No (0 Point) and ‘P’=Partial (0.5 Point)	

The articles must have been published in at least a grade 4 (Q4) ranking journal as per the Scimago Journal and Country Rank. The Q1 and Q2 rankings are given a “Y”, Q3 received a “P” and Q4 is scored as “N”. However, four articles out of the final 35 are excluded even though they receive more than the cut-off mark, as they are published in journals that are neither indexed nor ranked in Scimago. The articles that use only one technique to develop the model or the analysis are given a “P” and if the results are based on a literature review as well as another method is given a “P”. The QA score is finally checked and eventually five articles are removed including the ones that are incompatible with the ranking requirements.

Table 3 describes the summary of the overall SLR process and the number of studies that pass through each stage of the SLR.

Table 3. Number of papers in study selection process

Description	Number of Papers
Search results	460
After duplicates removed	327
Inaccessible or full text not available papers	2
After title and abstract screening	62
Excluded on inclusion and exclusion criteria	27
Excluded on low quality score	5
Final number of papers	30

3 Results and Analysis

A descriptive statistical process is employed to achieve the study objectives, that comprised of identifying the important insolvency factors and variables to develop a framework. Firstly, the summary of SLR findings is transferred into a table to rank the identified factors based on their frequency of usage. The summary of findings table represents the variables used in selected studies and the factors or the category group the variables fall under. The factors are directly taken from the studies where available and categorised the known variables under those factors for further analysis.

This study identifies 14 significant variable categories from 30 articles and tabulated their frequencies. Strategic management of the business, contractor characteristics, owner/manager characteristics, company resource management, and structural ratios have too little data to provide fair comparative results. Only a single or a couple of studies use those factors for their model development. The essential macro-environmental factors such as economic, social, cultural, technical, political, legal, market competition, and consumers' behaviour are represented as company macro forces for the analysis. Company resource management covers 'per employee ratios', as well as tangible resource management variables, where management efficiency represents activity, operational or efficiency ratios, used in studies.

A Pareto analysis for these 14 factors is conducted (Table 4) by compiling the total number of occurrences.

Table 4. Factors identified from insolvency prediction models and their occurrences

Index	Factors	Occurrences	Percentage of Occurrences	Cumulative Percentage of Occurrences
F1	Profitability	23	18.0%	18.0%
F2	Liquidity	22	17.2%	35.2%
F3	Management efficiency	20	15.6%	50.8%
F4	Leverage	19	14.8%	65.6%
F5	Company characteristics	9	7.0%	72.7%
F6	Cash flow	9	7.0%	79.7%
F7	Company macro forces	8	6.3%	85.9%
F8	Capital structure	5	3.9%	89.8%
F9	Contract/project characteristics	3	2.3%	92.2%
F10	Owner/manager characteristics	3	2.3%	94.5%
F11	Strategic management of the business	2	1.6%	96.1%
F12	Contractor characteristics	2	1.6%	97.7%

F13	Company resource management	2	1.6%	99.2%
F14	Structural ratios	1	0.8%	100.0%
	Total	128	100%	

This analysis demonstrates quantitative factors such as profitability, leverage, liquidity, and efficiency ratios are given an excessive importance in prediction models. The qualitative factors such as company macro forces and contract/project characteristics are given the least importance. However, most of the studies point out the significance of addressing those qualitative factors due to their direct correlation with construction projects. This analysis addresses the lack of availability of qualitative variables that are unique to the construction industry.

ASIC reports present an overview of statutory reports lodged by liquidators, receivers, and voluntary administrators (ASIC, 2019). The construction industry insolvency statistics, total of 56,200 for 15 financial years (FY) between 2014 and 2019 are collected from the ASIC insolvency statistics reports and tabulated. The occurrence of similar factors in those reports over the last 15 FYs are counted to calculate the trend and identify dominant causes. Table 5 below lists the 12 causes identified in the reports.

Table 5. The list of insolvency causes in Australian construction industry between 2004 and 2019

Index	Causes of Failure
Cause 1	Inadequate cash flow or high cash use
Cause 2	Poor strategic management of business
Cause 3	Poor financial control, including lack of records
Cause 4	Trading losses
Cause 5	Under-capitalisation
Cause 6	Poor economic conditions
Cause 7	Poor management of accounts receivable
Cause 8	Dispute among directors
Cause 9	Industry restructuring
Cause 10	Fraud
Cause 11	Deed of company arrangement failed
Cause 12	Natural disaster

The Pareto analysis for these 12 causes demonstrate the first five causes that are representing 79.8% of all insolvency causes in Australia. Those most critical causes are inadequate cash flow, poor strategic management of the business, poor financial control, trading losses, and under capitalisation. The critical causes should be addressed in the development of any effective prediction model, specific to the Australian context, to mitigate them in the future. The remaining causes represent 20.2% of the total frequency. As a result, natural disasters, frauds, deed of company arrangement failed, disputes among directors, poor economic conditions, poor management of accounts receivable, and industry restructuring are not considered for further analysis, as they are not critical based on the Pareto principle.

4 Discussion

The profitability of any construction firm is the most common single monetary factor that leads to the insolvency of construction companies if they consist of insufficient profit (Chan *et al.*, 2005). According to Singh and Tiong (2006), the profitability ratios reflect the better performance of other operational aspects of the businesses, which indicates the reason for the highest frequency of occurrences in assessed studies. Liquidity is given high importance in prediction models, as it is an indication of the firm's cash availability to execute construction projects (Alaka *et al.*, 2017). The management efficiency ratios are given higher significance due to their ability of checking the efficiency of the management team to utilise company assets and leverage (Bal *et al.*, 2013). This provides an insight of using leverage variables as the fourth ranking, since it helps to measure the management efficiency and overall debt of the company. The activity ratios measure the management's ability to turn company assets into cash and how well the company has been using its assets (Thomas *et al.*, 2011). Hence, the importance of using management efficiency as a critical factor for insolvency prediction and to resolve insolvencies cause due to liquidity problems is evident from the results. The construction firms are susceptible to high leverage, as they are paid for the segments they have completed; consequently, this causes delay payments for subcontractors and suppliers (Alaka *et al.*, 2017). It is thus apparent that leverage ratios have an interdependency with efficiency ratios, since the effective management of debt is also an element of management efficiency. Furthermore, this study identifies one of the management efficiency interdependencies with liquidity ratios. The findings identify the inventory turnover is common to measure the liquidity as well as the efficiency of a firm.

The surprising fact is that management efficiency and leverage are ranked in an interchanging manner by Alaka *et al.* (2017), which is contradicting to the results of this study. This implies a limitation associated with frequency analysis, as the level of importance is doubtful on the frequency scale (Alaka *et al.*, 2017) and the ranking order is subjected to change based on a number of studies. However, the critical factors remain the same, since this study integrated the Pareto principle to find their criticality. Interestingly, frequencies of some factors are the same, but the Pareto analysis did not provide an option to distinguish the dominant factors among them.

The only qualitative factor among the critical insolvency prediction factors is the company characteristics, which refers to company size, growth, age, maturity, experiences, and power (Alaka *et al.*, 2017). This study identifies the company size or the logarithm of total assets (Karas and Režňáková, 2017) as the best variable to predict the company characteristics. However, most of the other authors state that company age is the critical variable to measure company characteristics, due to the reason that young companies tend to fail because of their immaturity and construction firms usually gain experience, skills, and knowledge with the time (Alaka *et al.*, 2017).

The factors identified in this study demonstrate the construction domain and address most of the areas highlighted in business failure prediction models. One of the divisions of this study is to map those factors with the ACI insolvency causes and to develop a theoretical framework as a platform to select factors and variables.

The strategic management of the business is a vital factor for the ACI, due to the reason that poor financial and business judgement is a principal cause for insolvencies in Australia (Commonwealth of Australia, 2015). The contractors or subcontractors enter into the ACI fundamentally because of their technical skills rather than their business expertise (Coggins *et al.*, 2016). This indicates the strategic management of the business is not only depending on the management practices of the business, but also the characteristics of the owner, manager, or contractor. The inclusion of internal strategic factors, owner/manager characteristics, and contractor characteristics for developing a robust prediction model is thus manifested. The construction firms can maintain their solvency by engaging a reasonable cash flow in operations and a low cash flow in investment (Alaka *et al.*, 2017). Many contractors are lack of industry best practices and they become insolvent due to improper accounts, fail to collect debts, retentions, and late payments. The cash flow problems, that occur due to poor payment practices, are the main cause of increasing the risk of insolvency whereas burdensome payment terms, poor invoicing and poor record keeping practices contribute to this problem (Commonwealth of Australia, 2015). This implies the interrelated relationship among those factors.

Undercapitalisation is another critical financial related cause, which is common in the ACI (El-Kholy and Akal, 2021). Most of the contractors have a poor capital and they rely on the cash flow for their survival (Commonwealth of Australia, 2015) or they need to rely on trade credit and borrowed capital (Coggins *et al.*, 2016). It is clear, that the undercapitalisation results cash flow problems, trade credit, and poor payment practices, that has an interdepended relationship. Moreover, the company can focus on its total capital (Sueyoshi and Goto, 2009) and working capital policy (Mohamad *et al.*, 2014) variables in the company characteristics variable group to early forecast the undercapitalisation causes. Even though capital structure ranked lower in Pareto analysis, this factor is vital to the survival of the ACI. This explicates that any factor identified from SLR cannot be ignored.

Trade credit, over trading, and trading losses marked the fourth in the ranking that causes contractors' insolvency in Australia. In contrast, trade credit can link with the strategic management ability of the company, as lack of preparation of an exit strategy typically leads to higher losses. The surprising fact is that the results of this study do not capture any variable that directly discusses trading losses. However, leverage variables can be incorporated to early forecast this issue, as they calculate the degree to which a firm has been funded by debt and shareholders' reserves (Thomas *et al.*, 2011).

A table can be presented (Table 6) to demonstrate the mapping of insolvency prediction factors and critical insolvency causes in Australia.

Table 6. The mapping of insolvency prediction factors and critical insolvency causes in Australia

Causes of failure	Critical factors						Useful other factors							
	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14
Inadequate cash flow or high cash use	√	√	√	-	-	√	-	-	-	-	√	-	-	-
Poor strategic management of business	-	-	√	-	-	-	-	-	-	√	√	√	-	-
Poor financial control	√	√	√	-	-	-	-	-	-	√	√	√	√	-
Trading losses	√	-	-	√	-	-	√	-	-	-	√	-	-	-
Under-capitalisation	√	-	√	√	√	√	-	√	-	-	√	-	√	-

Note: F1 to F14 represents the prediction factors in Table 4. "√" indicates factors that are potential to predict the cause of failure and "-" indicates factors that are irrelevant to predict the cause.

This table implicates that, both quantitative and qualitative factors of insolvency prediction have the potential to early foresee the insolvency causes as discussed. Moreover, it illustrates useful other factors are likely to be more important for the Australian insolvency causes than the critical factors identified in the SLR process. The mapping process exhibits that the ACI insolvency causes require both quantitative and qualitative factors of insolvency prediction, rather than merely a quantitative model with financial ratios. The necessity of developing a customised prediction model is thus emerged. The framework (Figure 2) illustrates a summary of the important factors along with their best variables to predict the insolvency causes. This framework (Figure 2) will be an initial platform for practitioners to develop a more accurate, reliable, and valid early holistic prediction model for the ACI.

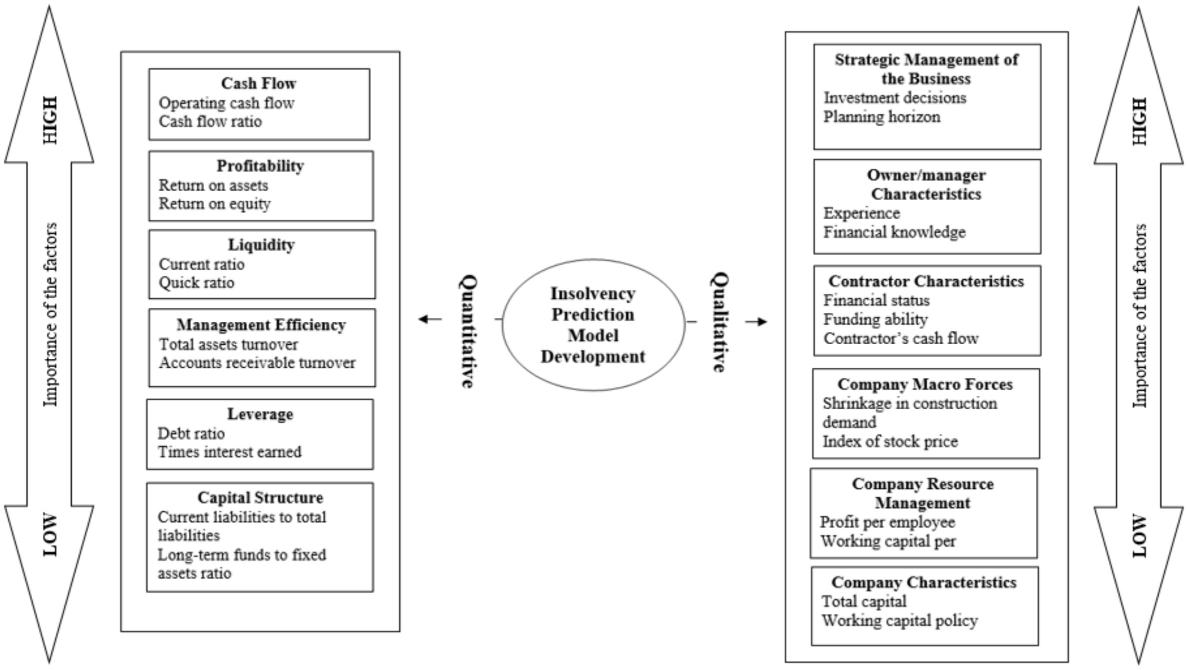

Figure 2. A framework with insolvency prediction factors and variables for the Australian construction industry

5 Conclusion

Insolvency is a prevalent issue in the ACI, which makes construction businesses functioning in Australia face excessively higher risks than the other industries. The status quo is similar to the construction industries of any country, but the prevailing insolvency causes vary and the severity of them has led to develop numerous insolvency prediction models to early foresee the status of the company and implement remedies to reduce the risk of being insolvent.

This study identifies critical insolvency prediction factors and their most significant variables to create a theoretical framework that summarises the vital insolvency factors with their relative importance. This study uses the SLR research strategy, triangulates with ASIC statistical report data to accomplish the central research aim. The results of this study reveal a number of quantitative and qualitative factors to resolve the lack of availability in previous literature.

The Pareto analysis results of the insolvency factors and the causes indicate that all identified factors are significant, but the priority or the ranking may vary depending on causes relevant to a country or a region. Less number of occurrences of qualitative factors from SLR demonstrates many prediction models have solely used quantitative insolvency factors. This is because they are readily available and qualitative factors are difficult to measure as they are subjective and most of them are beyond control. The quantitative factors should be carefully selected to assess the financial health of a company and must reflect financial obligations, profit generating ability, liquid assets of the company, possibility of receiving loans, and managerial actions. Overall, this study proposes the use of qualitative factors, together with quantitative factors and advocates for their critical necessity.

The framework that summaries the prediction factors for the ACI will benefit prospective researchers by serving as a benchmark platform from which the factors and variables can be selected. By resolving the lack of availability, this study will enhance the attention of developers to consider more qualitative factors for their models. This framework and the identified critical factors will guide the development of any effective prediction model because the early predictions cannot be achieved without those acute factors. The developers will not need to spend unnecessary attention on carrying out statistical analysis for many factors to select the best variables since this study narrowed down the variables of the important factors. The triangulated data shows that the insolvency causes may vary according to the country, and this entails the objectives of this study are valid and prediction models require modifications according to region-specific causes.

The variables to evaluate the trading losses of the ACI could not be identified from SLR results directly since the models did not discuss any special factor other than leverage to determine it. This study is limited by the small number of databases and by the limited number of keywords used for the SLR process. The Pareto analysis does not provide an option to distinguish the factors with similar frequencies. Therefore, future studies can breakdown each factor with similar frequencies and analyse them based on their sub-factors. The best variables for a few of the qualitative factors are not identified since most of the models are solely based on quantitative factors. Hence, further studies should attempt to find the best variables for such factors by surveying construction industry professionals to capture their perspectives on qualitative factors and consider insolvency data from other countries to highlight the seriousness of the problem. This will serve as a validation method even for the factors that have already been identified in this study. Consequently, this process will ensure that no important factor is left out and future studies should implement highlighted factors in developing their prediction models. Essentially, the contractors operate in the ACI should investigate the mitigation measures to cope with the dominant insolvency causes highlighted in this study as an immediate action for their financial stability.

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Causes and Effects of Cost Overruns in Construction Projects

Chinthaka Atapattu[1*], Niluka Domingo[1] and Monty Sutrisna[1]

[1]School of Built Environment, Massey University,
Albany Auckland 0632, NEW ZEALAND

n.d.domingo@massey.ac.nz, m.sutrisna@massey.ac.nz

* Corresponding author

Abstract:

Generally, cost overrun is inevitable in construction projects. However, due to the time, cost, quality constraints, and public impact, roads and highway projects face more significant issues due to cost overruns. Construction projects face a mean cost overrun of 28% inevitably. This paper investigates the causes of cost overruns and their severity based on a systematic literature review. The final selection and analysis are based on 142 journal articles. Collected journal papers were analysed using science mapping and thematic analysis. Quantitative results identified that project management, risk assessment, cost-benefit analysis, construction management, time overrun, decision-making, and design/ methodology/ approach triggers a significant effect on cost overruns. The major causes were categorised into three major divisions as management related issues, design/ methodology/approach-related issues, and project performance issues. The Thematic analysis was presented in the form of a fishbone diagram. It is recommended to have a proper management process from both consultant and contractor perspectives as project management and construction management are two significant causes identified. The identified causes will be investigated using actual data from the construction industry and accommodated into a cost estimation model which will minimise the inevitable cost overrun percentage. The research is limited to the literature findings of the past ten-year period. The study offers academics a comprehensive understanding of construction cost overrun (CCO) research to link current research areas to future trends. It also provides construction professionals with current practices and an interdisciplinary guide to better deliver construction projects.

Keywords:
Budget overruns, Causes, Cost overruns, Cost estimation, Construction, Effects

1 Introduction

Cost overruns in construction projects are considered one of the major issues globally, without any control or solution for the last 70 years. According to the facts, construction projects experienced 28% of the mean percentage of cost overrun (MPCO) (Flyvbjerg, *et al.*, 2003; Lind and Brunes (2015) studied Swedish infrastructure projects and identified that mostly the cost overruns take place at the initial stages of design and planning until the design is finalized due to technical and administrative issues. This means considering the avoidable causes of cost overruns, the project team should pay more attention to these pre-construction issues.

This emphasised the value of proper cost control of the project. According to Seeley (1996), the most important duty of a Quantity Surveyor is cost controlling while giving the value for money set against perceived expectations. Nonetheless, cost control alone cannot address the issue of cost overruns. There are three elements or processes of Cost Management; cost estimating, cost budgeting, and cost controlling (Owens *et al.*, 2007). Having accurate project estimates and a project budget accordingly is essential to delivering the project within the budget (Malkanthi, *et al.*, 2017).

Hence, to execute the project within the expected budget, the accuracy of the estimation is required, so that the decision-making can be done on a reliable project budget (Malkanthi *et al.*, 2017). Further, the researchers explained that the project cannot be carried out within the budget without monitoring the actual costs in the meantime the project is being implemented. In addition to that, current estimation and management practices of the project cost require in-depth exploration of the significant causes and their impact on the project development cost as it can be vital for the decisions of project owners, investment parties, project developers, and financing institutions (Johnson *et al.*, 2013). Hence, studying the factors affecting the accuracy of budget estimation and incorporating them into the cost estimation is vital to minimize cost overrun.

The traditional cost estimation models used for construction projects mainly focused on Base value (materials, labour, plant, and equipment cost), overheads and profits. Although there is a risk assessment done at the planning stage, it is doubtful, how deep those risk factors are used in estimation. Mostly the risk assessment is used in determining overheads, profits, contingencies, and preliminary works estimation. Therefore, today's construction industry is in need of a proper cost estimation model which will address all the possible causes of cost overruns. Therefore, this research examines the causes and their effects on the project cost in-depth. Once the major causes are identified, the results will be validated by an actual data collection process before accommodating them into the cost estimation model.

2 Research Methodology

A systematic review was undertaken in this study to examine the variables of cost overruns in an organised, transparent, and reproducible way to synthesise research findings and discover future studies (Snyder, 2019). The paper adopted mixed method data analysis techniques, including quantitative (science mapping) and qualitative (thematic) analysis. This approach has been extensively used in construction engineering and management to present knowledge domains and research topics (Luo, *et al.*, 2019; Ren, *et al.*, 2020). Science mapping was utilised to analyse and visualise bibliometric networks (Chen, 2017), while thematic analysis was adopted to describe data in rich detail and summarise and interpret various aspects of the research topic (Braun and Clarke, 2022).

The research process consists of three stages. In stage 1, the bibliometric search strategy used the keywords: "cost overrun" OR "budget overrun" OR "cost escalation" AND "construction" AND "factors" OR "causes" OR "determinants" via Scopus to determine the relevant CCO literature. Scopus was selected for document search because of its influential and all-inclusive database, covering more recent publications than other digital sources such as the Web of Science (Falagas, *et al.*, 2007). To narrow the scope of the review, a set of selection criteria were considered, including (1) English journal articles published at the final stage in the last ten years (2013-2022); (2) Relevant subjects in the construction research field; (3) Paper published in top-ranking journals in the construction field ranked by Scimago Journal and Country Rank (e.g. Engineering, construction, and architectural management), publishing the largest number of papers in the research context. The final selection includes 142 up-to-date journal articles. In stage 2, VOSViewer – a comprehensive science mapping tool based on Visualisation of Similarities (VOS) technology was adopted. It has unique advantages in clustering fragmented knowledge from different domains according to their similarity and relatedness. Compared with other options, the viewing capabilities of VOSViewer are beneficial for maps containing at least a moderately large number of items (e.g. at least 100 items), and the tool displays such maps in a satisfactory way (Van and Waltman, 2010).

VOSViewer was used to visualise and analyse three scientometric tests: (1) keywords/clusters co-occurrence analysis, (2) country-specific analysis, (3) document co-citation analysis. According to Van and Waltman (Van and Waltman, 2014), a node indicates a specific bibliographic item in the visualised networks, namely keyword, country, reference, etc. The node size signifies the counting of the appraised item, such as citation and occurrence. Link represents the co-citation and co-occurrence. The software automatically accomplishes the total link strength (TLS) to reflect the correlation between any two nodes in the created networks. The average normalised citation symbolises the normalised number of journal source, article, scholar, country, or organisation citations. The normalisation corrects the misinterpretation that older documents gain more time to receive citations than recent publications. In stage 3, a qualitative discussion was presented with a hierarchical knowledge structure of recent construction cost overruns research. We summarised ongoing main research topics, identified the research gaps, and proposed future research directions

3 Research Findings

3.1 Keywords Co-occurrence Analysis

A network of keywords was produced to exhibit the knowledge and rational organisation of the research themes. The options "All Keyword" and "Full Counting" in VOS Viewer analysis were chosen to acquire a holistic academic knowledge of construction cost overrun research. The minimum occurrence of a keyword was set at 3. Initially, 583 out of 999 keywords met the threshold. After removing duplicates and general items such as "construction", "cost overrun", etc., 158 keywords with 1595 links were selected for final consideration. In addition, using VOS Viewer, the whole network could be automatically divided into clusters labelled with terms from keywords. Studies within the same cluster might be more similar than those from other clusters. Ten clusters were identified in different colours, demonstrating latent semantic themes within the textual data, where the research patterns were perceived to uncover knowledge (Luo, 2019). Cluster #1 (22 keywords) focused on project design factors. Cluster #2 (21 keywords) contained items related to planning and scheduling, whereas Cluster #3 (20 keywords) emphasised on financial factors. Cluster #4 (16 keywords) contained items related to construction methodology and project delivery, while cluster #5 (15 keywords) is on delays, changes, and wastages. Cluster #6 (15 keywords) comprised with items related to risk and quality. Cluster #7 (15 keywords) focused on cost performance while cluster #8 (12 keywords) is on contracts, claims, and financial problems. Finally, cluster #9 (12 keywords) points out the factors on productivity and project control while cluster #10 (10 keywords) stressed variations and disputes. Figure 1 illustrates the mainstream of research keywords and their co-relationship.

This network represented the boundaries and central tendency in the CCO research area. The nodes sizes and the connection lines among keywords showed the most frequently studied and highly concerned terms, such as project management (frequency=114, total link strength (TLS)=480), risk assessment (frequency=45, TLS=208), cost-benefit analysis (frequency=40, TLS=190), construction management (frequency=29, TLS=129), time overrun (frequency=26, TLS=64), decision making (frequency=26, TLS=111), and design/ methodology/ approach (frequency=25, TLS=121), have been given close and thoughtful attention. Further investigation of the average citations demonstrated that the following keywords including cost and schedule cost estimating, project delivery, economic and social effects, change orders, disputes, and delays triggered much consideration.

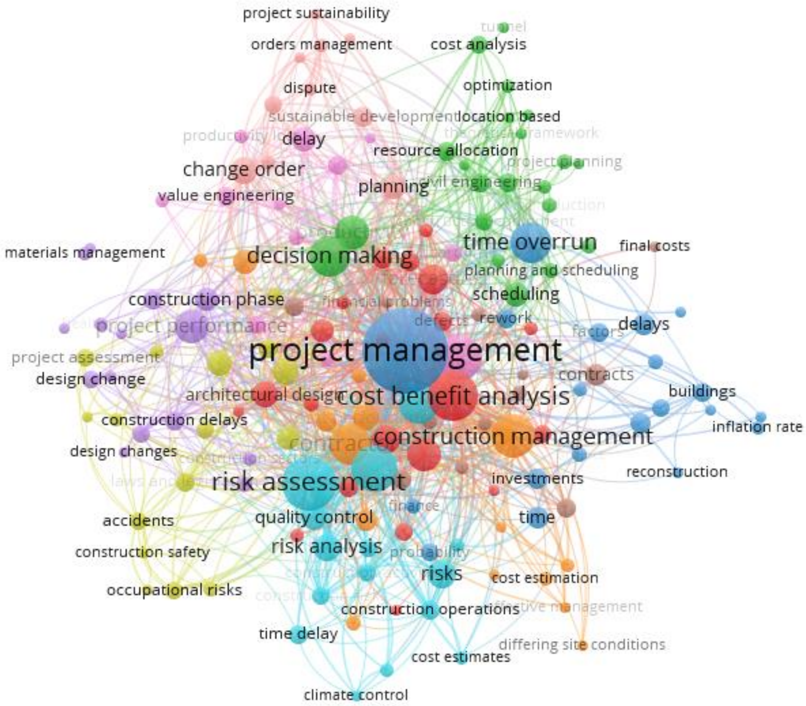

Figure 1. Mapping of co-occurrence analysis of keywords
Source: VOS Viewer

3.2 Country-specific Analysis

Keyword analysis specified several countries contributing to CCO research, comprising developed and developing economies like the United Kingdom (UK) and India. The study further determined countries active in global CCO research. The minimum of number documents and citations for a country was set at 2 and 20, respectively. Finally, a shortlist of 22 countries and 62 links was generated. Figure 2 illustrates the map of countries contributing to CCO research.

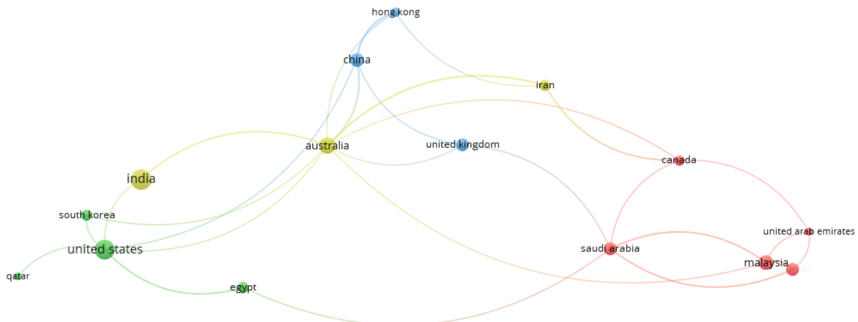

Figure 2. Mapping of the country’s contribution to CCO research
Source: VOS Viewer

According to the analysis, the following are the countries most contributed to the CCO research: the UK, China, Australia, India, the United States (US), Malaysia, Saudi Arabia, Canada, and Iran. United Arab Emirates (UAE), Egypt, South Korea, and Qatar. According to the strength of the links, India, the US, Australia, and China took the lead in the research on cost overruns in construction projects. Although with less strong links, middle east countries have contributed to a considerable level of CCO research.

Table 1. Major countries contributed to CCO research from 2013-2022
(Source: VOS Viewer)

Country	Number of publications	Number of citations	Country	Number of publications	Number of citations
India	42	141	Pakistan	17	41
Malaysia	39	152	Saudi Arabia	16	153
US	35	307	Egypt	15	44
Australia	25	454	Canada	12	112
China	31	199	Iran	11	42
UK	22	132	Nigeria	11	10
South Korea	20	447	UAE	10	96

3.3 Document Co-citation Analysis

A document co-citation analysis could disclose the underlying intellectual structure of a knowledge domain (Luo, *et al*., 2019). Therefore, the most influential journal publications in the last ten years were assessed with the co-citation network generated in VOS Viewer. The minimum number of citations was set to 20. Of the 404 authors, 90 meet the threshold, resulting in a co-cited visual network map, as shown in Figure 3. The most extensive set of related items consisted of 16 items. The nodes in the map denoted the documents, identified by the first author's name. The time of publication signified the colours of the nodes and the links.

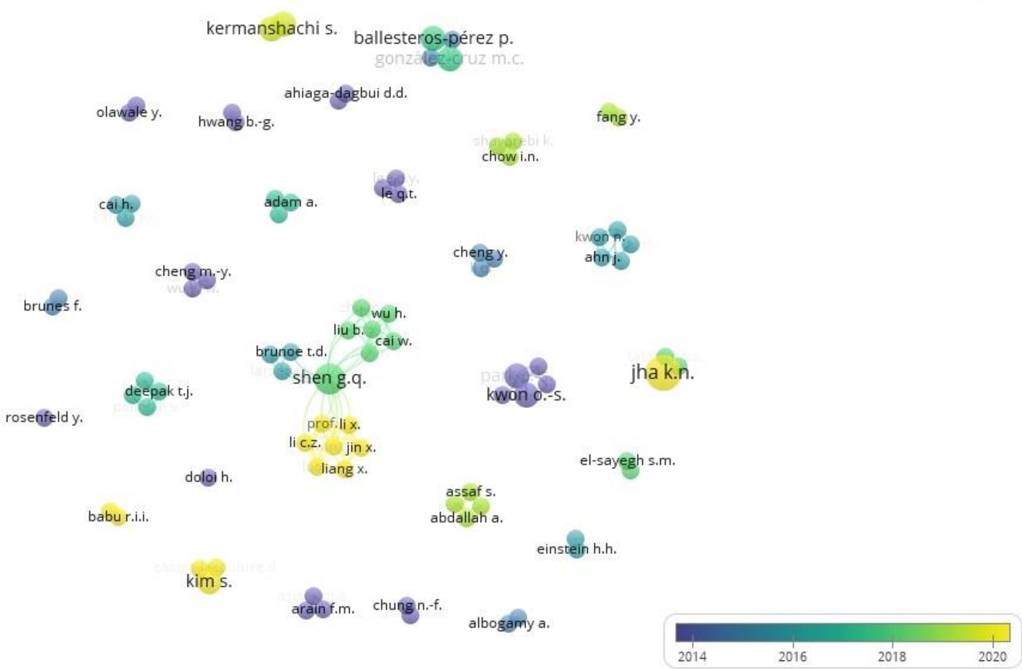

Figure 3. Mapping of the co-citation analysis
Source: VOS Viewer

The co-citation network showed an overall distribution with only a few sets of related items. This result indicated that the recent CCO research directions went beyond common ideas and results. According to the analysis, much research related to CCO was conducted during 2016-2020. The latest CCO research in the 2020s was expected to spread faster and more comprehensively. More details on the top-five most cited articles are demonstrated in Table 2 in the order based on the number of citations.

Table 2. High-impact publications in CCO research from 2013-2022
(Source: Scopus and VOS Viewer)

Authors	Year	Title	Citations	Keywords
Larsen J.K., Shen G.Q., Lindhard S.M., Brunoe T.D.	2016	Factors Affecting Schedule Delay, Cost Overrun, and Quality Level in Public Construction Projects	186	Journal of Management in Engineering
Doloi H.	2013	Cost overruns and failure in project management: Understanding the roles of key stakeholders in construction projects	150	Journal of Construction Engineering and Management
Rosenfeld Y.	2014	Root-cause analysis of construction-cost overruns	98	Journal of Construction Engineering and Management
Adam A., Josephson P.E.B., Lindahl G.	2017	Aggregation of factors causing cost overruns and time delays in sizeable public construction projects: Trends and implications	60	Engineering, Construction and Architectural Management
Ahiaga-Dagbui D.D., Smith S.D.	2014	Dealing with construction cost overruns using data mining	43	Construction Management and Economics

4 Discussion

According to the keyword occurrence analysis, seven major causes were identified with significant effects on cost overruns in the construction industry. They are project management, design/ methodology/ approach, risk assessment, cost-benefit analysis, construction management, decision-making, and time overruns. Similar results were observed in the research conducted by Doloi (2013), which identified eight significant causes. Out of those eight, similar causes were design efficiency, effective site management, contractor efficiency, project characteristics, and accurate planning and monitoring. Although these wordings are not the same, these aspects can be categorised together with the causes identified in this research. In addition to that, communication, due diligence, and market competition were also identified by Doloi (2013).

It is noticed that the keyword analysis has provided only a set of general and simplified yet widespread factors rather than specific and exact causes or issues leading to cost overruns. Going forward, Larsen, et al. (2016) investigated deep into detailed causes and identified five causes as errors or omissions in consultant materials, incomplete project documents, variations by the client, lack of initial investigation before design/ tendering, and lack of experience in the consultant team. Similarly, Rosenfeld (2014) also conducted a detailed investigation and identified 15 causes that lead to cost overruns and stated that these are universal root causes. Later they were categorised into three major divisions as organisational causes, project-related causes, and systemic Causes. Correspondingly, in this research seven major divisions can be identified as mentioned previously. The keywords identified in the Figure 1 map, which are the causes of cost overruns can be categorized into three main groups namely, management-related issues, design/ methodology/approach-related issues, and project performance-related issues.

4.1 Management-related Issues

All the management-related issues are categorised under this division. According to Figure 1, the most significant cause of cost overruns is project management issues. Therefore, not having a proper project management process, procedures and professionals will lead the project to failure and cost overruns. This was identified 114 times in the literature and identified as one of the most significant causes of cost overruns as identified by the researchers (Adam, *et al.*, 2017, Ahiaga-Dagbui and Smith, 2014, Doloi, 2013, Larsen, *et* al., 2016). In fact, Larsen *et al.* (2016), identified project management issues as a separate division in their categorisation. According to Figure 1, not just the project management but also the contractor's management and supervision also cause the project's significant cost overruns.

At the beginning of the project identification of risks and taking proper actions for those risks are very important. In other words, every project should have a proper risk management process implemented by both consultant and the contractor teams. Without identifying the possible risks, the project cannot be prepared to face the threats and thus the project will face cost overruns. Therefore, Figure 1 identified risk assessment and management as a major cause.

4.2 Design/ Methodology/ Approach-related Issues

Although variations in a construction project are inevitable (Alsuliman, *et* al., 2012), a long process for processing design changes, mistakes or errors in designs, and delays in designs can negatively impact the duration and cost of a construction project. Change in a project's design could be part of a construction project's nature because of its inherent complexity and uncertainty. Design issues cause delays as they need to be reviewed and approved by the client. The lack of clearly defined project objectives and scope was mainly the cause of frequent change orders in construction projects. Design-related issues during the pre-contract stage will lengthen the time of the design and tender stage. There may be several tender clarifications and drawing revisions to be issued and which will delay the tender submission (Aljohani, *et al.*, 2017).

Poor planning and scheduling at the pre-contract stage or just before the start of construction could lead to issues in the project control and monitoring phase. The reasons behind this cause may be poor programme management skills of the Contractor's team, and Poor team working and coordination skills. Because planning requires inputs from the design team, cost management team, Engineering team, project management, and procurement team. Therefore, team working, and coordination skills are very important.

Immature tendering documents were identified as causes of cost overrun in thirteen out of seventeen studies. Several factors have caused this issue including the involvement of the designer as a consultant; communication gaps occurring between the contractor and designer; insufficient details in the working drawings and a lack of coordination between the parties. Also included is a lack of human resources in the design firm, the designers' lack of knowledge of available materials and equipment, and the use of incomplete shop drawings and specifications.

It is required to have a proper ground investigation at the design stage to ensure that the design address any kind of situation the Contractor will face when the earthwork starts. But it is evident that the proper and complete ground investigation will not happen until the project is awarded to a Contractor. This may impact the change of the design, which may lead to variations. Reasons for this cause maybe there are not enough technical experts within the design team to carry out a proper and detailed investigation. On the other hand, the time constraints at the pre-contract stage could also be the reason.

Cost estimating could be defined as the process where an estimator arrives at an expenditure of resources necessary to complete a project in accordance with plans and specifications. The preparation of a detailed cost estimate for a particular construction project requires collecting, retrieving, and manipulating large amounts of independent, but related cost, and non-cost data and information in a time-effective manner. Cost estimation for projects is a characteristically complex exercise. Although estimation techniques have improved over the years, they are still regarded as imperfect. Because of the high uncertainty of construction projects, clients along with the contractor become better informed about the specific technological and material requirements of the project work after a project moves from the design phase to the implementation phase. E.g., poor ground conditions.

There are several causes for an inaccurate cost estimate, and some of these causes may be like other causes of cost overrun. One of them is the psychological cause. Psychologists believe that most people tend to be more optimistic than realistic which is called optimism bias. In this situation, estimators and contractors make their decision based on delusional optimism (higher than actual rewards and lower than actual risks) rather than rational measuring of profits and losses. Other causes are: (1) The data used to estimate the bid may be unreliable. 2) The absence of a national database for prices to rely on. (3) Lack of estimators' experience. (4) Honest mistakes.

4.3 Project performance-related issues

Project performance is a very important division of a project. According to Figure 1, the performance of the project can be affected significantly by (1) poor or lack of cost monitoring and control, (2) health and safety issues, (3) defects or reworks, (4) scheduling errors which lead to time overruns, (5) improper construction methodology. These issues are jointly agreed upon by other researchers as well (Adam, *et al.*, 2017, Ahiaga-Dagbui and Smith, 2014, Doloi, 2013, Larsen, *et* al., 2016).

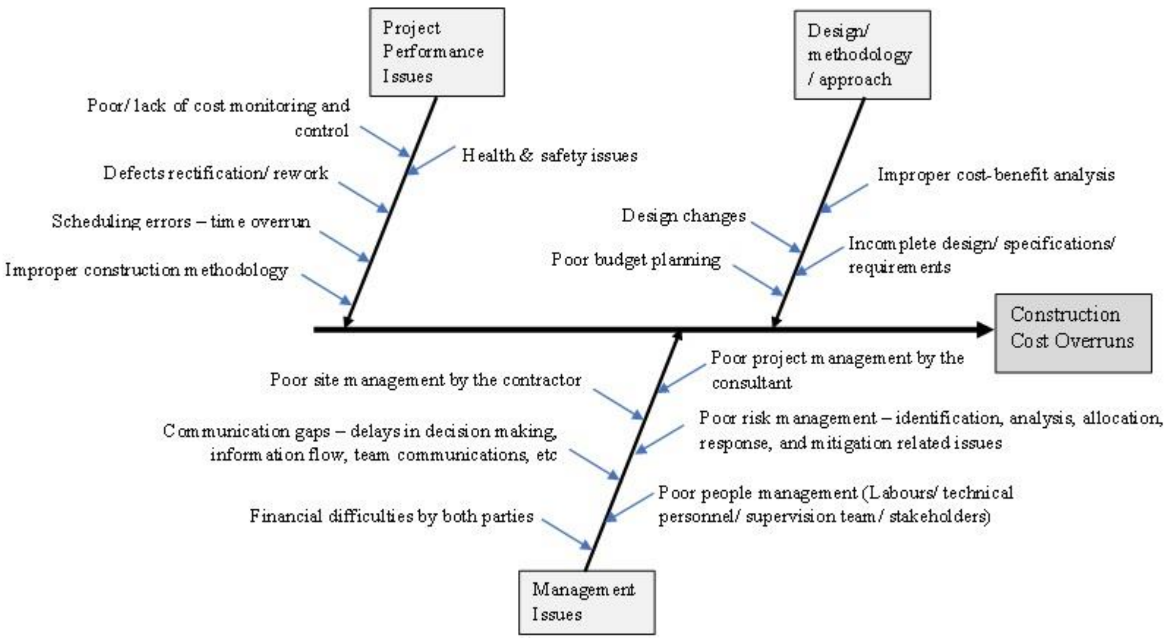

Figure 4. Fishbone diagram – causes of cost overruns

Following the qualitative discussion, the findings can be drafted into a mind map called a fishbone diagram to summarise this research. Figure 4 shows the fishbone diagram drafted based on the above discussion. Rosenfled (2014) created a similar mind map with three different categories organisational, systemic, and project related. Although the causes are different, it is observed that the factors show similarities and connections to the factors identified in Figure 4 map.

5 Conclusion and Further Research

Construction projects around the world will normally have poor performance in terms of achieving cost, quality, and time targets. Therefore, cost overruns are considered a common feature in construction projects. 158 keywords related to construction cost overruns were identified through an existing literature survey. The studies show that the causes of cost overruns are similar in all contexts. However, the impact or the severity can differ from country to country. As a result, it would not be accurate to identify the causes of cost overrun for a specific country from global literature only. Out of those causes, seven factors were recognised as factors that make the most significant effect on the cost of construction projects in general, namely (1) project management, (2) risk assessment, (3) cost-benefit analysis, (4) construction management, (5) time overrun (6) decision making, (7) design/ methodology/ approach. One of the potential solutions to reduce the effect of cost overrun in construction projects is the embedding of an effective resources (human, technical, and material) management system within construction projects as it seems that most of the causes of cost overrun are related to poor resource management. Moreover, effective communication between a project's internal and external stakeholders is a very important task to deliver projects successfully and reduce cost overrun. Finally, the risk is more important in construction megaprojects to identify these causes beforehand so that the team can take necessary actions to prevent them or reduce the effect of the risk. Therefore, a proper risk assessment at the beginning of the project is essential to identify these causes. This research is based on systematic keyword analysis. Therefore, the causes cannot be completed and accurately derived through keyword analysis. Therefore, it is recommended to carry out a systematic literature review to identify specific causes of cost overruns commonly in construction projects. Then those factors can be studied based on actual data collected through industry professionals to identify the impact and severity. These causes can be a valuable set of variables for a cost estimation model or for a risk register.

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Sustainable Procurement and Modern Slavery Risks in Development and Construction: A Case Study in Australia

Vasilios Papastamoulis[1], Yingbin Feng[1*], Peng Zhang[1] and Marissa Saunders[2]

[1]School of Engineering Design & Built Environment, Western Sydney University,
Locked Bag 1797 Penrith NSW 2751, AUSTRALIA
[2]Stockland, Level 25, 133 Castlereagh Street, Sydney NSW 2000, AUSTRALIA

v.papastamoulis@westernsydney.edu.au; y.feng@westernsydney.edu.au; p.zhang@westernsydney.edu.au;
marissa.saunders@stockland.com.au
* Corresponding author

Abstract:
Modern Slavery is a global issue as approximately 50 million people were living in modern slavery globally. Construction and property is considered among the top five sectors accountable for modern slavery methods along with 'food and agriculture', 'finance', 'mining' and 'health'. The high fragmentation and complexity of construction projects as well as poor transparency and visibility of the construction supply chain facilitate modern slavery, while the labour shortage due to COVID-19 may exacerbate the problem. It is estimated that 18% of the construction workforce worldwide are modern slavery victims. This number is not negligible as the construction sector itself accounts for 7% of the global workforce. Therefore, minimising modern slavery risks in the construction industry is of great importance. This research aims to examine how sustainable procurement practices can help to minimise such risks across the construction supply chain. A case study with a private listed organisation from the Australian property and building sector was conducted. Data were collected through document review and interviews. The framework for enabling sustainable procurement (Feng et al. 2021) was used to analyse the case. The results suggest that best practices such as 'leadership and collaboration', 'policy and governance' and 'supplier engagement' can significantly contribute to the minimisation of modern slavery risks in the construction supply chain. Also, the findings show that novel data management tools such as 'online supplier questionnaires' and 'web interactive dashboards' can be used by construction organisations to effectively identify and address modern slavery risks.

Keywords:
Construction, Descent work, Modern slavery, Sustainable procurement, Social procurement.

1 Introduction

Modern slavery is an international issue with severe social and economic impacts. It involves human trafficking, sex workers, forced marriage, debt bondage, worst forms of child labour and other forms of unfree labour (Christ & Burritt 2018). Modern slavery in supply chains can be defined as the exploitation of vulnerable individuals who lack fundamental human rights and forcibly work under a fake contract or a debt, in order to unethically produce goods and services for the end user (Gold et al. 2015, p. 487). In 2016, modern slavery victims were estimated at 40.3 million worldwide (Trautrims et al. 2021). The number of people in modern slavery has risen significantly since 2016. Ten million more people were in modern slavery in 2021 compared to 2016 global estimates. According to the latest Global Estimates of Modern Slavery, fifty million people were living in modern slavery in 2021 (ILO, Walk Free, and IOM, Geneva, 2022). Around 25 million are particularly in 'forced or underpaid labour' in various occupations and industries such as 'electronics', 'textile', 'fish', 'coffee' and 'palm oil' as well as 'mining', 'steel' and 'construction' (Fellows & Chong 2020; LeBaron & Ruhmkorf 2019).

In the global construction industry, eighteen per cent of its workforce was exploited to forced or unpaid labour work (KPMG & AHRG 2020). The complexity and fragmentation of the construction supply chain, the labour flexibility and short-term relationships contributed to modern slavery practices in the construction sector (Craven 2015; Trautrims et al. 2021). Additionally, the shortages in labour due to the COVID-19 pandemic, and the lack of visibility in the global supply chain nourished the problem (Christ & Buirritt 2018; Trautrims et al. 2021).

Studies have shown that modern slavery is a complex issue that needs to be addressed using a holistic approach involving not only the law but also collaborative, organisational and procurement practices (Meehan and Pinnington 2021). Sustainable procurement incorporates such a holistic concept as it adds value to the supply chain by creating positive social, economic and environmental outcomes over a lifecycle basis (Gormly 2014). Accountability, transparency, respect for human rights and ethical behaviour are some of the main principles of sustainable procurement (ISO 2017). Within this context, sustainable procurement has been acknowledged as a strategic instrument against modern slavery, where public and private organisations can utilise it to address modern slavery risks (Stoffel 2020). This research aims to examine how sustainable procurement practices could help to minimise modern slavery risks in the development and construction sector using a case study from Australia.

2 Literature Review

2.1 Recent Scholar Studies on Modern Slavery in Construction

Modern slavery practices in the construction industry has recently attracted the attention of many scholars. Shilling et al. (2021) mentioned that modern slavery is a universal issue that is well hidden in the intricated global supply chain. They found that the construction supply chain is globally accountable for forced labour methods due to the increased domestic supply chain demands, thus modern slavery flows are destined to construction from agriculture and trade, respectively, to satisfy such demands. Figure 1 below depicts that the majority of modern slavery victims are in the construction sector either for production or consumption of construction goods and services, with more than eight million to be working as forced labour in both scenarios. Contrary to that, Trautrims et al. (2021) mentioned that the global supply chains are greatly subjected to modern slavery risks than the regional and local supply ones because of their operations at a global scale as well as their reputation damage. Thus, they highlighted the importance for construction organisations to conduct a risk assessment in the design phase of projects rather than during their implementation phase, in order to develop ethical construction supply chains (Trautrims et al. 2021, p. 281).

Apart from conducting a risk assessment, organisations should consider developing supplier and procurement staff capabilities through education and training on modern slavery as well as including the latter in their major policy documents to minimise modern slavery risks in the supply chains (Gold et al. 2015; Meehan & Pinnington 2021; Trautrims et al. 2021). Gutierrez-Huerter et al. (2021) argued that a broad collaboration is needed among organisations, government, construction unions and local societies to early identify and successfully address modern slavery risks in the UK construction industry. However, a study conducted by Liu et al. (2022) in Australia revealed that governance, ongoing due diligence and monitoring and reporting of performance against modern slavery on behalf of construction enterprises are additionally required to tackle the relevant risks, apart from education and capability building. The crucial role of organisational governance, culture as well as management controls against modern slavery in the construction industry is also evident from a case study that was recently carried out for an Australian not-for-profit housing provider (Dodd, Guthrie and Dumay 2022).

2.2 Global Standards to Combat Modern Slavery in the Supply Chain

From a global perspective, several standards and frameworks regarding sustainability exist in the literature that can be used to tackle modern slavery issues. Three of them are the most renowned ones worldwide: the first one is the ‘United Nations Global Compact’ (UNGC), the second one refers to the Global Reporting Initiative (GRI) standards, and the third one has been developed by the International Standardisation for Organisations (ISO) and has been widely embraced by the industry. The rationale of each framework is briefly explained in the following paragraphs.

In particular, the UNGC framework was introduced in 2000 and it encompasses ten core principles to encourage businesses to align their strategies and operations with sustainability objectives (Haque & Ntim 2018). The fourth principle of the framework is particularly related to modern slavery, while the first two broadly refer to the responsibility of businesses to protect human rights. Also, the UN adopted the ‘2030 Agenda for Sustainable Development’ in 2015, which includes seventeen sustainable goals (17 UNSDGs), where target 8.7 aims to specifically eliminate modern slavery issues and end child labour by 2025 (Gleason & Cockayne 2018). There is a strong relationship between the 10 principles of the UNGC framework and the 17 UNSDGs; Principle 4 is related to 1,3,5,8,9,10,16 and 17 goals which refer to poverty, health and wellbeing, gender equality, inclusive and sustainable economic growth, resilient infrastructure and innovation, inequalities and peace and justice, respectively (United Nations Global Compact 2016). Additionally, in 2021 the UNGC launched the ‘SDG 16 Business Framework: Inspiring Transformational Governance’ to inspire organisations to transform their practices and promote ethics and corporate responsibility within the global value chain (Anon 2021).

The GRI framework provides a series of global standards for reporting, that multi-national organisations can adopt to assess and benchmark their own sustainability performance (Barkemeyer et al. 2015). Generally, series 200, 300 and 400 refer to economic, environmental and social performance, respectively. Specifically, the ‘GRI 408: Child Labor 2016’ and ‘GRI 409: Forced or Compulsory Labor 2016’ have been developed to assist businesses to report their impacts on topics that are directly related to modern slavery (Christ & Burritt, 2021). Furthermore, in 2019, the GRI collaborated with the ‘Responsible Business Alliance’ to develop ‘The Modern Slavery Reporting Toolkit’ to progress reporting on modern slavery (GRI & RBA 2019). The Toolkit can practically inform corporations about the legal requirements on modern slavery reporting and how to improve due diligence accountability and transparency in their operations, thus achieving a value chain (GRI & RBA 2019).

The third one refers to ‘ISO 20400 Sustainable Procurement-Guidance’ which was launched in 2017 by the International Standardisation for Organisations (ISO) to guide organisations on how to incorporate sustainable practices during the procurement phase (ISO 2017). ISO 20400 embraces the core principles of sustainable procurement such as accountability, transparency, respect and ethical behaviour among others. Thereby, it can increase the visibility and traceability of the construction supply chain towards mitigating modern slavery risks. It is noteworthy that ISO 20400 is built on the ISO 26000 sustainability framework, which was introduced in 2010 and is mainly developed to guide organisations to achieve social responsibility (ISO 2017). Therefore, both ISO 20400 and ISO 26000 frameworks are powerful instruments that organisations can use to successfully deal with forced labour related issues and contribute to the 17 UNSDGs.

2.3 Government Efforts and Other Initiatives Against Modern Slavery

Shilling et al. (2021) argued that strong economic countries such as Australia, Japan, North America and Western Europe, may be accountable for modern slavery risks due to imported goods from developing countries. Nevertheless, a few countries have currently established laws to directly combat modern slavery across supply chains. Particularly, in the 27 European Union countries (EU-27), only France and Netherlands have introduced the '2017 French Duty of Vigilance Law' and the '2019 Child Labour Due Diligence Law', respectively (Antislavery 2020). Though, Austria, Denmark, Germany, Italy, Luxemburg, Switzerland and Finland have launched action plans and have politically committed to establishing modern slavery legislation (Antislavery 2020). It is noteworthy that two-thirds of businesses in the EU-27 territory are not implementing due diligence on human rights and environmental impacts (European Commission 2020). Thus, the European Commission publicly consulted in 2021 with most of the G20 countries including Brazil, India and South Africa on an overarching perspective of modern slavery legislation for the EU-27 territory (Antislavery 2021).

In the U.S.A., California State requires businesses to comply with specific modern slavery legislation; the US Federal Government have in place the 'US Trade Facilitation and Trade Enforcement Act' since 2015 but it fights forced labour that is only related to imported products (Antislavery 2020). Although Canada committed to combat modern slavery at the G20 Summit in Germany, the relevant law is still under consultation. Conversely, the UK and Australian Governments have enacted the 'Modern Slavery Act 2015' and 'Modern Slavery Act 2018', correspondingly. Both require businesses to annually report on modern slavery if their annual turnover is larger than £36 million and AUD$100 million, respectively (McGaughey 2021; Trautrims et al. 2021).

Apart from legislation, there are also some voluntary initiatives against modern slavery at a business level. For example, the 'Liechtenstein Initiative in 2018 for a Financial Sector Commission on Modern Slavery and Human Trafficking' is a significant international collaboration between the public and private sectors as a response to G7 and G20 requests (Cockayne 2020). However, 11 out of the G20 countries still have not taken any action against this criminal phenomenon (Walk Free 2018). Another significant initiative is the 'Global Business Coalition Against Human Trafficking', which was resulted from the collaboration of the 'Business for Social Responsibility' organisation with the ILO Global Business Network on Forced Labour (Chandra 2019).

3 Research Methodology

This research employs a case study to achieve its aim. Selecting a case study as a research design is widely proposed to obtain in-depth knowledge of a complex research problem (Crowe et al. 2011). The case was drawn on the procurement practices of an Australian private listed organisation (referred to 'Entity' onwards).

The reasons for selecting the particular Entity in this research are: (1) it is a committed leader in developing sustainable commercial and residential projects for 70 years; (2) the Entity is required to report its actions against modern slavery to comply with the 'Modern Slavery Act 2018'; and (3) the Entity has implemented several key collaborative initiatives to address modern slavery issues.

The case study was conducted and analysed based on Feng et al.'s (2021) framework for enabling sustainable procurement. The framework consists of four key steps to practically guide organisations to enable sustainable procurement. The first step is ‘Enabling Awareness’, where drivers and barriers of sustainable procurement need to be analysed as well as the role of the key stakeholders and their potential benefits. The second step is ‘Enabling Alignment’, where sustainability objectives must be aligned to organisational targets and sustainable procurement policy and strategy must be developed. The third step is ‘Enabling Organisation’, which refers to the governance and capability of an organisation to implement sustainable procurement. Thus, procedures and systems, targets, and action plans should be established, while suppliers and other key stakeholders should early be engaged. ‘Enabling Process’ is the final step which includes preparing a sustainable sourcing strategy, establishing specifications that address sustainability criteria, awarding the contract to supplier, integrating sustainability in contract management, and evaluating and improving sustainability performance (Feng et al. 2021).

Data were collected by reviewing documents and records from the Entity and interviewing relevant staff. Data collection was guided by a structured data collection instrument that was developed following Feng et al.’s (2021) framework. The instrument consists of questions that aimed to explore the sustainable procurement practices implemented by the entity to address sustainability issues including modern slavery. The data analyses were organised into four categories including practices for enabling awareness, practices for enabling alignment, practices for enabling organisation, and practices for enabling process.

4 Findings and Discussion

The analysis of the case resulted in the identification of sustainable procurement practices that have contributed to addressing modern slavery issues. Following Feng et al.’s (2021) framework, these practices are summarised into four categories including enabling awareness, enabling alignment, enabling organisation and enabling process.

4.1 Enabling Awareness

To enable awareness, the Entity implemented two best practices including ‘leadership and collaboration’ and ‘risk and opportunity’. In particular, the Entity collaborated with the Property Council of Australia (PCA) and its members to develop the ‘online supplier platform’, which involves a questionnaire of more than 100 questions on modern slavery. The Entity also collaborated with its main contractor and another tech expert company to identify and assess modern slavery risks on seven major building materials for a pilot community project in New South Wales. The project involved the construction of 273 community residences, while the seven materials were ‘brickwork’, ‘carpets’, ‘joinery, ‘skirting’, ‘soffit lining and cladding’, ‘tiles’ and ‘window architrave’.

4.2 Enabling Alignment

The Entity utilised another two best practices that the Framework proposes. The first one is ‘strategy and action plan. The Entity has recently launched its sustainability strategy that embraces nine key priorities, one of which concerns the minimisation of modern slavery issues. To achieve this, it developed six key actions such as ‘collaboration’, ‘risk assessment’, ‘due diligence’, ‘policy’, ‘supplier engagement’ and ‘education’. In line with these actions, the Entity has set minimum requirements for material suppliers against unfree labour, based on which all of its suppliers must be annually assessed. The second one is related to the ‘sustainable procurement policy’. Particularly, its procurement policy expects the potential suppliers to demonstrate prior to the contract that their procurement practices are free from all forms of modern slavery. Additionally, the Entity has launched an online form, namely ‘Tell me’ within its ‘Whistleblower Policy’, through which its staff and suppliers can report actions that might put the Entity at ethical risks.

4.3 Enabling Organisation

The Entity implemented three key practices towards enabling organisation including staffing and resources, supplier engagement and training and education. The staff of the Entity are highly committed to sustainability and against any procurement practices and services that may be subjected to modern slavery risks. Thus, the Entity established the ‘Modern Slavery Working Group’ in 2019 to empower its Governance on this matter and to comply with the Modern Slavery Act 2018. The ‘Modern Slavery Working Group’ conducts monthly meetings with staff from other fields, specifically procurement, operations, sustainability, project management, legal, risk, investor relations as well as people and culture. Concerning the ‘supplier engagement’, the Entity engaged its ‘high-risk’ suppliers before the procurement stage to obtain the required data and finally assess suppliers for potential modern slavery risks. The Entity approached the suspected suppliers (Tier 1 supplier → Tier 5 manufacturer) to discuss the problem positively and to evaluate their knowledge and awareness of modern slavery. After that, it requested its suppliers to fill out three different types of questionnaires to evaluate the knowledge and capability of suppliers on reporting requirements around this matter. The third best practice is ‘training and education’. The Entity collaborated with several industry experts regarding modern slavery. The Supply Chain Sustainability School was one of them, where the Entity has established a partnership to educate and train its staff and suppliers, thus improving their knowledge and raising awareness about modern slavery.

4.4 Enabling Process

To enable the process towards addressing modern slavery risks, the Entity implemented practices such as ‘digitalisation and innovation’, ‘data tools and procedures’ and ‘monitoring and reporting’. Particularly, the Entity employed her partners’ novel digital tools (i.e., PCA platform, interactive dashboards etc) to assess the due diligence of its suppliers on modern slavery. In the first collaborative initiative, the Entity assessed more than 3,500 suppliers in four groups: ‘high risk-high spend suppliers’ (Group A), ‘high risk-low spend suppliers’ (Group B), ‘low risk-high spend suppliers (Group C)’ and ‘low risk-low spend suppliers’ (Group D). The risk assessment process involved modern slavery indicators taken from the ‘Social Hotspot Database’ such as ‘child labour’, ‘forced labour’, ‘excessive working time’, ‘safe working conditions’ and ‘exploitation of migrant labour’. Using the PCA platform, the Entity was able to assess its 26 Group A-suppliers for modern slavery risks successfully.

In the pilot community project, the risk analysis considered the origin of materials, the type of industry and modern slavery risk factors. ‘Skirting’, ‘soffit lining and cladding’ and ‘window architrave’ were identified as the materials with the highest potential modern slavery risks. The initial risk assessment process indicated that there was potentially one slave per 273 premises, which was considered by the Entity that it should be addressed before starting the project. Thus, a working group consisting of representatives of the Entity, the contractor and the consultant was formed to directly conduct with the high-risk materials’ suppliers. This working group developed and sent to potential suppliers three types of questionnaires: short, medium and long Property Council questionnaires. The first two types were sent to ‘less sophisticated non-reporting entities’, whereas the third one was sent to the ‘reporting entities’. Finally, the targeted suppliers provided the necessary data to the working group to successfully address the actual modern slavery risk of the high-risk building materials.

Regarding the practices in ‘monitoring and reporting’, the Entity was required to report its actions against unfree work to comply with the requirements of the ‘Modern Slavery Act 2018’. One such reporting requirement is to develop and publish every year the ‘Modern Slavery Statement’, in which the Entity reported 6 key actions against modern slavery. The Entity has been developing and updating tender packages to address the modern slavery, diversity and inclusion requirements. Suppliers must meet these requirements prior to contracting with Entity. Generally, the Modern Slavery Working Group is responsible to monitor suppliers for ethical risks, complete the corrective action plans and report to the Executive Committee periodically.

5 Conclusion and Further Research

This research employed a case study in the Australian construction industry to investigate sustainable procurement practices that could minimise modern slavery risks. The framework for enabling sustainable procurement developed by Feng et al. (2021) was used to analyse the case. The case study demonstrated how a large Australian property entity has responded to modern slavery issues through sustainable procurement practices. The key practices that contributed to addressing modern slavery risks include, leadership and collaboration, risk and opportunity, strategy and action plan, sustainable procurement policy, staffing and resources, supplier engagement, training and communication, digitalisation and innovation, data tools and procedures, and monitoring and reporting. The research findings imply that minimising modern slavery issues in the construction supply chain requires a holistic managerial approach and a high level of collaboration between stakeholders. A limitation of the current practices is the lack of evidence-based data to support modern slavery risk management. Existing sustainable procurement practices rely largely on self-reporting and self-assessment by the suppliers. In the future, studies can be conducted to develop innovative approaches that can capture and analyse objective evidence-based data to perform a modern slavery risk assessment and provide decision support for risk management.

6 Acknowledgement

This research has been developed with support provided by Australia’s Sustainable Built Environment National Research Centre (SBEnrc). SBEnrc develops projects informed by industry partner needs, secures national funding, manages collaborative research and oversees research into practice initiatives. Core Members of SBEnrc include ATCO, BGC Australia, Government of Western Australia, Queensland Government, Curtin University, Griffith University, RMIT University and Western Sydney University. This research would not have been possible without the valuable support of our core industry, government and research partners.

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Examining Site–Office Conflict in Construction Contracting: Adding to an Already Stressful and Stagnant Industry

Matt Stevens[1*], John Smolders[1] and Ali Alashwal[1]

[1]School of Engineering Design & Built Environment, Western Sydney University, Locked Bag 1797 Penrith NSW 2751, AUSTRALIA

matt.stevens@westernsydney.edu.au; j.smolders@westernsydney.edu.au; a.al-ashwal@westernsydney.edu.au

* Corresponding author

Abstract:
Site workers comprise approximately 80% of construction employment. These personnel deliver outputs that exceed or fall short of the contractor's estimate, such as safety, quality, cost and schedule. However, construction organisations have disparate working conditions and career paths between their site and office staff. Other factors, such as job security and travel requirements, add to the differences in attitudes toward their office counterparts and construction firms. This paper explores these dynamics and attempts to survey perceptions of these two groups. In construction, craft skill leads to quality which is a high priority. The study found different levels of conflict, but no one reported it as non-existent. It is dependent on the individual and the company for which they work. The data points to a need for continuing discussion and inclusion of all company members about the motivators and demotivators, especially those who staff the site. With turnover rates in triple-digit percentages in recent years, adding higher site-office conflict can lead to increased disloyalty to employers, decreased project performance and less labour availability.

Keywords:
Construction personnel, Contracting human resources, Field office, Interpersonal conflict

1 Introduction

All formally organised contractors have field and office operations. Each executes critical functions in the ongoing life of a construction firm. However, they have conflict historically. They don't get along in some ways due to personality differences or process requirements. It may be because of style, demands or perceptions, but it can be tragic for construction firms. Any internal conflict is controllable, however, left unaddressed threatens the revenue dollar with slower turns and higher costs. Change is inevitable in the industry and its projects. It is a result of a response to a dynamic environment, such as technological advances and the client's changing needs. The incongruence of project goals and objectives, such as its schedule, priorities, and competition for scarce resources, can cause conflict. Project organisations are significant sources of confrontation as they create an environment with incongruent goals and objectives. This is coupled with ambiguous roles, interface conflict, poor communication, the need for consensus, a high-stress environment, and high uncertainty about continual employment.

Construction contractors are essentially concerned with making project progress, reducing waste, focusing on efficiency and aiming to produce products and services at the lowest cost as quickly as possible. Critically, site workers deliver physical tasks, either exceeding or beating the estimate. The insistence on voicing the phrase "doing more with less" as a path may be off-putting to veteran site workers and office staff due to the industry's extremely high layoff rates. Stakeholders have not focused formally on the "too hot, too cold" nature of construction employment. Their advocacy for consistent company employment is missing.

Site-Office conflict is a specific type of workplace dynamic based on the experience and interaction of two distinct employee types and different job demands and conditions. This paper explores the gap in the literature about the significant differences in demands and working conditions between home office staff and site workers. It is theorised that these dissimilarities manifest in adverse outcomes such as conflict, stress and disloyalty. The survey proposed is the first step in understanding the depth and breadth of all effects.

2 Literature Review

The paper focused on the factors that create a site-office conflict. The topic of site-office conflict and various keywords demonstrated light research in this area. Our literature databases were SCOPUS and Google Scholar.

2.1 Sources of Conflict

Conflict is a prolonged disagreement between individuals or parties that impacts relationships and work. There are two kinds of conflict – small "c" as in a contract and large "C". Small c is functional. Large C is an intense conflict where both sides are losing (reputation, unproductive time, expense) but choosing to fight. This is viewed as dysfunctional. Research shows that functional conflict is a construction community problem. Site-Office conflict is not contract-based; thus, it can be dysfunctional because of the unbounded rules of human interactions (Smith 1992).

Interpersonal conflict arises when an individual in a group senses others blocking the desired outcome (Applebaum, Abdellah & Shapiro, 1999). This definition includes two general elements: a) individuals engaging together to achieve a goal, b) perceiving that one person in this group is not working toward that primary goal but has another (Raver & Barling, 2008).

Site-Office conflict may be caused by several factors such as misunderstandings due to poor communication, sensitivity of people, values (e.g., different values between the blue- and white-collars), interests and expectations, and personalities (e.g. how people react to lack of understanding) (Whitfield, 2012). Furthermore, Whitfield (2012) explained how a site supervisor used to refer to office employment 'as being reserved for the weak of mind and body'. Other project-related factors causing conflict include change, incongruence of aims, and structure of the project organisation (Adams, 1997).

Worker status is not articulated in accepted definitions of Lean Construction. Subsequently, the social costs of this focus are questioned by industry and academia (Huo and Boxall 2018). The researchers theorise that this drive to do more with fewer resources penalises site workers. Factors in the successful implementation of Lean include transformational leadership (Gaiardelli 2019). Furthermore, involuntary employment separation (Lost Last Job) ranged from 76% to 274% of the total employment population between 1991 and 2019 (ABS 2022). Organisations have to win new projects so all employees, especially site workers, can continue working; contractors' low-profit margins (ASX 2022) mean that stockpiling people between projects is impractical, and construction's hypersensitivity to economic activity (IBIS World 2022).

Over the years, the general approach has evolved from heuristic tools to a human-centric approach concerning quantitative and qualitative factors (Salentijn 2021). An organisation's learning curve is a critical management issue in reaching profitable productivity (Abdelkhalek et al. 2020).

Contrastingly, home or regional office workers focus on a portfolio of projects they manage. However, given their office comforts, safe work environment and non-viewed space in which to make mistakes, these white-collar workers are sometimes resented by site staff. These and other factors lead to Site-Office conflict. Lingard and Francis (2004) point out that adverse relationships are common due to how construction contracting organisations operate

There are some structural and process differences between site and office that traditional construction has borne from its approach. Stevens (2019) observes a litany of site-office differences in focus based on today's conventional structure and hierarchy of the industry. See Table 1.

Table 1 – Comparison of Site and Office Duties and Culture (Stevens 2019)

Field	**Office**
Builds projects with the help of the office.	Assists in the field and administrates the construction of projects.
Coordinates the workforce on one project.	Coordinates the workforce on all projects.
Receives, inventories, and installs material furnished by the office.	Purchases and coordinates material delivery, works with vendors on any delivery problems and returned material.
Maintains and utilises equipment.	Acquires equipment at the most reasonable price and condition.
Reports productivity, equipment utilisation, field conditions and other important information.	Uses this information for tracking this project's performance, discussions with client and for bidding next project(s).
Mistakes happen and are seen by all since they occur in open setting – the jobsite.	Mistakes happen and are not seen by all since they occur in a closed setting – the office.
Tied to one job. Lack of a project can mean unemployment.	Tied to multiple jobs. Lack of one job does not mean end of employment.
Project success is tied to contract agreement with clients (an office process).	Determines final price and agrees to contract with clients.
Directly manages installation process and reports physical progress to office	Indirectly manages and assists physical progress. Sends pay request to clients based on physical progress and then collects payment.
Directly controls safety, quality and productivity. assisted by office	Directly controls budgets and flow of information affecting safety, quality and productivity.
Critical to have successful field experience	Not critical to have successful field experience.
Measured by metrics established and data collected by office.	Establishes metrics and collects data that measure project performance.

Job satisfaction is a significant antecedent to higher productivity. Work conflicts, whatever their source, decreases that (Wang et al. 2020). Leung et al. (2002) argued that the construction team members' satisfaction diminishes as conflict escalates. Marzuki et al. (2012) asserted that construction job satisfaction is a predictor of several work-related factors like performance, commitment, motivation and productivity, which are required for project success. In relationships, it is easier and less expensive to resolve a conflict when it occurs and not ignore it until there is a dramatic effect on the people involved (Thomas, 2002). However, the stress of projects can alienate involved parties, diminish cognitive reasoning, lower motivation, and make a project extremely difficult at best. In addition, their families significantly affect employees' lives, both positively and negatively. If an interpersonal battle occurs at work, they cannot engage in home life effectively and vice-versa (Greenhaus and Beutell 1985). These factors may lead to emotional exhaustion, where a cascading effect of all stresses leads to suboptimal performance (Richards et al. 2019). Adding to these dynamics, Lingard and Francis (2004) found that site-based employees work longer, more irregular hours (before 8 a.m. and after 5 p.m.) than their office counterparts. The average number of hours worked each week was 62.5 among site-based survey participants in direct construction activity, 56.1 among respondents who work primarily on-site with some office duties and 49.0 among respondents dedicated to working in a corporate or regional office. Due to these complicating issues, every project team, including site and office personnel, requires clear communication, problem notification in real-time, and a high level of cooperation for error-free installation (Vaux and Kirk 2018). Duhigg (2016) notes high performing project teams benefit from norms such as openness and a supervisor standing up for one's point of view or blunting criticism for a member's mistake. Generally, it is regarded as "psychological safety" for individuals to express themselves.

Additionally, high-achieving teams have high average social sensitivity. Several dynamics were not observed in top quartile work teams, such as harsh judgements or "workface" i.e. members do not act differently inside and outside meetings. The research concluded that a group's emotional profile correlates weakly with accomplishment.

3 Research Methodology

The researchers employed an anonymous survey in their university's Qualtrics software system. This is due to the emotional and stressful subject matter. Additionally, as part of the survey preamble, we listed three free counselling services for those that needed them. The questionnaire was created from the 'researchers' industry experience and literature study. The survey targeted full-time professionals and working students employed in the construction industry. Our sample size was twelve qualified responses. We endeavour to recruit participants as this topic is developed further. A statistically significant sample computes to be 304 based on standard assumptions about generalisability. See Table 2.

Table 2. Survey Questions for Examining Site-Office Conflict and Response %)

Question	Possible Answers	Result
1. My current position is considered:	a) On-Site b) Home or Regional Office c) I have a desk in both places and spend significant time in each area	58.33% 25.00% 16.67%
2. I am considered:	a) Senior or Executive Management b) Middle Management c) Entry Level	0.00% 33.33% 66.67%

3. My specific role is	a)	Work Acquisition, such as Quantity Takeoff, Estimating, Tendering or Business Development	16.67%
	b)	Office Management, such as Project Management, Procurement, Financial Management, or Human Resources	25.00%
	c)	Site Management such as the Site Manager, Foreman, Site Engineer, Leading Hand or Workshop Manager	25.00%
	d)	A mix of 2 or more of the above	33.33%
4. Which duties do you perform that comprise 20% or more in a typical day	a)	Project Management, including Work Scheduling	18.75%
	b)	Procurement Activities	18.75%
	c)	Labour Management, including Safety duties	21.88%
	d)	Equipment Workshop Duties	3.13%
	e)	Office Management and Human Resources	6.25%
	f)	Financial Management	6.25%
	g)	Quantity Takeoff or Cost Analysis	9.38%
	h)	Client Development and Marketing	6.25%
	i)	Other	9.38%
5. What internal conflict between employees have you experienced or observed in your company?	a)	Physically contact	11.11%
	b)	Loud arguments	18.52%
	c)	Direct insults	18.52%
	d)	Gossip intending reputation harm	29.63%
	e)	Exclusion from important meetings that will affect a person's job performance	14.81%
	f)	Other	7.41%
6. What percentage growth (+) or decrease (-) of your company's employee count from 3 years ago?	a)	+25% or greater	41.67%
	b)	+10% to 24%	16.67%
	c)	0% to 9%	25.00%
	d)	-1% to -9%	16.67%
	e)	-10% to -24%	0.00%
	f)	-25% or greater	0.00%
7. Overall, our Site - Office personnel work well together - personally and professionally	a)	Strongly Agree	25.00%
	b)	Agree	50.00%
	c)	Neither Agree nor Disagree	8.33%
	d)	Disagree	16.67%
	e)	Strongly Disagree	0.00%
8. Our Post-Tender/Pre-Construction Planning is a full and transparent transfer of information so the Site teams can be successful.	a)	Strongly Agree	58.33%
	b)	Agree	8.33%
	c)	Neither Agree nor Disagree	25.00%
	d)	Disagree	8.33%
	e)	Strongly Disagree	0.00%
9. Our managers share equipment and tools across projects fairly	a)	Strongly Agree	25.00%
	b)	Agree	25.00%
	c)	Neither Agree nor Disagree	25.00%
	d)	Disagree	16.67%
	e)	Strongly Disagree	8.33%
10. Our Site and Office personnel meet face-to-face (or Zoom) regularly as needed	a)	Strongly Agree	33.33%
	b)	Agree	33.33%
	c)	Neither Agree nor Disagree	25.00%
	d)	Disagree	8.33%
	e)	Strongly Disagree	0.00%
11. Working together, our Project Managers and Site Managers review, summarise and document critical information fully as practical before each project mobilises.	a)	Strongly Agree	25.00%
	b)	Agree	50.00%
	c)	Neither Agree nor Disagree	16.67%
	d)	Disagree	8.33%
	e)	Strongly Disagree	0.00%
12. Our managers share personnel across projects	a)	Strongly Agree	41.67%
	b)	Agree	8.33%

fairly	c) Neither Agree nor Disagree d) Disagree e) Strongly Disagree	8.33% 33.33% 8.33%
13. Our culture discourages escalating conflict between employees - we always try to resolve it quicker rather than slower.	a) Strongly Agree b) Agree c) Neither Agree nor Disagree d) Disagree e) Strongly Disagree	50.00% 25.00% 25.00% 0.00% 0.00%
14. Our company fairly manages any comments or criticisms about the accuracy of the project tender including the cost estimates quantities and unit cost.	a) Strongly Agree b) Agree c) Neither Agree nor Disagree d) Disagree e) Strongly Disagree	25.00% 25.00% 41.67% 8.33% 0.00%
15. In our Company, Site experience is glorified and encouraged	a) Strongly Agree b) Agree c) Neither Agree nor Disagree d) Disagree e) Strongly Disagree	25.00% 58.33% 16.67% 0.00% 0.00%
16. In our Company, Employee performance measurements are equally fair to Site and Office personnel	a) Strongly Agree b) Agree c) Neither Agree nor Disagree d) Disagree e) Strongly Disagree	8.33% 66.67% 16.67% 8.33% 0.00%
17. Our Head Office's main focus is to support the Site teams fully, i.e., with information, material, trouble-shooting suggestions, and early notification of potential problems.	a) Strongly Agree b) Agree c) Neither Agree nor Disagree d) Disagree e) Strongly Disagree	41.67% 16.67% 41.67% 0.00% 0.00%
18. In your experience with the company, the current morale of Home Office personnel is	a) Strongly Agree b) Agree c) Neither Agree nor Disagree d) Disagree e) Strongly Disagree	8.33% 33.33% 41.67% 16.67% 0.00%
19. In your experience with the company, the current morale of Site personnel is	a) Strongly Agree b) Agree c) Neither Agree nor Disagree d) Disagree e) Strongly Disagree	16.67% 33.33% 16.67% 16.67% 16.67%
20. Please rank by moving with your cursor each statement from most valuable (1) to least valuable (9) to you.	a) Early notice of a home office request or change b) A full explanation of a problem or decision c) Clear graphics explaining a problem or decision d) Being included in conversations about company decisions e) Being told what I do well and could do better f) Fair arbitration of significant conflicts between employees g) Quickly informed about a new project and its information h) Clear instructions about my work assignment and expectations about completing it i) Professional support and help with my work challenges	5.92 3.83 5.00 5.17 5.42 5.34 7.21 3.09 4.34

4 Findings and Discussion

The sources and solutions to field-office conflict are not apparent to the outsider. However, the researchers have experienced the dynamic through their industry careers and literature review. Fundamentally, all formally organised contractors have field and office operations, which should be aligned with completing work safely and productively while meeting the specifications. Sometimes, however, mismatches between the culture and practices of the office and the field can interfere with employees' ability to keep the larger goal in mind. This paper is about articulating that breakdown, the nature of the disconnect, and creating ways to talk about working together that can unite companies.

The demographic questions (1-4) demonstrate a professionally heterogenous group engaged in the survey, i.e. site and office; all functions of a construction contracting firm and diverse titles. Although Senior management was not represented, the entry-level and middle-management employee segments might be better since they are the vast majority of employees directly harmed by this specific conflict.

Question 5. What internal conflict between employees have you experienced or observed in your company – the answers indicate that conflict is evident in the construction firms that the employees are employed by. 27 responses were recorded indicating that, on average more than two conflict incidents per employee were recorded.

Questions 15-17 focus on the organisational culture concerning site support. The results reveal that the organisations surveyed are generally supportive and positively regard field operations and their personnel.

Questions 18-19 concern the morale of the site and office personnel. The results show a disparity average between them, with site staff lower by one point on a scale of five. This aligns with previous research's conclusions.

Question 20 concludes that the three most desired company actions by employees are communication about complex issues - h) Clear instruction about my work assignment and expectations about completing it (mean ranking 3.09); b) A full explanation of a problem or decision (mean ranking 3.83) and i) Professional support and help with my work challenges (mean ranking 4.34). This seems to indicate a more family or "clan" culture where areas of employee performance are discussed actively and not once a year during a performance review.

The office and the field execute key functions in the ongoing life of a construction firm. However, they have conflict historically due to the condition under which they work. Sometimes, distrust occurs because of working style, personality or perceptions, but it can be tragic for construction firms. Any internal conflict is controllable, however, left unaddressed threatens the revenue dollar with slower turns and higher costs.

The field and the office are separate but equal. Each is critical and cannot be eliminated. The problem is that their different working styles and cultures create a lack of understanding that can lead both sides to see the other as less critical, less central, or less productive than the other. The general role of office personnel is to ensure that a contractor wins projects, builds those projects profitably and gets paid for it. To do this, they need to track everything. Paperwork is a legal and practical requirement. The office style is formal; written communication is desired and sometimes demanded due to potential legal liability. From the field's perspective,the building process is dirty, dangerous and deadline oriented, but the office needs the information written documentation immediately.

However, the field as a group influences or controls the majority of the organisation's project costs. 100% of revenue is generated by project progress. However, the office coordinates all resources and allocates them with a balanced perspective. Additionally, factual and up-to-date information about pending change orders, requests for information and material delivery dates is desired. They also want preferred crews on the job consistently.

Field versus office conflict is evident in all construction firms, whether its intensity is minimal, strong, or somewhere in between. Enlightened companies acknowledge it and constantly monitor it, informally acting to lessen it. Of course, they do so for their benefit, as optimising the performance of employees is the most efficient path to the project and organisational success. Losing valuable employees may be the quickest way to a firm's demise.

Our literature has confirmed that this topic is significantly dynamic but lightly researched. This research asserts that human resources make the most considerable difference. Site-office conflict is just one component of an organisation's culture, but minimising it facilitates people to work together better.

5 Conclusion and Further Research

Site-Office conflict in construction organisations has been minimally researched. The topic appears to be an opportunity since people still build projects and significant contractors have a distinct site and office staff. The difference in styles, duties and working conditions are substantial.

This research can establish a framework for analysing, diagnosing, and healing site-office conflict, which affects safety, quality, cost and schedule. Adverse outcomes can emerge if distrust and active conflict are not addressed. Some of the poor results include organisational weakness in communicating information to assist in managing—secondly, the limited flexibility of an organisation in staffing project teams due to interpersonal problems. Also, employee turnover caused by a productivity loss, i.e., a replacement's learning curve, significantly adds cost. Lastly, unresolved conflict may relate to the workers' high-stress levels and psychological distress.

Further research should be pursued about remedies for field and office conflict and other interpersonal strife in construction organisations. In addition, other questions about company cultures, such as family, team and clan, must be answered in light of management and labour shortages and high turnover rates.

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What's in a Job? Indigenous Construction Workers' Employment Preferences

George Denny-Smith[1*] and Martin Loosemore[2]

[1]RPS | Social Advisory and Research,
Level 13/420 George St, Sydney, NSW 2000, AUSTRALIA
[2]Faculty of Architecture and Building, University of Technology Sydney, PO Box 123
Broadway NSW 2007, AUSTRALIA

george.denny-smith@rpsgroup.com.au; Martin.Loosemore@uts.edu.au
* Corresponding author

Abstract

Indigenous procurement policies (IPPs) have created more business and employment opportunities for Indigenous Australians. IPPs in Australia require contractors tendering on government-funded projects to include more Indigenous businesses and employees in supply chains. This type of social procurement, as it is called, is a new approach to addressing the complex socioeconomic inequities experienced by Indigenous Australians through market-driven business and employment opportunities and create social value with Indigenous businesses and workers. But although IPPs have increased demand for Indigenous construction workers, Indigenous Australians continue to experience racial discrimination in the workplace. Therefore, the aim of this paper is to mobilise cultural- and construction-specific employer of choice insights to investigate construction practices contributing to social sustainability in an Indigenous procurement context. Drawing on a sample of 31 Indigenous respondents to an online survey, the results indicate that Indigenous construction workers prefer workplaces that have culture benefits (looking after families and communities and cultural security) and are culturally responsive and have structured career progression pathways when selecting a job. The results presented in this paper are a significant contribution to promoting social sustainability in the construction industry. Construction managers wanting to promote Indigenous employment on projects or in their companies can use these insights to influence workplaces that promote sustainable employment outcomes with Indigenous staff. Policymakers could also use these insights in policy development and encourage contractors to create workplaces that address discrimination and collaborative solutions to creating social value in the industry.

Keywords

Employer of choice, Indigenous employment, Indigenous procurement, Social procurement, Social value

1 Introduction

Project management research has recently shifted focus to the value that projects deliver to a broader range of stakeholders (Green and Sergeeva, 2019). This has occurred simultaneously with a change in construction project management to focus on how construction employment can be used to address the socioeconomic inequities facing marginalised groups and migrants in Australia and internationally (Loosemore *et al*., 2022; Troje, 2022). Known as social procurement, these nascent practices aim to create social value in the communities in which projects are built. Social value typically refers to the economic and social impacts of construction projects, although scholars acknowledge that social value is still in development as a conceptual and operational term, and there is a general lack of consensus on what it means and how best to create it (Raidén *et al*., 2019). Nevertheless, the growing interest in how the construction industry can create social value is of great interest to policymakers aiming to address longstanding socioeconomic inequities, and socially responsible companies interested in leaving a positive legacy in their communities through socially sustainable business practice.

The growing interest in social value and social sustainability in construction has been in response to the socioeconomic inequities experienced by Indigenous Australians compared to non-Indigenous Australians since Australia was colonised in 1788. For example, Indigenous Australians are more likely to be employed on a casual basis and face significant employment barriers like digital exclusion (Minderoo Foundation and Generation One, 2021). This is widespread, where Indigenous health workers' cultural and community knowledge can be overlooked in favour of established health professions (Bond *et al*., 2019). The exclusion of Indigenous workers in construction may be more significant – non-Indigenous contractors view Indigenous businesses and workers as a significant time, cost, quality and safety risk to their operations (Loosemore, Alkilani and Mathenge, 2020). These barriers are significant challenges to using construction employment to promote social sustainability by addressing socioeconomic inequities because they may enable unconscious bias towards Indigenous contractors and employees. Unconscious bias towards Indigenous employees could result in adverse impacts if it leads to workplace racial discrimination or barriers to career development and progression (DCA/Jumbunna Institute, 2020).

To address the barriers touched on above, Australian governments have been encouraging the private sector to employ more Indigenous Australians and address perceptions of Indigenous businesses and workers through Indigenous procurement policies (IPPs). IPPs are a form of social procurement that require contractors working for government clients to meet procurement and employment targets (NIAA, 2020). Advocates of this approach argue that promoting Indigenous businesses in supply chains causes greater growth in Indigenous businesses, which drives greater demand for Indigenous employees (Evans *et al*., 2021). In the context of the construction industry, IPPs require companies tendering for government construction contracts to create 'social value' for Indigenous people living in the communities in which they build. The social value targeted by IPPs typically involves business and employment opportunities for Indigenous Australians, as government agencies and contractors must meet specified targets to use Indigenous suppliers and workers during project delivery. Social value is implied to be created as Indigenous suppliers and workers financially benefit from IPP requirements and reinvest in their businesses or professional skills. Social value in an IPP context may therefore be similar to the ability of Indigenous peoples to pursue their own forms of economic development (United Nations, 2007).

However, several barriers may limit the effectiveness of IPPs that stimulate Indigenous employment. As Gurmu *et al*. (2022) found, social sustainability initiatives in construction are often overlooked when contractors must decide between economic performance, environmental impacts, health and safety, and social outcomes. Indigenous employment creating social value may therefore be a lower priority for contractors if they need to spend time developing a construction workplace that creates social value. In an operational context, this means that Indigenous construction workers, who face some of the highest perceived barriers to employment of the groups targeted by new social procurement policies (Loosemore, Alkilani and Mathenge, 2020), may face further barriers if contractors view Indigenous employment as an extra task they must perform. This could perpetuate discriminatory behaviour if Indigenous contractors or workers are seen as too hard to employ or support or too inexperienced. Indeed, a recent study on the workplace experiences of Indigenous Australians found that 64 percent of participants had heard racial or ethnic slurs in their workplace, while 73 percent of participants reported being treated unfairly at work because they are Indigenous (DCA/Jumbunna Institute, 2020). More recent research on the impacts of contractors' compliance behaviour in an IPP context found some jobs are created in construction for compliance and tokenistic work (Denny-Smith, 2021). Denny-Smith's (2021) research found that tokenistic jobs that offer no meaningful work or career path create more negative impacts than positive ones because Indigenous employees feel excluded from productive work. Such is the importance of this subject that the Australian Government issued a public call for contributions to the new Indigenous skills, engagement and employment program introduced in 2021-22 (NIAA, 2021).

Therefore, the aim of this paper is to present new empirical insights into the workplace preferences of Indigenous Australians in the construction industry. The paper specifically answers the research question: How can construction workplaces promote social sustainability and social value for Indigenous employees? This work is timely and relevant given the discrimination Indigenous Australians face in the workplace (DCA/Jumbunna Institute, 2020). Research like this also addresses the need for employers to better value the skills and perspectives of Indigenous Australians (NIAA, 2021). Overall, this research promotes the conference theme of social sustainability in construction because the findings below demonstrate how construction workplaces can be designed so Indigenous employees have a more positive experience and therefore create social value in the form of positive impacts experienced by staff. The following section critically reviews theories of employer of choice (EOC) used which have been used to develop a theoretical framework that explores Indigenous employees' workplace preferences.

2 Employers of Choice

EOC research is built on Holland's (1997) Theory of Career Choice that argues people have a choice of where to work and realise that different career choices are likely to lead to different levels of job success and satisfaction. The concept of employer of choice builds on Holland's work to argue that workers will choose employment where they can take advantage of their skills and there is a balance between theirs and the organisation's values (Elving *et al.*, 2013). In general, EOC literature provides the insight that people look for employers who offer various combinations of the following criteria, in no specific order of priority: pay, conditions and benefits; employee engagement; leadership quality; safety and well-being; quality of workplace relationships; positive workplace culture and climate; equal opportunities, career development opportunities; flexible work practices, worker involvement and empowerment; receiving and giving feedback on work performance; clear company strategy and values; healthy and stimulating work environment; and corporate citizenship and sustainability (Kuhnel, Sonnentag and Westman, 2009; Song *et al.*, 2020).

The EOC literature is particularly useful for conceptualising how construction workplaces can promote social value because it highlights the intersection between employees' values and workplace experiences that create an enjoyable workplace. This insight is reflected Elving et al. (2013) who developed five variables to explore how employers brand themselves to become EOCs: Organisation attractiveness refers to whether potential employees see a company as a desirable and positive place to work; Job and organisational characteristics and person-organisation fit refers to companies that share similar characteristics and attitudes to employees; Corporate image involves perceptions of the company that increase or decrease organisational attractiveness by signalling positive job attributes, therefore increasing the quality and quantity of candidates; Employer image refers to a company's reputation as an employer in the labour force and; Employer branding serves as a management framework that can help improve employee recruitment, retention and commitment in addition to increasing productivity.

While construction EOC research is limited, what research exists gives potential insight to construction-specific workplace preferences. Burt's (2003) research into the factors that influence construction graduates' decision about a future employer found that the most important factors were, in order of priority: company culture; advancement opportunities, type of work; location; training opportunities; company size; salary; entry position; and signing bonus. More recently, Sedighi and Loosemore (2012) explored the preferred workplace characteristics of graduates in the construction and engineering field and found that the top ten factors included, in order of rated importance: Good quality working relationships; Being able to learn on the job; A workplace that is passionate about work; A relaxed, fun and social workplace; Seeing and understanding the purpose of tasks; Recognition and encouragement of my contribution; A workplace with training programs; Training in how to use new technologies; Working with people who have the same values and approach to work and; Flexible hours. Other research has found the following indicators of construction EOCs: technology, business culture, commute time, salary compensation, health, and the implementation of work-life balance initiatives.

Recently, Denny-Smith *et al.'s* (2021) research on how construction employment can assist Australia's economic and social recovery from COVID-19 argued that employers who provide 'culture benefits' and 'work benefits' are more likely to promote social value because they align with the values and workplace preferences of employees. Interrelated constructs, culture benefits refers to the environment a workplace creates such as engagement with local communities, mental health promotion and an inclusive work environment. Work benefits refers to things like pay and income, employee autonomy and routinised behaviour and tasks. Although useful, these industry-focused insights need to be balanced with Indigenous EOC insights, discussed below.

Research on the relationship of Indigenous workers to their employers is relatively scarce (Hunter, 2015). What is known is that Indigenous businesses have significantly better outcomes for Indigenous workers compared to non-Indigenous businesses (ibid.). This is because Indigenous workers may choose to work in organisations that understand Indigenous cultural norms, values, or obligations.

Indeed, research on Indigenous entrepreneurs who start their own business has found they have inherently prosocial motivations, where Indigenous entrepreneurs aim to create positive socioeconomic outcomes for their family and community (Evans and Williamson, 2017). Other research argues that ideal employment characteristics for Indigenous peoples allow them to perform customary activities while earning income (Cairney and Abbott, 2014). Financial rewards like income are also only one element of good employment characteristics and Indigenous workers may use the pay on offer as a precondition necessary to realise other benefits, such as: respect for and preservation of traditional values and practices; reduction of poverty; improvement in living conditions; further employment creation, and so on (Dana, 2015).

Therefore, Indigenous workers may seek employers who provide these non-financial benefits in preference to financial benefits. Recent research by leading Indigenous organisation Supply Nation (Burton and Tomkinson, 2015) and other Indigenous and non-Indigenous researchers suggest that Indigenous workers would derive greater benefits from employment opportunities which (Bond *et al.*, 2019; Wilson *et al.*, 2019): Provide a culturally safe and supportive environment; provide economic outcomes like paid employment and education; Sustain a connection to culture; Provide career structure and pathways where Indigenous professionals are not questioned on the legitimacy of their roles, as occurs with non-Indigenous professionals; Support communities; Provide a safe and welcoming space to connect with each other and; A positive approach to interacting with family and community which strengthens empowerment.

The above review gives several critical insights for exploring the workplace preferences of Indigenous construction workers. The EOC literature explains that positive construction workplaces may align with employees' values and workplace preferences. Taken together, these insights form the theoretical framework used in this research. The method to test the theoretical framework is discussed below.

3 Method

Acknowledging that Indigenous peoples have often been viewed as subjects of study by curious non-Indigenous researchers (Janke, 2021), this research adopted a participatory approach to research design, data collection and analysis. The researchers worked with two large Indigenous contractors to co-design the research including methods of data collection and analysis. This helped overcome the researchers' positionality as non-Indigenous researchers and ensured any cultural biases they brought were acknowledged and circumvented. A survey tool was employed after consultation with participating organisations in the Australian construction industry. The two organisations were based in the Australian state of New South Wales. One of the industry partners has worksites across Australia, and the partners' involvement allowed the research team to maximise the reach of the recruitment and data collection strategy. Online surveys offered several benefits to partnering organisations, including reducing costs to distribute and collect survey responses from geographically dispersed sites in regional areas of Australia where staff were based, maximising survey coverage to the target sample population, improving response rates because of improved ease to complete the survey, and reducing social desirability bias (Dillman, Smyth and Christian, 2009).

The survey consisted of two sections, and respondents were identified and approached through partner contracting organisations using purposive nonprobability sampling on the basis of their employment in the construction and property maintenance industries. The first part of the survey asked demographic questions about age, cultural identity, and the state or territory they worked in. The second part of the survey asked respondents about their values based on the research by Bellou *et al.* (2015) which showed that EOC's have values that are strongly aligned with the values of employees. The third part of the survey asked respondents to rank the importance of 31 EOC characteristics from the results of EOC research on construction graduates by Sedighi and Loosemore (2012) and based on a four-point Likert scale (1 = unimportant to 4 = important). The four-point scale was used as a forced-choice question that makes respondents choose an option for or against a question. Forced-choice questions were used in this survey to minimise the risk of social desirability bias and helped highlight respondents' relationships between different questions. The questions in this part of the survey were adapted to include social and cultural variables based on the literature review above. An open-ended final question allowed respondents to insert EOC variables not covered in the survey.

After developing the survey using the above variables, industry partners were consulted for further discussion on how data would be collected and managed. For example, the research team took direction from industry stakeholders on the format of the survey, and a shared agreement was reached that the content was accurate to investigate social value in a construction context, thus improving the content validity of the survey (Fowler, 1995, p. 139). The survey was distributed to 190 people working for two industry partners across Australia, using purposive sampling to ensure the survey was distributed to workers in the construction industry. To maximise the response rate, an email was sent to each respondent with an invitation letter which ensured respondent anonymity and allowed them to ask any questions of the research team and withdraw their data at any time. The results of completed surveys are presented below.

4 Results

142 surveys were completed of the 190 issued to staff at the research partner organisations indicating a high response rate of almost 75%. In total, 31 respondents (21.8%) were Indigenous and most (65.5%) were based in New South Wales. A geographic spread in the sample was expected because one of the partnering organisations has sites across Australia, where they contract building and facilities maintenance services for government clients. The majority of respondents being in New South Wales was also expected because both partners are headquartered in that state and that is where the majority of their work is. While the sample size of Indigenous respondents could be considered low, the proportion of Indigenous respondents reflects the disproportionate employment of Indigenous workers in Indigenous organisations (Minderoo Foundation and Generation One, 2021). Therefore, the 31 Indigenous survey responses is helpful for an exploratory study that builds foundations of workplace designs that create social impact and promote social value.

Table 1 below shows the ranked mean scores of Indigenous respondents' values. The relatively low standard deviation of the five highest ranked variables indicates a higher degree of agreement between respondents. Table 2 shows that the values most important to respondents (where mean is greater than 3.50) were: *Finding things out and learning for myself*; *Respecting my Elders and what they have to teach me*; *Sharing with and looking after my family*; *Making sure I have enough for today*; *Knowing who I am and where I came from*; *Staying connected with my wider relatives and community*. These values display egalitarian tendencies and support earlier research that has explored values important to Indigenous Australian cultures (Bessarab and Forrest, 2017). In a construction employment context, this could mean that workplaces that encourage egalitarian values may be more likely to attract Indigenous workers and, consequently, create social value for Indigenous construction workers. Theories of workforce inclusion that argue workplaces that are authentic, respect and value the workforce, and recognise, honour and advance community and workforce inclusion may help employers do this.

Table 1. Indigenous respondents' values by ranked mean (Denny-Smith, 2022).

Value variable	Mean	SD
Finding things out and learning for myself	3.76	0.511
Respecting my Elders and what they have to teach me	3.72	0.528
Sharing with and looking after my family	3.72	0.528
Making sure I have enough for today	3.67	0.480

Knowing who I am and where I came from	3.64	0.559
Staying connected with my wider relatives and community	3.59	0.628
Making sure traditions, rituals and practices are maintained	3.45	0.686
Sharing with and looking after my community	3.28	0.797
Building wealth for future purposes (i.e. tomorrow and beyond)	3.24	0.872
Travelling widely and experiencing the world	2.90	0.817
Staying close to the place I was born	2.83	0.805
Having possessions (like a house, car, fashion items) to show my status	2.66	0.974
Making lots of money	2.62	0.903
Making sure people know about my achievements	2.28	1.032

Table 2 below shows the ranked mean scores of Indigenous respondents' preferred workplace characteristics. The top ranked workplace characteristics are variables related to non-financial workplace characteristics such as *Being able to learn on the job* and *A good reputation*. This is useful because employers could develop these characteristics in the workplace to create social value for Indigenous employees. For instance, if employers want to develop a good reputation as a culturally supportive environment for Indigenous staff, they should focus on their workplace's readiness to include Indigenous staff in sustainable career development opportunities (DCA/Jumbunna Institute, 2020). This includes mentoring and training opportunities and as Table 2 below shows, these preferred characteristics are likely to create social value when applied in the context of construction employment.

Table 2. Indigenous respondents' workplace preferences (Denny-Smith, 2022).

Workplace characteristic variable	**Mean**	**SD**
Being able to learn on the job	3.85	0.362
A good reputation	3.79	0.499
Good quality of working relationships	3.77	0.514
A workplace that is passionate about work	3.75	0.441
Working with people who have the same values and approach towards work	3.71	0.460
A workplace that has a high commitment to work	3.70	0.465
Receiving and giving feedback on work performance	3.70	0.542
A workplace that is relaxed and people can have fun and enjoy social interaction	3.68	0.548
High level of personal physical safety	3.61	0.685
A manager that focuses on leadership and energy in the workplace	3.56	0.577
A workplace that cares about protecting the environment	3.54	0.576
Training in how to use new technology	3.52	0.802
A workplace with training programs	3.52	0.580
A workplace that allows me to stay connected to my culture	3.50	0.638
Seeing and understanding the overall purpose of tasks	3.48	0.643
A manager who is aware of and responsive to my heritage and culture	3.43	0.790

Being involved with my local community	3.39	0.685
An employer who encourages me to feel strong about who I am	3.32	0.723
Emotional stability and feeling protected by the organisation	3.29	0.810
A manager that focuses on management and administration	3.26	0.712
Clear pathways for me to progress in the organisation	3.26	0.813
A workplace with flexible work hours	3.22	0.892
Recognition and encouragement of my contribution	3.22	0.751
Having a say in decisions that affect day-to-day business	3.11	0.956
Working extra hours (paid or unpaid)	3.07	0.675
A high standard of accommodation and fit-out of the workplace	2.93	0.940
High pay and income	2.89	0.737
Travelling to different locations to perform my work duties	2.81	0.786
Paid on a salary basis, with a set annual income	2.74	0.984
Paid by the hour	2.43	1.034
Union membership	1.89	1.121

Finally, Spearman's rank correlation test was used as a nonparametric test to identify relationships between variables, demonstrating that Indigenous participants' values and workplace preferences may be linked. This is useful to employers and policymakers who may want to encourage certain values or workplace characteristics because they may be related to other characteristics. The Spearman correlation test gives a figure between -1 and +1, with a relationship of 1 indicating a perfect relationship. Table 3 shows the results of a Spearman's rank correlation where $r > 0.650$, indicating a strong relationship between two variables.

Table 3. Spearman's correlation rest results (Denny-Smith, 2022).

Workplace benefit	Mean	Correlating culture benefit	Mean	r	p
A workplace that allows me to stay connected to my culture	3.50	Sharing with and looking after my community	3.28	0.781	0.000
Emotional stability and feeling protected by the organisation	3.29	Sharing with and looking after my community	3.28	0.722	0.000
A manager that focuses on leadership and energy in the workplace	3.56	Sharing with and looking after my community	3.28	0.711	0.000
Working extra hours (paid or unpaid)	3.07	Having possessions (like a house, car, fashion items) to show my status	2.66	0.650	0.000

5 Discussion

Synthesising the exploratory results above, the analysis found several culture and work benefits that workplaces could aim to provide, which could create social value. Critical culture benefits include: Staying connected with my wider relatives and community; Sharing with and looking after my community and; Culturally supportive and inclusive workplaces. Critical work benefits include: Good quality working relationships; A workplace with training programs and; Participatory workplaces. These characteristics could be inserted into policy documents that become contract clauses. For example, they could be used to put specific employment practices in New South Wales' Aboriginal procurement policy or Victoria's Social procurement framework, to require contractors to report on their community engagement or efforts to promote mental health in the workforce. Building on Gurmu *et al*.'s (2022) recent thematic social sustainability work, the employment characteristics could therefore serve as 'policy guidelines' and 'social sustainability performance indicators' that are used to regulate contractors' behaviour on government-funded projects and monitor the social value created by IPPs. Encouraging these types of construction workplaces that create social value make IPPs more likely to attain the social outcomes and value that social procurement policies aspire to (Loosemore *et al.*, 2021).

Regarding Indigenous EOCs, the findings in this paper support some elements of existing research and add important new insights. For example, correlated findings like *Sharing with and looking after my community, A workplace that allows me to stay connected to my culture* and *A manager who is aware of and responsive to my heritage and culture*, provide a new, construction-specific evidence to prior research that indicates sustained cultural connections in the workplace, supportive work environments and support communities are critical employment factors for successful Indigenous employment (DCA/Jumbunna Institute, 2020). This is an important insight because, while Loosemore et al.'s (2021) research found that social procurement in a facilities management company can create strengthened relationships and create social value for disadvantaged cohorts, this finding highlights that workplace relationships may also be important for experiencing social value in a separate context relevant to Indigenous workers. Other variables like *Having a say in decisions that affect day-to-day business* and *Paid on a salary basis* also support research that emphasises the importance of sustainable career pathways for improved work environments for Indigenous staff (DCA/Jumbunna Institute, 2020), that are not limited by assumptions about the legitimacy of Indigenous professionals (Bond *et al.*, 2019). Workplaces that encourage staff to find things out and learn for themselves, instead of constantly being told how to act and work, could create more social value for staff if they promote staff autonomy. This could contribute to holistic notions of social value that emphasise the importance of community, context and culture for community and economic development (tebrakunna country, Lee and Eversole, 2019).

For Indigenous workers in a construction context, the results above indicate that social value is best created when Indigenous staff are able to work in positions that offer career development and recognition of Indigenous governance. This includes being mindful of the cultural values and obligations of Indigenous staff. This is a significant contribution of this research that can be used to promote social value and maximise the impact of construction employment in the context of existing employment and employment facilitated by new social procurement policies like IPPs. While other research has proposed strategies for businesses to better include the voices of Indigenous staff through means like structured career pathways and addressing discrimination (DCA/Jumbunna Institute, 2020) led by Indigenous staff (Bond *et al.*, 2019), authors have previously not specifically addressed the notion of creating social value in construction workplaces. The findings in this paper address these limitations, and the lack of theoretical insight into creating social value. Findings highlight the culture and work benefits that can be used to create structured career pathways, by having formal support and training programs, and address discrimination by using principles of cultural responsiveness. This is an important contribution to social sustainability research in construction that has identified a need for deeper project-level resources and relationships to develop the bottom-up approaches needed to better implement social procurement on construction sites (Troje, 2022).

6 Conclusion

This paper presented the results of an online survey to respond to explore how social value might be created for Indigenous construction workers in the context of construction employment created by IPPs and assist construction employers to promote social sustainability in their business. For Indigenous construction workers the results indicate culture benefits like looking after families and communities and cultural security are important for creating social value in an IPP context. The results also indicate that workplace characteristics that are likely to create social value include culturally responsive workplaces and structured career progression pathways. This is a significant contribution to the Indigenous EOC literature because it develops recent research calling for strengthening connections with family and social networks (Dudgeon *et al.*, 2021) or demonstrating the need for workplace readiness so that Indigenous staff experience less cultural strain and discrimination (DCA/Jumbunna Institute, 2020). Ultimately, the insights above could be embedded into policy aiming to create sustainable Indigenous employment in construction. Because a portion of non-Indigenous Australians also still hold inherent biases towards Indigenous Australians (Thurber *et al.*, 2021), this paradigm shift will require sustained efforts to better educate construction contractors.

7 References

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Review of Maturity Models Developed in the Construction Industry: Definitions, Applications and Methodologies

Sara Rashidian[1*], Robin Drogemuller[1] and Sara Omrani[1]

[1]School of Architecture & Built Environment, Queensland University of Technology, George Street QLD 4000, AUSTRALIA

sara.rashidian@hdr.qut.edu.au; robin.drogemuller@qut.edu.au; s.omrani@qut.edu.au
* Corresponding author

Abstract
Maturity models (MMs) have emerged as significant tools to support organisations' management. These models demonstrate how the capabilities required to support a specific function or activity can be developed over time. This enables businesses to plan how to build new capabilities, track the current status of implementation of these capabilities, and plan the actions that will lead to the desired outcomes. In recent years, there has been a rise in the use of maturity models (MM) throughout the construction industry. However, no study has reviewed the areas covered by maturity models in this sector. This paper aims to provide insights into the recent updates in the literature on MMs in the field of construction studies, discuss the direction and objectives of the studies in the development of the MMs, and identify the methodology employed to develop the models. The results were obtained through a systematic literature review (SLR) covering the years 2012 to 2022 and by using the PRISMA method to guarantee that reliable references are discovered and incorporated into the investigation of recent developments in research trends, MMs applications, and definitions in the construction industry. Out of 299 publications on MMs in construction, 64 papers on MMs development were chosen, while papers with the goal of evaluating and verifying MMs were removed. The research revealed that the majority of MMs focused on Building Information Modelling (BIM), followed by sustainability and construction safety. In addition, the evaluation indicated a lack of certainty in the methods used to establish the maturity levels and the paper's direction according to the MMs' declared goals.

Keywords:
Construction industry, Domain application, Maturity model, Systematic literature review

1 Introduction

Maturity models (MMs) have become a significant enterprise management tool to assist decision-making in the organisation and achieve business excellence by aligning their activities and processes with their business goals, policies, and strategies. MMs indicate how a particular method has evolved through time, helping organisations to evaluate the current situation and improve the planning of activities to achieve the desired results (Rashidian *et al.*, 2022). In construction companies, such models help provide the operational circumstances required to successfully manage organisational transformation (Wendler, 2012, Becker *et al.*, 2009).

While the MMs emerged from software engineering, their application is broad, and the diversity of the researched disciplines indicates the MMs' applicability in various sectors (Wendler, 2012). More specifically, their application has been adopted by the construction industry at an ever-increasing rate (Santos-Neto and Costa, 2019). However, although MMs can leverage the success of organisations by monitoring the evolution of processes, the lack of maturity structure design procedures for evaluating and operating MMs may be a barrier that brings confusion among the users (Wendler, 2012). For instance, a detailed description of the characteristics of MMs, attributes and levels is lacking, as is an account of how they were created (Liang et al., 2016). In addition, there is a dearth of reviews on the various applications of MMs in the construction industry. Despite prior research highlighting the significance of MMs in many sectors, the publications' scope is too broad to cover all the fields used or too narrow to cover a particular domain. In addition, no systematic review specifies what already exists or should be addressed in the future under this emerging topic. Santos-Neto and Costa (2019) conducted a systematic review of enterprise maturity models and covered the MMs in all applied areas. However, this paper extends their work with the goal of a) providing an overview of the existing implications of MMs in the construction sector in particular; b) identifying the themes associated with the major domains in construction; c) revealing the methods applied to develop the MMs; and d) providing a deeper understanding of the MMs' development purposes. This analysis will be helpful for identifying prospective topics for further investigation. Based on the established objectives, this study investigates the areas of development of MMs and answers the following questions:

1. How has the number of published papers changed over time?
2. In which domain are MMs applied in the construction industry?
3. What are the key development intentions of MMs?
4. What method is used to develop the maturity model's general structure?
5. What method is used to develop the maturity levels?

This paper is structured into five sections. Following the introduction, section two of this paper presents an overview of the MMs, their definitions, and their historical evolution. Section three will provide an analysis of the descriptive and content analysis of the identified papers. The fourth section discusses the use of MMs across the construction industry as well as the model's use objectives. The conclusion will be presented at the end of the paper.

2 Maturity Models

Maturity models reflect the organisation's major transformational change (Nesensohn, 2014). Organisations can benefit from MMs' practical measurement tools for their process quality assurance (Wendler, 2012). Current MMs are based on the first widely used maturity model known as the Software Engineering Institute's Capability Maturity Model (CMM), designed by the Software Engineering Institute (SEITM) in 1986 at Carnegie Mellon Software Engineering Institute (SEI). CMM is an innovative theme emerging in various disciplines recently to monitor continuous improvement through a stepwise approach (Omotayo *et al.*, 2019). The CMM framework's target was software providers willing to improve their products. CMM itself has its roots in the field of quality management. The first Quality Management Maturity Grid, developed by Crosby (1979), has six measurement categories and five maturity stages, following two primary objectives, measuring an organisation's maturity level and providing direction for the future development plan.

Nesensohn (2014) has emphasised three broad management contexts and scopes where MMs can be applied, project maturity, process maturity, and organisational maturity. Project maturity indicates or measures the organisational capability to efficiently manage different types of projects based on the set goals (Nesensohn, 2014; Andersen and Jessen, 2003). Process maturity models offer organisations a simple but effective possibility to measure the quality of their processes. Langston and Ghanbaripour (2016) explained that there is a link between project management excellence and mature organisational process. The process maturity concept is associated with Total Quality Management, where the improvement of maturity leads to minimising the variability in the process (Maier *et al.*, 2012). Organisational maturity requires a concerted effort of continuous review and reflection at the level of organisation management. However, this paper argues that the MMs in the literature goes beyond these three areas covering further detailed aspects of the focused area in the organisations, which will be discussed in this paper.

3 Methodology

A systematic literature review (SLR) was utilised to gather studies that target MMs from the published literature. An SLR is a method for evaluating and analysing all available research pertinent to a certain research question, subject, or phenomenon of interest (Kitchenham 2007). In the previous section on the evolution of MMs, the historical perspective was provided in order to contextualise the article. The following sections will discuss the development papers' search strategies, content, and trend analysis.

This paper uses PRISMA for identifying and filtering pertinent articles. It includes publications in academic journals covering the years 2012–2022 using Scopus, As the purpose of this study is to update the literature on the latest applications of MMs in the construction sector. The journals that deal with the subject are selected in two steps. First, all scholarly journals in the categories of construction management, construction and building technology, and built environment were identified using the search terms ABS-KEY ((maturity model) AND (construction industry)). The reference sections and bibliographies of identified articles were also searched. The publications were filtered using a set of inclusion and exclusion criteria. The papers around MMs can be divided into three categories: development, review, and validation (Filho, 2018). Due to the large number of articles related to these areas of study, the eligibility criteria needed to be defined. The final set of papers covered the years 2012 to 2022, and the articles were limited to those that focused solely on the development of MMs for the following reasons:

- Understanding the intention of the MMs development,
- The MMs structure and development methodologies.

As a result, the papers that reviewed MMs or validated the existing models were excluded, as were those written in languages other than English. In order to provide a structure for the review, a framework was made up as the basis for the papers' analysis as follows:

(1) title of the publication, author(s), and year of publication, journals in which the papers were published,

(2) the domain of application and related themes,

(3) aims and objectives of using the maturity model. This category was included in order to capture the main drivers' intentions for using the maturity model,

(4) the methods used to develop the maturity model, and, more specifically, the maturity levels,

As a result, the most relevant journals to the scope of the research were selected to be checked by reading the abstract, keywords, and titles to exclude the irrelevant ones. Finally, 65 papers were finalised for analysis in this study through the filtering process.

4 Descriptive Analysis

4.1 Publication Distribution by Year

The number of annually published articles in MMs in the construction industry within the research time span of 2012- 2022 is summarised in Fig. 1. In 2019 and 2021, the number of publications has reached its peak of 17% and 21 %, respectively. Overall, the results trend shows that interest in maturity model development in the construction industry increased among the researchers.

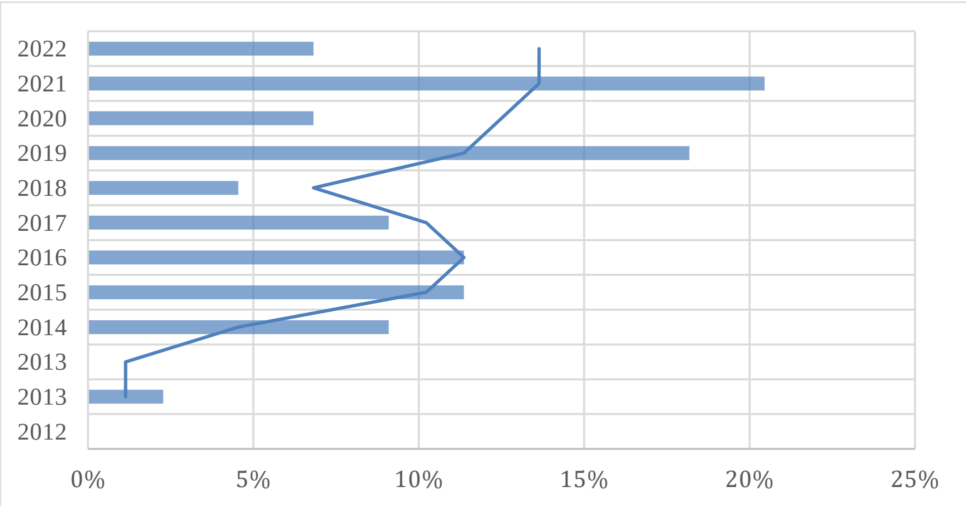

Figure 1. Publication distribution by year

4.2 Publication Distribution by Journal

The nominated papers have been published in 29 construction-related journals, with 15 comprising the most articles, as indicated in **Figure 2**. "Journal of Construction Engineering and Management" and "Sustainability" have published the majority of the MMs development articles in the given period.

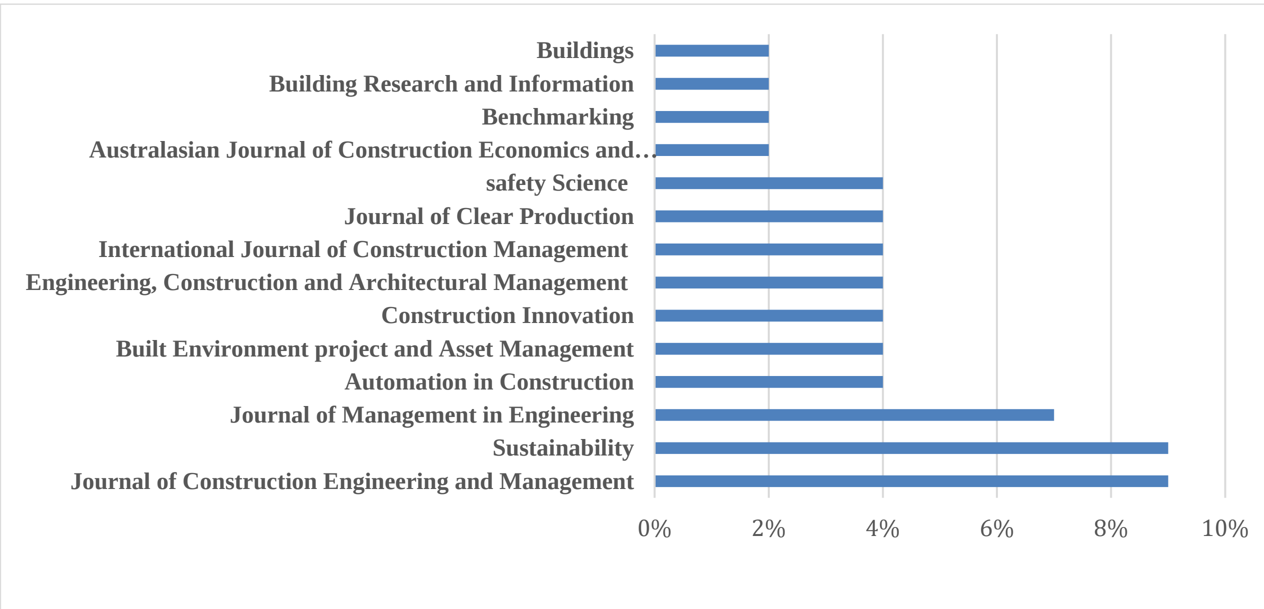

Figure 2. Publication distribution by journal

5 Content Analysis

5.1 Areas of the MMs Application in Construction Research

In order to define the domains across the construction sector where the MMs are developed, the keyword frequency was generated in the word cloud and led to a grouping of the domains under frequently repeated keywords (Figure 3). The MMs with scope overlap were merged to form a domain covering the broader sub-domains.

Figure 4 shows the 14 domains that come up most often in the literature of the 64 papers that were looked at. MMs' development in the domains of "BIM", "sustainability", and "safety" features remarkably. In addition, each identified domain is accompanied by some elaborated themes as follows:

Figure 3: Keywords word cloud

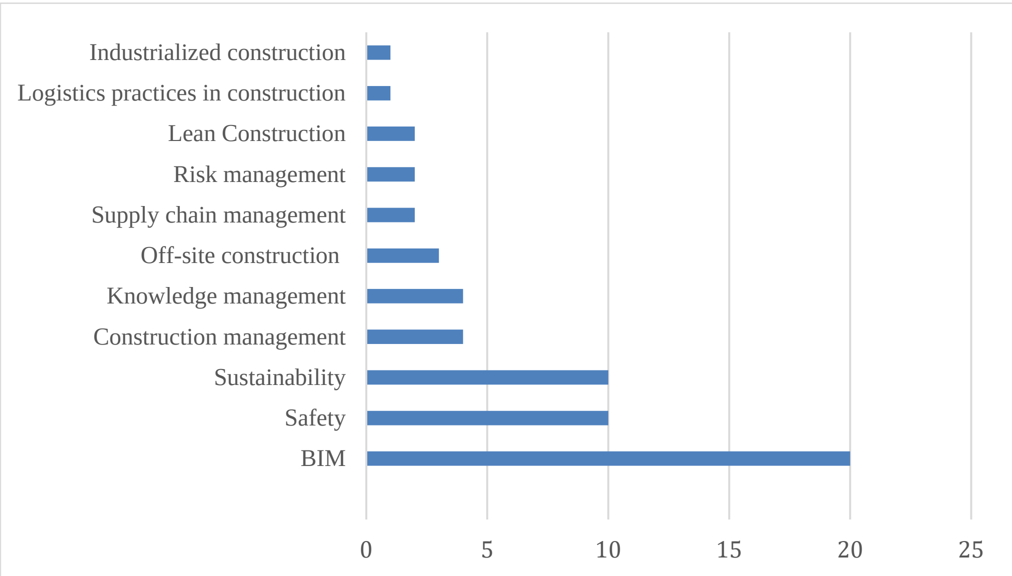

Figure 4. Areas of the MMs application in construction research

Building Information Modelling is a computer-generated representation of precise physical and functional data required to support the design, construction, fabrication and procurement activities (Azhar *et al*., 2008). BIM can also be defined as a virtual model, business process, tool, interdisciplinary set, technology and transformation approach (Assaad *et al*., 2020; Ozorhon and Karahan, 2017, Azzouz, 2016). Organisation, process and project performance and capability in BIM implementation have been the major focus area of the MMs (Rashidian et al., 2022). The other areas in which BIM is assessed through the MMs are industry BIM adoption maturity, interoperability, whole-of-life BIM adoption, asset management, and operation and maintenance maturity management. These studied areas indicate that the level of maturity of BIM implementation can be tied to a range of micro and macro scale attributes and goes beyond the technical aspects.

Safety in construction is no longer solely connected with technical issues. Further detailed areas have been integrated into safety management, such as safety culture and safety climate, policies, procedures, and practices in the MM context (Wilson and Koehn, 2000). Rather than referring to the direct impressions of people, "safety culture" refers to the underlying beliefs and values that influence organisational behaviour (Griffin and Curcuruto, 2016). Safety climate, on the other hand, is often seen as the surface characteristics of the safety culture as determined by the attitudes and views of the workforce at a particular moment (Flin *et al*., 2000). In addition to the safety culture and climate, occupational safety and health, construction disability management, lower back pain prevention, health and environmental (SHE) management, building fire emergency response and leadership maturity are assessed through the MMs in the literature.

Designing a sustainable maturity model seems critical for analysing the status of the sustainable development process and positioning existing performance levels. Despite developing various sustainable evaluation methods such as LEED, BREEAM, and Green Globes, they have confined the assessment to environmental aspects and less emphasised socioeconomic issues. Existing sustainability-oriented MMs, however, have attempted to address this gap by including all elements of sustainability within the MMs (Dianawati and Adhisthana, 2021). Environmental management, labour sustainability, sustainable building, and supply chain sustainability are sustainable-related MMs developed in the construction literature.

Knowledge management (KM) can be understood as the application of collective knowledge to achieve the goals and objectives of an organisation. It is a process that involves different activities, such as knowledge capture, sharing, storage, retrieval, and reuse (Wang & Meng, 2019). Therefore, by referring to the knowledge-based view, their organisational knowledge can be seen as a primary and strategic asset for maintaining competitiveness (Hartono, 2019). Knowledge management-related MMs in construction are related to collaborative social networks, knowledge sharing, and information integration MMs.

Organisations with mechanisms representing a mature project environment are more likely to execute successful projects (Langston & Ghanbaripour, 2016). Construction management-related MMs include construction project management, project performance, and project control systems (PCS) MMs.

Construction supply chain management (CSCM) refers to the management of information and cash flow in developing a construction project. The only supply chain-related MMs identified in this study is the purchasing function in construction firms.

In addition to the domains specified, logistics practices in construction, industrialised construction, purchasing functions in construction firms, risk management, and Lean construction were identified at a lower frequency.

5.2 Identifying the Key Development Intentions of MMs

This part of this study intends to identify the key purposes of MMs in construction studies. In the Collins Dictionary (Collins Dictionary and Thesaurus, 2006), maturity is "the state of being fully developed or grown-up with plans and theories, sensible and balanced in personality and emotional behaviour, etc.". According to Andersen and Jessen (2003), "maturity is the quality or state of being mature.". They have pointed out that project management maturity is a state of being in perfect condition to meet the project's objectives. The concept of maturity models can be defined as a ladder enabling organisations to move from one level of capability to the next higher one over time (Andersen and Jessen, 2003). Likewise, the identified papers in this study have defined a maturity model to address a specific purpose. The definitions of the studied papers have been collected, and the intention to apply MMs is divided into ten major categories as follows: "assessment of capabilities", "organisational learning", "communicating", "tactical and strategic decisions", "the evaluation of capability in addressing the goals", "facilitator levers", "maturity characterisation", "strengths, weaknesses recognition and benchmarking", "identifying appropriate improvement paths", "standard for comparison", "have a detailed vision of goals", "transformation support of a phenomenon". In conclusion, the literature review demonstrates that the adaptation of MMs in the construction industry helps to capture industry characteristics better. And this encapsulation offers a more robust platform and an action-oriented road map for participants to achieve process maturity.

Table 1). Due to the ambiguous concept of maturity and the subjective nature of maturity measurement, many researchers have attempted to clarify and define this concept (Khoshgoftar and Osman, 2009, Cooke-Davie, 2004;). In the Collins Dictionary (Collins Dictionary and Thesaurus, 2006), maturity is "the state of being fully developed or grown-up with plans and theories, sensible and balanced in personality and emotional behaviour, etc.". According to Andersen and Jessen (2003), "maturity is the quality or state of being mature.". They have pointed out that project management maturity is a state of being in perfect condition to meet the project's objectives. The concept of maturity models can be defined as a ladder enabling organisations to move from one level of capability to the next higher one over time (Andersen and Jessen, 2003). Likewise, the identified papers in this study have defined a maturity model to address a specific purpose. The definitions of the studied papers have been collected, and the intention to apply MMs is divided into ten major categories as follows: "assessment of capabilities", "organisational learning", "communicating", "tactical and strategic decisions", "the evaluation of capability in addressing the goals", "facilitator levers", "maturity characterisation", "strengths, weaknesses recognition and benchmarking", "identifying appropriate improvement paths", "standard for comparison", "have a detailed vision of goals", "transformation support of a phenomenon". In conclusion, the literature review demonstrates that the adaptation of MMs in the construction industry helps to capture industry characteristics

better. And this encapsulation offers a more robust platform and an action-oriented road map for participants to achieve process maturity.

Table 1: Key MMs' development intentions

MMs development purposes	Publications examples
Assessment of capabilities	(Yilmaz *et al*., 2019a), (De Carvalho and Scheer, 2017), (Jayasena and Weddikkara, 2013), (Vaidyanathan and Howell, 2007)
Organisational learning	(Rodegheri and Serra, 2019)
Communicating, tactical and strategic decisions	(Rodegheri and Serra, 2019)
Evaluation of capability in addressing the goals	(Siebelink *et al*., 2018)
Facilitator levers,	(Joblot, 2019)
Maturity characterisation indicator	(Joblot, 2019)
Strengths, weaknesses recognition and benchmarking	(Mollasalehi *et al*., 2018), (Lu *et al*., 2018), (Arup 2015)
Identifying appropriate improvement paths	(Wu *et al*., 2017), (Arriagada and Alarcón, 2013)
Establishing a standard for comparison	(Kam *et al*., 2017), (Kerzner, 2006)
Detailed vision of goals	(Azzouz, 2017)
A phenomenon transformation supports	(Nesensohn *et al*., 2014), (Sarhan and Fox 2013)

5.3 Research Methods Used to Develop MMs

Various research methods have been applied to develop the MMs, to define a set of competency criteria or attributes as well as the levels (Figure 5). The review of the papers showed that Delphi is the most frequent method for developing the models' attribute structure. Interviews were the second most popular method among the reviewed articles.

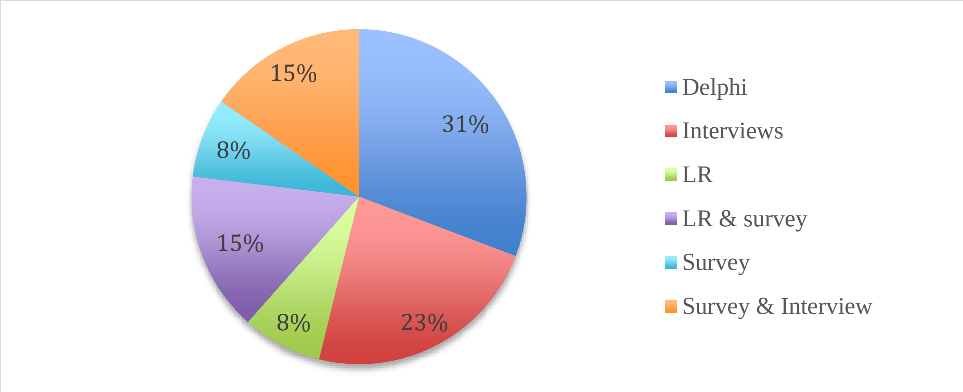

Figure 5. Research methods used to develop MMs structure

Figure 6 depicts the methodology used to develop the MM levels. The surprising finding is that most MMs' published materials' methods for level development are not specified. This may explain why the absence of a defined framework for the maturity levels might lead to subjective and ambiguous judgments when employing the MMs.

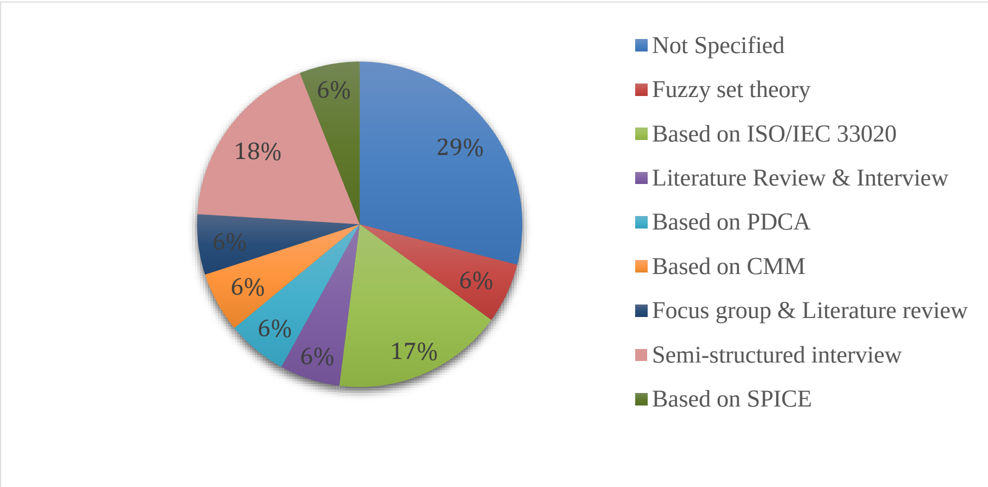

Figure 6. Research methods used to develop maturity models

6 Conclusion and Further Research

This study looked at the applications of MMs in the field of construction studies from 2012 to 2022, covering 65 relevant publications published in 29 peer-reviewed journals. Eleven predominant research streams for using MMs were identified, BIM, safety, sustainability, construction management, knowledge management, off-site construction, supply chain management, risk management, Lean construction, logistics practices in construction, industrialised construction, and purchasing functions in construction firms.

It was observed that MMs are widely used in the BIM areas evaluating a wide range of factors affecting the maturity of BIM implementation, such as the degree of maturity in the construction market as a whole and the level of maturity of BIM adoption in different phases of a project. The area of safety, as well as sustainability, are the second most integrated domain with MMs. Other disciplines, such as prefabrication and knowledge management, have conducted limited research on MM-related topics. New studies should attempt to address and get a detailed understanding of related themes when the domains have not gone beyond confined themes. Further, there is a need for greater study on the MMs' level establishment methodologies to prevent the subjective evaluation of models and provide a clear direction towards maturity design.

The development intentions of the MMs were classified in this study based on the reviewed MMs' definitions. It may be beneficial to determine if the purpose of the new MMs is consistent with the identified objectives in this study and whether the various Model development objectives advocate a certain methodology for the models' structure design.

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Measuring Knowledge Sharing Processes Through Social Network Analysis Within Construction Organisations

Navodana Rodrigo[1*], Sepani Senaratne[2], Xiao-Hua Jin[2], Srinath Perera[2] and Parya Rezaeian[2]

[1]School of Architecture and Built Environment, University of Adelaide,
Adelaide, SA 5000, AUSTRALIA
[2]School of Engineering Design & Built Environment, Western Sydney University,
Penrith, NSW 2751, AUSTRALIA

navodana.rodrigo@adelaide.edu.au; S.Senaratne@westernsydney.edu.au; xiaohua.Jin@westernsydney.edu.au; srinath.perera@westernsydney.edu.au; 19223373@student.westernsydney.edu.au
* Corresponding author

Abstract:
The construction industry is a knowledge intensive and information dependent industry. Organisations risk losing valuable knowledge, when the employees leave them. Therefore, construction organisations need to nurture opportunities to disseminate knowledge through strengthening knowledge-sharing networks. This study aimed at evaluating the formal and informal knowledge sharing methods in social networks within Australian construction organisations and identifying how knowledge sharing could be improved. Data were collected from two estimating teams in two case studies. The collected data through semi-structured interviews were analysed using UCINET, a Social Network Analysis (SNA) tool, and SNA measures. The findings revealed that one case study consisted of influencers, while the other demonstrated an optimal knowledge sharing structure in both formal and informal knowledge sharing methods. Social networks could vary based on the organisation as well as the individuals' behaviour. Identifying networks with specific issues and taking steps to strengthen networks will enable to achieve optimum knowledge sharing processes. This research offers knowledge sharing good practices for construction organisations to optimise their knowledge sharing processes.

Keywords:
Construction, Formal and informal knowledge sharing methods, Knowledge sharing, Social network analysis, Social networks

1 Introduction

Knowledge management (KM) refers to the process of capturing, storing, sharing, and using knowledge (Lee 2001). Knowledge sharing results in dissemination of information and knowledge through the whole department/ organisation (Senaratne et al. 2017). The construction industry is information and knowledge intensive. In construction, KM associates with the management of organisational knowledge (Tan 2015). Once a construction project is completed, the project team is usually dissolved. However, the knowledge learned by team members through knowledge sharing can be transferred to new team members and be applied in other projects (Ma et al. 2008). Research on KM has revealed that knowledge sharing is a key as well as a challenge for successful KM in theory and practice (Grant 1996).

Lee (2001, p. 324) defines knowledge sharing as "activities of transferring or disseminating knowledge from one person, group, or organisation to another". Knowledge sharing occurs between at least two parties where one party possesses knowledge while the other acquires knowledge, and as a result of effective communication, knowledge sharing occurs (Gunasekara et al. 2022; Ma et al. 2008). Knowledge sharing relates to an organisation's competitive advantage because knowledge that is not shared tends to slow the improvement of an organisation (Issa and Haddad 2008). According to McDermott and O'Dell (2001), the organisational culture plays an important role for knowledge sharing and effective knowledge sharing may depend on the mutual understanding and respect of team members (Bostrom 1989). Informal relationships created between different enterprises based on common interests and the will to share knowledge, in order to integrate and transfer of knowledge is much more effective than formal enterprise processes.

A social network comprises several actors connected through relations that hold them together (Yang et al. 2017). SNA maps and measures relationships and flows between people, organisations, and other information/knowledge entities. In SNA, nodes represent people, while the links indicate the relationships or flow of information between nodes. SNA provides visual and statistical analysis of human relationships (Hanneman and Riddle 2005). Instead of the attributes possessed by the actors, their behaviour is affected more by their ties and the social networks, in which they are embedded (Wellman 1988). Hence, studying actors based on data attributes may not be enough to emphasise the characteristics of the relationships between nodes (Xu et al. 2006). SNA explores the network features, which affect actors' interactions. SNA is used in various industries such as KM in Semantic Web (Jamali and Abolhassani 2006), biology, business (Oliveira and Gama 2012), sustainable construction (Hewa Welege et al. 2021) and so forth; however, its use for KM in the construction industry is not fully explored, especially in the Australian context. An attempt by Senaratne et al. (2021) compared formal and informal knowledge sharing in general in one Australian development organisation. This study extends to explore the impact of formal and informal knowledge sharing methods and its implications to construction stakeholders as well as construction organisations in Australia.

2 Research Methodology

This study aimed at evaluating the formal and informal knowledge sharing methods in social networks within construction organisations and identifying how knowledge sharing could be improved through case studies in Australian construction organisations. To evaluate the impact of social networks, a case study approach along with SNA was selected, as it allows to analyse and measure the relationships between people, groups and other information/knowledge processing entities. Two case studies were selected, where an estimating team involved in each case study was considered for data collection purposes. The details of the participants are illustrated in Table 1. Semi-structured interviews were conducted to identify the formal and informal knowledge sharing arrangements within the network. Semi-structured interviews were selected as the interviewer has the freedom to add, omit and change the questions to suit the flow of the interview, and to carry out in-depth conversation to capture all data required.

Table 1. Participant details

Project Details		Participant Details	
Project	Scope	Designation	Experience in Years
Case Study 1	A road project in New South Wales	Project Manager	0-5
		Senior Estimator	Above 16
		Senior Quantity Surveyor	Above 16
		Contracts Manager	11-15
Case Study 2	Construction of 54 residential apartments across two mixed use buildings 5 storeys high in New South Wales	Project Manager	11-15
		Contract Administrator 1	6-10
		Contract Administrator 2	6-10
		Cadet Contract Administrator	0-5

The participants were asked to identify the formal and informal knowledge sharing methods used within their organisation. Then, for each method, the team member with whom the knowledge was shared and their frequency (E.g.: daily, weekly, fortnightly, monthly, more than monthly) were asked. The answers provided by the team members of Case Study 1 for formal knowledge sharing method, email, is shown in Table 2. If a team member shares knowledge to a particular team member daily via email, that was indicated using 5. For example, the second row of data in Table 2 means Senior Estimator shares knowledge with the Project Manager, Senior QS, and Contracts Manager, daily as indicated by 5.

Table 2. Responses of Case Study 1 Participants

	Project Manager	Senior Estimator	Senior QS	Contracts Manager
Project Manager	0	1	0	1
Senior Estimator	5	0	5	5
Senior QS	5	4	0	4
Contracts Manager	0	0	0	0

The collected data were analysed using UCINET to calculate SNA measures, while NetMiner was used to develop the sociograms. UCINET provides values for in-degree centrality, out-degree centrality, betweenness centrality, eigenvector centrality and density. All centrality-related measures would vary between 0 and 1. Centrality generally describes the social power and the influence of a node based on how well connected the node is in the network. In-degree centrality refers to how often a team member receives knowledge and out-degree centrality refers to how often a team member shares knowledge. If in-degree value of a team member is closer to 1, the others may be reporting to this team member. If a team member’s out-degree centrality value or betweenness centrality value is closer to 1, this team member may be an influencer. Density can be used to decide which knowledge sharing method is most frequently used. These were used to evaluate the nature of the social networks within the organisation.

3 Research Findings

3.1 Formal and Informal Knowledge Sharing Methods in Case Study 1

The findings related to formal and informal knowledge sharing methods used in Case Study 1 have been presented in Table 3.

Table 3. Findings of Case Study 1 on formal and informal knowledge sharing methods

	Formal knowledge sharing methods									
	Values for email					**Values for meeting**				
	In-Degree Centrality	**Out-Degree Centrality**	**Betweenness Centrality**	**Eigenvector Centrality**	**Density**	**In-Degree Centrality**	**Out-Degree Centrality**	**Betweenness Centrality**	**Eigenvector Centrality**	**Density**
Project Manager	0.667	0.133	0	0.465	-	0.667	0.000	0	0.480	-
Senior Estimator	0.333	1.000	1.000	0.561	-	0.467	0.800	1.000	0.577	-
Senior Quantity Surveyor	0.333	0.867	0	0.537	-	0.267	0.467	0	0.444	-
Contracts Manager	0.667	0.000	0	0.426	-	0.400	0.533	0	0.490	-
Minimum	0.333	0.133	0	0.426	-	0.267	0.000	0	0.444	-
Average	0.500	0.500	0.250	0.497	2.500	0.450	0.450	0.250	0.498	2.250
Maximum	0.667	1.000	1.000	0.561	-	0.667	0.800	1.000	0.577	-
Sum	2.000	2.000	1.000	1.988	30.000	1.801	1.800	1.000	1.990	27.000
Standard deviation	-	-	0.433	0.054	2.217	-	-	0.433	0.049	1.785
Variance	-	-	0.188	0.003	-	-	-	0.188	0.002	-
Centralisation	0.222	0.667	-	-	-	0.289	0.467	-	-	-
	Informal knowledge sharing methods									
	Values for social dinner or lunch break					**Values for coffee break**				
Project Manager	0.444	0.000	0	0.418	-	0.467	0.533	0	0.475	-
Senior Estimator	0.222	0.778	1.000	0.619	-	0.600	0.933	2.000	0.631	-
Senior Quantity Surveyor	0.333	0.333	0	0.517	-	0.333	0.000	0	0.325	-
Contracts Manager	0.333	0.222	0	0.418	-	0.600	0.533	0	0.521	-
Minimum	0.222	0.000	0	0.418	-	0.333	0.000	0	0.325	-
Average	0.333	0.333	0.250	0.493	1.000	0.500	0.500	0.500	0.488	2.500
Maximum	0.444	0.778	1.000	0.619	-	0.600	0.933	2.000	0.631	-
Sum	1.332	1.333	1.000	1.972	12.000	2.000	1.999	2.000	1.951	30.000
Standard deviation	-	-	0.433	0.084	0.913	-	-	0.866	0.110	2.179
Variance	-	-	0.188	0.007	-	-	-	0.750	0.012	-
Centralisation	0.148	0.593	-	-	-	0.133	0.578	-	-	-

According to the findings related to knowledge sharing via email, the contracts manager has an out-degree value of zero, which indicates that the contracts manager does not communicate with other network participants using email. On the contrary, the senior quantity surveyor communicates with all other participants almost daily. Therefore, the senior quantity surveyor shows an out-degree value of 1. On the other hand, the project manager and contract manager both indicate an in-degree value of 0.667, which means that these actors holding a managerial position receive emails from other participants, however, their out-degree values are closer to zero as they do not report to the actors often. This indicates the role of each team member. The senior estimator holds a 'betweenness centrality' value of 1, which indicates that the senior estimator is a strong influencer within the network. The eigenvector value indicates how many high-scoring nodes are connected to each node. As the network is small, though the senior estimator indicated a high betweenness centrality, its eigenvector centrality is closer to 0.5. However, the highest eigenvector centrality is demonstrated by the senior estimator, who could be considered as an influencer within the network. This network has a comparatively higher density indicating that email is the most popular mode of formal communication for the team members.

According to the findings related to knowledge sharing through meetings, the senior estimator indicated the highest out-degree value as it is his responsibility to manage the works within the organisation. On the contrary, the project manager indicated an out-degree value of 0, as he does not conduct meetings with the other team members. The project manager is informed through emails, however, meetings are not a very common mode for communications with the project manager. The in-degree values are closer to 0.5 indicating that meetings are not a very common mode for formal knowledge sharing. The senior estimator indicated the highest betweenness centrality and eigenvector centrality highlighting that the senior estimator is the influencer within the network.

Subsequently, the findings of informal knowledge sharing methods in Case Study 1 are presented in Table 3. Most of the in-degree and out-degree values related to knowledge sharing via social dinner/lunch break, being less than 0.5 indicate that this informal knowledge sharing method does not occur frequently. However, the senior estimator showed an out-degree value of 0.778 indicating his more involvement. This is supported by betweenness centrality and eigenvector centrality values being highest for the senior estimator. These results clearly show that the senior estimator is the influencer within the network. However, the density being very low indicate that informal knowledge sharing through social dinner or lunch break is not a popular method.

According to the findings related to informal knowledge sharing via coffee breaks, most of the in-degree and out-degree values being closer or more than 0.5 indicate that coffee breaks are somewhat popular as an informal knowledge sharing mode. However, the senior estimator showed the highest in-degree value of 0.6 and out-degree value of 0.933 indicating his more involvement. This is supported by betweenness centrality and eigenvector centrality values being highest for the senior estimator. These results clearly show that the senior estimator is the influencer within the network. The density being comparatively high indicate that informal knowledge sharing through coffee breaks is a somewhat popular method.

3.2 Formal and Informal Knowledge Sharing Methods in Case Study 2

The findings related to formal knowledge sharing through email and meetings as well as informal knowledge sharing methods, social dinner/lunch break and coffee break, are presented in Table 4.

Table 4. Findings of Case Study 2 on formal and informal knowledge sharing methods

	Formal knowledge sharing methods									
	Values for email					Values for meeting				
	In-Degree Centrality	Out-Degree Centrality	Betweenness Centrality	Eigenvector Centrality	Density	In-Degree Centrality	Out-Degree Centrality	Betweenness Centrality	Eigenvector Centrality	Density
Project Manager	1.000	0.867	0	0.500	-	0.800	0.800	0	0.455	-
Contract Administrator 1	1.000	1.000	0	0.500	-	0.933	0.800	0	0.514	-
Contract Administrator 2	0.933	1.000	0	0.500	-	0.867	0.933	0	0.514	-
Cadet Contract Administrator	0.933	1.000	0	0.500	-	0.867	0.933	0	0.514	-
Minimum	0.933	0.867	0	0.500	-	0.800	0.800	0	0.455	-
Average	0.967	0.967	0	0.500	4.833	0.867	0.867	0	0.499	4.333
Maximum	1.000	1.000	0	0.500	-	0.933	0.933	0	0.514	-
Sum	3.866	3.867	0	2.000	-	3.467	3.466	0	1.997	-
Standard deviation	-	-	0	0	0.373	-	-	0	0	0.471
Variance	-	-	0	0	-	-	-	0	0	-
Centralisation	0.044	0.044	-	-	-	0.0889	0.0889	-	-	-
	Informal knowledge sharing methods									
	Values for social dinner or lunch break					Values for coffee break				
Project Manager	0.467	0.800	0	0.455	-	0.800	1.000	0	0.500	-
Contract Administrator 1	0.867	0.800	0	0.514	-	1.000	1.000	0	0.500	-
Contract Administrator 2	0.933	0.600	0	0.514	-	1.000	0.867	0	0.500	-
Cadet Contract Administrator	0.867	0.933	0	0.514	-	1.000	0.933	0	0.500	-
Minimum	0.467	0.600	0	0.455	-	0.800	0.867	0	0.500	-
Average	0.784	0.783	0	0.499	3.917	0.950	0.950	0	0.500	4.750
Maximum	0.933	0.933	0	0.514	-	1.000	1.000	0	0.500	-
Sum	3.134	3.133	0	1.997	-	3.800	3.800	0	2.000	-
Standard deviation	-	-	0	0	1.187	-	-	0	0	0.595
Variance	-	-	0	0	-	-	-	0	0	-
Centralisation	0.2000	0.2000	-	-	-	0.0667	0.0667	-	-	-

According to the findings related to knowledge sharing via email, in-degree values and out-degree values between network participants are 1 or closer to 1 indicating that all participants communicate well either daily/weekly through emails. The betweenness centrality is 0, which indicates that no actor relies on other nodes within the team. The eigenvector centrality is 0.5 and it indicates that no specific actor plays a critical role in the team. Therefore, there is no influencer in the network. These indicate an optimal structure of knowledge sharing.

The findings related to knowledge sharing via meeting indicate that the in-degree and out-degree values are slightly less than in-degree and out-degree values related to email or intranet. However, the in-degree and out-degree values are closer to 1, indicating that knowledge sharing through meetings occur weekly or daily but is slightly lesser than the other two formal modes. This network has a betweenness centrality of 0 and an eigenvector centrality closer to 0.5, which indicates that no actor relies on other nodes within the team and there is no influencer within the network. This demonstrates an optimal structure of knowledge sharing.

According to the values related to informal knowledge sharing through social dinner/lunch break, the in-degree value of the project manager is comparatively less indicating that the other team members do not meet up with him often for informal knowledge sharing via dinner or lunch. The out-degree value of contract administrator 2 is low compared to others indicating that he doesn't participate in informal knowledge sharing through social dinner or lunch breaks. The 'betweenness centrality' is 0 and eigenvector centrality is closer to 0.5 indicating there is no strong influencer within the team.

According to the findings related to knowledge sharing via coffee breaks, the in-degree and out-degree centrality are closer to 1 indicating that all team members participate in informal knowledge sharing during coffee breaks almost daily. This demonstrates an optimal structure of knowledge sharing. Betweenness centrality is 0 and eigenvector centrality is 0.5. Thus, the actors don't rely on each other and there is no influencer within the network.

3.3 Cross-case Analysis

The cross-case analysis was carried out to compare the findings related to Case Study 1 and Case Study 2 considering their formal and informal knowledge sharing methods.

3.3.1 Formal Knowledge Sharing - Email

The sociograms demonstrating formal knowledge sharing through email for Case Studies 1 and 2 have been illustrated in Figure 1.

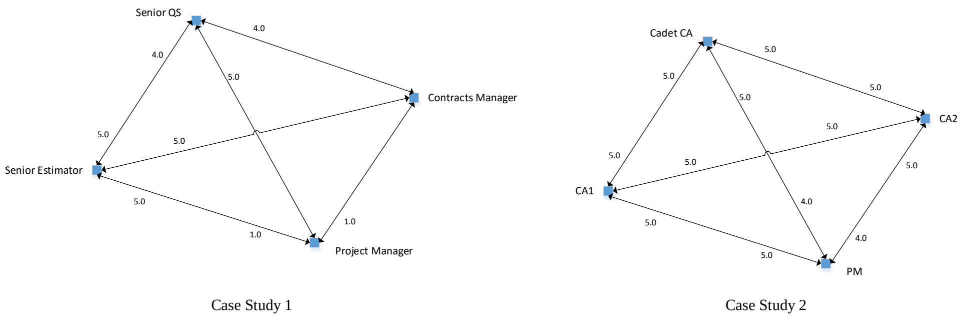
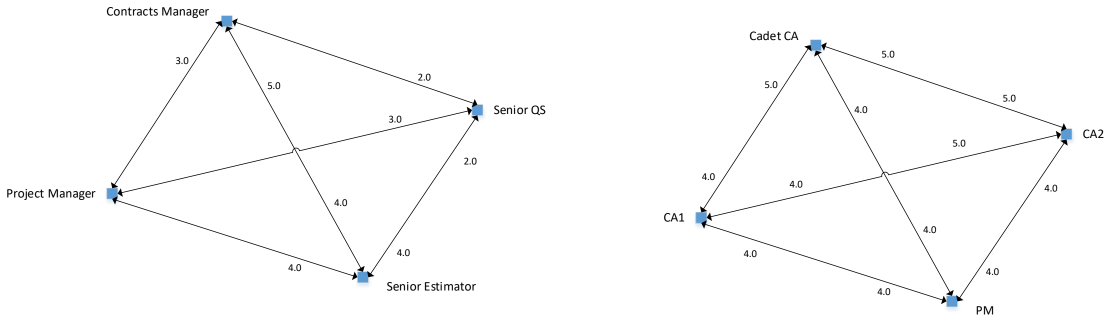


Figure 1. Sociograms for Case Studies 1 and 2 on formal knowledge sharing via email

Case Study 1 consisted of team members at the senior level, hence their communications via email was not frequent, when compared to Case Study 2 participants, who were at an equal level. Case Study 2 participants communicated daily or weekly with all network participants to exchange information through email. In Case Study 1, communication through email was mostly noticed when lower-level team members were reporting progress to the middle-level management or when middle-level managers were providing instructions to the low-level team members. It is evident that based on the nature and hierarchical levels of the team members, the sociograms could display various outcomes as indicated by varied values in Figure 1.

3.3.2 Formal knowledge sharing - Meeting

The formal knowledge sharing in meetings of Case Studies 1 and 2 have been demonstrated in the sociograms as shown below (Figure 2).



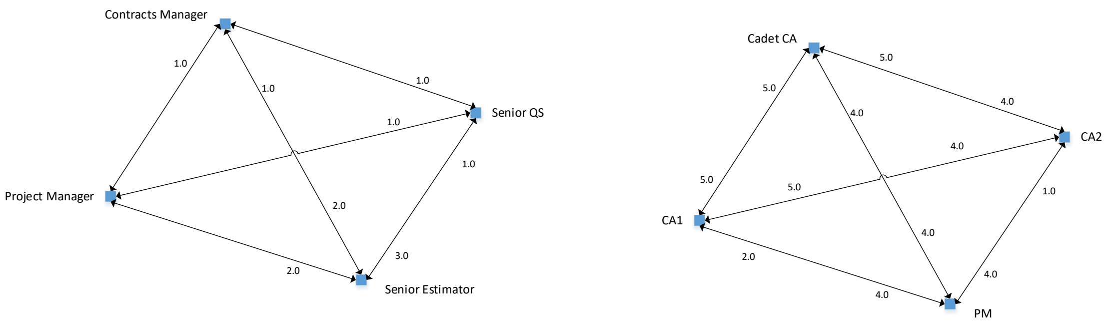
Case Study 1 Case Study 2

Figure 2. Sociograms for Case Studies 1 and 2 on formal knowledge sharing via meeting

According to Figure 2, Case Study 1 indicated that between some team members formal knowledge sharing through meetings does not happen often. As identified previously, some of the team members within its network are senior members, therefore, some meetings happen for reporting purposes or to provide instructions, therefore this happens weekly or monthly. However, Case Study 2 consists of team members of similar levels and they demonstrated an optimal level of knowledge sharing. Therefore, these team members communicate with each other more often than the Case Study 1 participants for meetings as well.

3.3.3 Informal knowledge sharing - Social dinner or lunch break

Figure 3 presents the sociograms of Case Studies 1 and 2 for informal knowledge sharing through social dinner/lunch.



Case Study 1 Case Study 2

Figure 3. Sociograms for Case Studies 1 and 2 on informal knowledge sharing via social dinner or lunch break

In Case Study 1, social dinner/lunch is not very common, while in Case Study 2, it occurs often as an informal knowledge-sharing event. The reasons for the differences could have been due to the nature of participants, hierarchical level of team members, social backgrounds, and so forth as found in the case of email communication and meetings.

3.3.4 Informal Knowledge Sharing - Face to Face Coffee Break

The sociograms of Case studies 1 and 2 on informal knowledge sharing through face-to-face coffee breaks have been displayed in Figure 4.

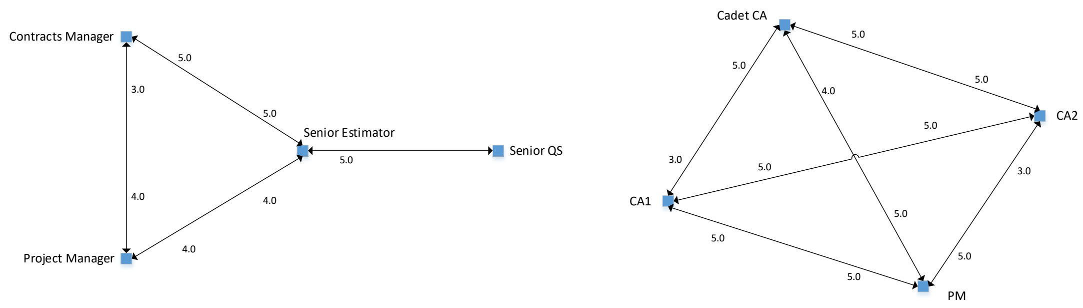


Figure 4. Sociograms for Case Studies 1 and 2 on informal knowledge sharing via coffee break

According to Figure 4, the team members in Case Study 1 exchanged informal knowledge through coffee breaks except for the senior manager, who has been placed outside the loop. This indicates that these three members have an optimal level of knowledge sharing. On the other hand, all members in Case Study 2 participate in face to face coffee breaks daily or weekly to share informal knowledge. The team members in Case Study 2 demonstrate good and optimal informal knowledge sharing qualities compared to Case Study 1.

Overall, the above case studies in the Australian context showed that the team members who were at an equal level shared knowledge using informal as well as formal methods quite frequently showcasing an optimal level of knowledge sharing. However, when there were high-level management representatives within a team, the knowledge sharing was not so frequent and these personnel became influencers within their network due to their authoritative capacities. A similar study conducted by Senaratne et al. (2021) showcased similar results where all three mini networks in an Australian construction company demonstrated optimal knowledge sharing through formal and informal methods. Schröpfer et al. (2017) examined the knowledge transfer practices in social networks in five construction projects in the UK and Germany and found that networks with strong ties share tacit knowledge effectively. Similarly, the team members in Case Study 2 indicated strong ties as they were at the same level and reached an optimum level of knowledge sharing. Cross et al. (2002) collected data from 40 informal networks from 23 organisations and found that informal relationships among employees provide more reflection of the way work happens in an organisation rather than relationships established by the organisational hierarchy.

3.4 Implications for knowledge Sharing Good Practices for Construction Organisations

The SNA carried out on the case studies and their cross-case analysis revealed that the findings may not be similar or consistent. It is evident that the findings depend on various factors, such as the composition of the network, nature of the network members, designation of the network members, work-relationship with network members, and so forth. Therefore, it is difficult to generalise the findings of SNA. Each social network would be different from one another. However, each social network could be analysed using SNA to observe and identify influencers, network ties, and among others. Any construction organisation could observe their social networks through SNA to understand the qualities of SNA and try to achieve the ideal social networks to improve productivity and build a good office environment.

- Optimal knowledge sharing

If a network has an optimal structure of knowledge sharing, it is a highly balanced network without any influencers, which is good for the organisation and projects handled by such networks. Teamwork in a network that consists of employees of the same level will treat each other as equals, which would contribute to optimal knowledge sharing. In Case Study 1, an influencer was noticed in formal and informal knowledge sharing methods, however, in Case Study 2, there were no influencers, making it a more optimal knowledge-sharing network. To improve productivity as well as achieve a good working environment, organisations could be advised to ensure optimal knowledge-sharing networks are created.

- Identification of strong/weak ties

Team members that share strong ties tend to share knowledge through various knowledge sharing modes. It was noticed that if informal knowledge sharing between members occur frequently, formal knowledge sharing between the same members is also good. This emphasises that if strong ties were noticed in informal knowledge sharing modes, they could be seen in formal knowledge sharing modes too. On the contrary, some team members show weak ties in informal networks, however, these members show strong ties in formal knowledge sharing modes. The reason for this may be due to the responsibilities assigned to them as per their respective designation/job description. Senaratne et al. (2021) found that the strength of ties has a significant impact on the efficiency of the network in general and especially for knowledge sharing. Building strong ties between team members could improve knowledge sharing in organisations. Similarly, members that share strong ties could be incorporated into one team to improve productivity as well as create a good working environment.

- Motivation for equally divided workload

Formal knowledge sharing could be improved by explaining its consequences to the team members. For example, when all the team members are knowledgeable on specific skills such as using CostX, estimating or preparing the bill of quantities of specific projects, among others, the workload could be equally distributed among members rather than one specific member having to do all the difficult tasks. This kind of indirect advantage could motivate team members to improve formal knowledge sharing within organisations.

- Tacit knowledge sharing

Tacit knowledge is difficult to share and it is generally passed on by working with that person. However, when the expert leaves the organisation, the tacit knowledge leaves with the person. Therefore, the participants need to extract the necessary tacit knowledge from experts before they leave. Team working environments could assist in sharing tacit knowledge among the team members. According to Schröpfer et al. (2017), strong ties, identified by trust, lengthy time frames and close relationships, are better options for sharing tacit knowledge within members in an organisation.

- Trust

Trust plays an important role in knowledge sharing. If the recipient is not trustworthy, the sender would not be confident in sharing knowledge. Trust is built with time among team members and if a conflict arises by any means, it would be difficult to build a good and trustworthy relationship between the team members again. According to Issa and Haddad

(2008), trust improves positive behavior, encourages network relations, reduces conflicts and transaction costs, and improves the working environment.

- Improvements in IT

IT-related improvements could be accommodated to improve knowledge sharing in construction organisations. Cloud-based shared storage, document management platforms such as Aconex, could be introduced, to improve formal knowledge sharing mechanisms within organisations. These would improve the existing issues in formal knowledge sharing modes. All team members are updated on all changes contributing to time-saving, reducing data redundancy that results in requiring low data storage capacities, having a central storage for all files, among others.

4 Conclusions

This paper aimed at evaluating the formal and informal knowledge sharing methods in social networks within construction organisations and identifying how knowledge sharing could be improved. A case study approach was adopted along with a cross-case analysis to analyse the formal and informal knowledge sharing methods used in two leading construction organisations. The results of Case Study 1 revealed that the senior estimator was an influencer within the network, which was noticed in all formal and informal knowledge sharing methods. However, in Case Study 2, there were no strong influencers within the team members. The reasons for the difference between the two case studies would have been because Case Study 1 consisted of members from both medium level and low level while Case Study 2 comprised mostly from low level and only one medium level member. This indicates that the hierarchy and the job positions have a strong impact on the relationships in social networks. The cross-case analysis emphasised that the network in Case Study 1 had an influencer while the network in Case Study 2 consisted of an optimal knowledge sharing structure. However, these results depend on organisation, project and team members. Therefore, the findings cannot be generalised over the entire construction industry. This is a key limitation of this study. In addition, the number of participants within the estimating team being 4 in both case studies could also have an influence on the results. However, based on lessons learned from the case studies and literature findings from other contexts, possible strategies to improve knowledge sharing through formal or informal knowledge sharing methods were identified.

SNA could be used by construction organisations to analyse their social networks and improve the relationships to implement optimal knowledge sharing processes. Including same level team members would emphasise equality resulting in achieving optimal networks. This ultimately contributes to increased productivity and a better working environment. Identifying strong and weak ties in social networks would assist in forming conflict-free and productive teams. Formal knowledge sharing could be improved by explaining the benefits for the team members, for example, reduction in workload when more members are knowledgeable. Trust is a key factor that influences knowledge sharing among team members in construction organisations. IT-based solutions such as cloud storage and document management platforms could be introduced for faster and improved knowledge sharing. SNA could be used by construction organisations and stakeholders, to observe the relationships between team members and use suitable solutions to achieve optimal knowledge-sharing networks.

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Engaging External Project Stakeholders within Social Distancing Parameters in Community Development Projects in South Africa

Pride Ndlovu[1*] and Prisca Simbanegavi[1]

[1]School of Construction Economics and Management, University of the Witwatersrand, Johannesburg, SOUTH AFRICA

pride.ndlovu@wits.ac.za; prisca.simbanegavi@wits.ac.za.

* Corresponding author

Abstract:
External stakeholders are engaged in construction projects to work together with internal stakeholders to achieve project goals. In community development projects, external stakeholders such as local communities play a significant role in influencing the project as typically, they are the end user of the product at completion. However, engaging external stakeholders whilst adhering to health protocols imposed during COVID-19 in an unequal country like South Africa is intricate. This study aims to explore challenges faced by construction project managers in engaging external stakeholders in community development projects the during COVID-19 period. The study adopts a qualitative design and uses in-depth interviews to source data from construction project managers. A purposive sampling technique was used and sampled construction project managers who were actively managing projects during the COVID-19 pandemic period in South Africa. 15 in-depth interviews were conducted. Thematic analysis of data was used, and six themes emerged from the data. The challenges were centered around six themes namely: communication difficulties; access restrictions; unintentional exclusions; lack of connectivity (power and internet); lack of access to information (misinformation) and inadequate infrastructure. These findings revealed gaps in engaging external stakeholders in a social distancing context of unequally resourced stakeholders in community development projects. Construction project managers could use the recommendations provided to enhance their approach to engaging with external stakeholders in community development projects during a similar crisis.

Keywords:
COVID-19; construction; stakeholders, external stakeholders; stakeholder engagement, social distancing.

1 Introduction

External stakeholder engagement can be defined as the channel of incorporating organizational activities and plans utilized to include external stakeholders in the project tactics and decision-making (Greenwood, 2007). External stakeholders are individuals or groups who are impacted by the projects and their outcomes (Wembe, 2020) represented on the project by an elected assemblyman or woman (Tengan *et al*. 2017). Often, external stakeholders are not contractually appointed by the company leading the project. The company is not directly dependent on external stakeholders to deliver the project but may be severely impacted if the external stakeholders are not involved throughout the lifecycle of a project (Tengan *et al.* 2017). The consequence of not engaging or neglecting external stakeholders manifests in many ways and has dire consequences for the project. Delays in obtaining planning permission (Alenezin, 2020), stoppages of projects due to community protests (Eyiah-Botwe *et al*. 2015; Pleyers, 2020), vandalism/blockage of access to construction sites (Pleyers, 2020), scope changes affecting budget (Eyiah-Botwe *et al.*, 2015; Alenezin, 2020) and many other undesirable outcomes affecting project success can be identified. These are among some of the risks that may impact project success as a result of omitting a range of external stakeholders such as local authorities, communities, trade organizations, unions, media, and suppliers among others. External stakeholders have the power to redirect project goals and impact project success. PMI (2013) affirms that a major success factor for project success is meeting stakeholder needs and satisfaction. Thus, projects are supposed to create value for stakeholders. Sutterfield *et al.* (2006); Yang, (2010) identified effective stakeholder management as contributing to meeting stakeholders' needs and project success. Furthermore, Othman (2013) identified a crucial part of project success in developing countries suggesting that project success is vital as construction infrastructure projects are connected to development intervention for improved socio-economic development. External stakeholders such as communities depend on these community development projects for jobs and the improvement of their lives and livelihoods.

When COVID-19 pandemic engulfed the world and interrupted the traditional routine utilized in project engagement of project stakeholders, transformations and innovations were introduced to maintain business operations. The way of doing business as it was traditionally known was disrupted during the COVID-19 period and all industries including the construction industry had to adapt to a new way of operating. Many construction projects that were ongoing during the COVID-19 period experienced many challenges in adjusting to the changes. Governments introduced responses to COVID-19 and implemented varied policies such as social distancing. Due to these changes, many industries moved from a traditional face-to-face mode of working to a virtual mode to resume business activities. Other industries had a seamless transition whereas the construction industry experienced difficulties with switching to virtual mode as the nature of their business comprised of activities that could not be replaced with virtual mode (Aigbavboa *et al.* 2020) and also challenges of access to virtual platforms in emerging countries became prevalent affecting delivery of projects. In an unequal country like South Africa, most internal stakeholders were able to switch to virtual platforms such as project managers, clients, engineers, quantity surveyors, and most professionals contracted to the project by the project owner/client. However, external stakeholders such as communities had the most difficulty as they are often not employed or remunerated for participating in the project. These external stakeholders have an interest in the project but do not accrue interest or remuneration for their involvement in the project. A range of diverse issues in developing countries like South Africa presented difficulties in the implementation of strategic interventions (Aigbavboa *et al.* 2020) to curb the spread of COVID-19. Amoah and Simpeh (2021) cited predominant issues relating to lack of compliance, ignorance, and the absence of adequate personal protective equipment, amongst others. Therefore, it is necessary to study how construction project managers dealt with some of the issues encountered in community development projects to offer learnings to improve responses on similar occasions in the future.

To successfully deliver projects, the engagement of stakeholders is fundamental. Community development projects require the engagement of both internal and external stakeholders to ensure the success of the project. Stakeholder engagement is the process of communicating with, interacting with, and influencing the project stakeholders for the overall good of the project as a whole. Stakeholder engagement is significant as project completion frequently depends on how stakeholders see it. This study seeks to investigate the challenges of engaging external stakeholders during the COVID-19 pandemic period and the research question is indicated below:

What were the challenges experienced by construction project managers when engaging external project stakeholders during the social distancing period in community development projects in South Africa?

The study has three objectives, and these are listed below:

- To explore the challenges of engaging external stakeholders in community projects during social distancing restrictions
- To identify the solutions adopted by project managers when engaging external stakeholders during covid 19 pandemic period
- To assess if strategies adopted by construction project managers to engage external stakeholders during the Covid-19 pandemic yielded desired results.

This paper, therefore, explores the engagement of external stakeholders during the COVID-19 pandemic in community development projects. It aims to explore challenges that construction project managers experienced with engaging external stakeholders during the pandemic.

2 Literature Review

Ramakrishnan (2019) submits that at the center of stakeholder theory is the creation of value. Ansoff (1965) defined stakeholder theory as the “reconciliation of conflicting interests of various stakeholders”. This suggests that within groups of different participants, there exist different interests, views, and priorities. Construction project managers are tasked with finding, harmonizing, or modifying the misalignment of project stakeholder interests to achieve project success. Stakeholder theory is described as an interrelationship among the various actors involved in the firm and offers an alternative purpose for the firm (Freeman, 1995). Stakeholder management is intended to create methods to manage different groups and relationships. This means that organizations need to better understand their stakeholders and how to strategically manage them.

Construction projects are configured distinctively combining many interested parties and organizations with a share of those affected by the project known as stakeholders. Led by construction project managers, projects comprise multiple professionals, from different organizations, communities, governments, and other trade associations among others. Stakeholders have been identified as the client, project management team, consultant and design team, contractor, subcontractor, supplier, employees, local community, funding bodies, and government authorities by other scholars (Olander and Landin, 2005; Atkin and Skitmore, 2008; Yang, 2010, Heravi *et al.* 2015). Project stakeholders are broadly categorized as internal and external stakeholders. Internal stakeholders are defined as participants of the project team, who plan, design, implement and provide finance and whilst external stakeholders are defined as those affected by the project scope (Winch, 2002; Sutterfield *et al.* 2006). Project managers are tasked with managing both internal and external stakeholders in a project (Savage *et al.* 1991).

Stakeholder Management

Locke, (2007) advised that stakeholder management (SM) involves a logical methodology of identifying, analyzing, planning activities, communicating, and negotiating aimed at shaping project stakeholders. Freeman *et al.* (2010) highlighted that stakeholder management commences in strategic management theory and the construct of stakeholder engagement characterizes the approach utilized to manage stakeholders. They suggest the approach to be theoretically grounded in stakeholder theory which supposes that the organization’s existence is that of creating value for all stakeholders (Noland and Phillips, 2010). This suggests that an organization has a legal responsibility to its stakeholders (Burton & Dunn, 1996) and should include all its stakeholders in operations and decision-making (Gibson, 2000).

Yang and Shen (2014) classified six categories for stakeholder management namely: "precondition; stakeholder identification; stakeholder assessment; decision making; action and evaluation; and continuous support". They view issues that influence stakeholder management as practices and activities that should be addressed to ensure effective management of stakeholders in a construction project (Yang and Shen, 2014). They further identified thirty factors contributing to the success of stakeholder management. These are divided into six main groups including management support; identification of stakeholder information; stakeholder assessment; decision-making; action and evaluation; and a continuous support group.

The approach to stakeholder management before the COVID-19 pandemic normally comprised "physical engagement in terms of collaboration and effective coordination among stakeholders towards successful construction projects" (Najib, *et al.* 2022). In their diagrammatic illustration of how the stakeholder management approach has transformed from before COVID-19 to the period during COVID-19, Najib *et al.* (2022) identified many changes to stakeholder management including among others "prioritizing risk management to include COVID-19, implementation of working remotely, interaction through the online meeting, designing work-life balance teleworking, adopting a zero-tolerance policy on procedures and restriction on the number of visitors and workers on-site". Like many sectors, the construction industry underwent a major shift during the pandemic that saw traditional face-to-face on-site activities being replaced by new procedures imposed by governments (Aigbavboa *et al.* 2022) to save lives.

A hybrid stakeholder management approach was suggested as the approach for the foreseeable future likely to manage and satisfy stakeholder needs (Najib *et al.* 2022). There is an acceptance that a combination of the virtual and physical methodologies will be difficult, whereby the transformation to sophisticated technologies will also transform the workplace culture and environment (Najib *et al.* 2022). Suggesting that the principles of stakeholder management in the construction industry will change with new requirements and improvements based on the restrictions imposed during the COVID-19 pandemic (Subramanian *et al.* 2021). At the same time, it is substantial to engage with stakeholders and their environment through transitions to improve sustainability. "Stakeholder management with good determination, effective planning and design, teamwork, adaptability, imagination, and the correct time may be able to overcome these obstacles" (Najib *et al.* 2022).

2.1.1 Stakeholder Engagement Strategies

Stakeholder engagement is a critical part of stakeholder management that safeguards project success. Eyiah-Botwe, *et al.* (2015) defined it as a "two-way communication process involving stakeholders' exchange of information and promoting interaction between decision-makers and other stakeholders". It was also emphasized by Mot *et al.* (2015) that sending an accurate message, "using suitable means, clarifying project values and benefits are essential for effective communication in stakeholder engagement". Stakeholder engagement methods are "how stakeholder views information and opinions are elicited, or by which stakeholders are involved in decision making" (Helbig, *et al.* 2015). Stakeholder engagement can use different methods in different contexts. There are five levels of engagement identified by the International Association for Public Participation namely informing, consulting, involving, collaboration, and empowerment (IAPP, 2007). Power and influence were suggested by Bourne and Walker (2005) as useful instruments for use by project managers, where they can "identify and prioritize" fundamental stakeholders to engage with and establish a connection. Bourne,

(2005) further suggested a simple five-step process to facilitate stakeholder engagement that included the following actions: “identify, prioritize, visualize, engage and communicate”. The process is simple and applies to all stakeholders. In contrast, Mitchell *et al.* (1997) proposed a framework that classified stakeholders according to their “power, legitimacy and claims urgency”. Whereas (Yang *et al.* 2011) favoured an approach to SM that is developed for developing countries, to account for contextual nuances.

Clarkson, (1995) and Freeman, (1984); (1994) categorized stakeholder responses into four different strategies namely reactive, defensive, accommodative, and proactive (RDAP). Each of the strategies can be applied when dealing with both internal and external stakeholders for different outcomes. Yang *et al.* (2022) suggested that proactive and accommodative strategies required an affirmative approach from organizations demonstrating compassion and eagerness to accommodate stakeholders. They differentiate the two strategies citing that, proactive strategies require actions/ resources whilst accommodative strategy may be a mere symbolic gesture to stakeholders. When comparing defensive and reactive strategies, the differences lie in an organization that “either fight against addressing stakeholder concerns or ignores them” (Yang, *et al.* 2022). In a COVID-19 pandemic context, construction project managers leading projects are assigned the responsibility of assessing stakeholders, identifying and prioritizing them, and adopting the appropriate innovative response strategy to engage them on projects. Thus, engaging external stakeholders in disadvantaged communities during a COVID-19 pandemic requires a unique approach. Stakeholder theory allows for varied approaches to be adopted when handling stakeholders.

This study aims to explore the challenges experienced by construction project managers when engaging external stakeholders within social distancing limits in community development projects. The response strategies adopted during COVID-19 may have had an impact on external stakeholders’ role in projects. Construction project managers have the responsibility to engage with other key stakeholders to assess the types of stakeholders involved in a project and adopt a response strategy on how to engage them to enhance project success. The approach aids to discern stakeholder groups to be managed closely and those that are unlikely to create conflict or competition.

3 Research Methodology

The study used qualitative methods and followed an interpretivism philosophy (Saunders *et al.* 2012). A case study design was used to explore the phenomenon within its context or a real-life setting (Yin, 2015). The study explored how construction project managers engaged external stakeholders in projects during the social distancing restrictions and the challenges they faced. This is a cross-sectional study as it looks at the phenomenon at a particular point in time.

3.1 Sampling Techniques

From a population of construction project managers working on community development projects, the purposive sampling technique was used to identify participants that were actively managing projects during the Covid-19 pandemic period. The construction project managers sampled were registered professionals with the South African Council of Construction Project Managers to ensure that participants know about managing projects and have experience in dealing with stakeholders. This ensured validity of the results.

3.2 Profile of Participants

20 construction project managers were identified and invited to participate in in-depth interviews with researchers using a virtual MS Teams platform. 15 responded and participated in 1hour long interviews. The profile of the participant is indicated below:

Table 1. Profile of participants

Participants (CPM)	Gender	YOE	Active project during COVID-19
Construction Project Manager 1	Male	12	Yes
Construction Project Manager 2	Male	11	Yes
Construction Project Manager 3	Female	7	Yes
Construction Project Manager 4	Male	6	Yes
Construction Project Manager 5	Male	25	Yes
Construction Project Manager 6	Male	14	Yes
Construction Project Manager 7	Male	8	Yes
Construction Project Manager 8	Male	12	Yes
Construction Project Manager 9	Male	11	Yes
Construction Project Manager 10	Male	18	Yes
Construction Project Manager 11	Male	22	Yes
Construction Project Manager 12	Male	16	Yes
Construction Project Manager 13	Male	5	Yes
Construction Project Manager 14	Female	13	Yes
Construction Project Manager 15	Male	10	Yes

Legend: YOE – years of experience, CPM – construction project manager

3.3 Data Collection

Data was collected through in-depth interviews with participants from 20th January to 30th March 2021. All interviews were recorded on MS Teams as permitted by participants. Emails communication requesting interviews were sent and interviews were scheduled via the MS Teams platform. Each interview went on for an average of 1 hour.

3.4 Data Analysis

20 participants were invited to participate in the study, however, 15 participated in interviews reflecting a 75% response rate. Data that was collected was manually analyzed using thematic analysis. Six themes emerged from the collected data and are discussed further in the findings below.

4 Findings and Discussion

The findings of the study indicate that many innovative approaches were adopted by construction project managers to adhere to COVID-19 health restrictions to enable project progress. The participants interviewed discussed strategies they implemented to engage various external stakeholders during the COVID-19 period and six themes that emerged are discussed below:

4.1 Communication Difficulties

100% of participants (construction project managers) indicated that they struggled to communicate with external stakeholders during the COVID-19 period. This was attributed to the fact that project meetings switched from traditional face-to-face to virtual mode for all meetings. All project stakeholders were required to adhere to social distancing protocols that were in place. ,A significant number of participants (80%) indicated that most external stakeholders lacked the resources to virtually connect, participate and give input on projects. This was a huge challenge for internal stakeholders and additional face-to-face meetings had to be arranged whilst observing social distancing and other health protocols to discuss urgent matters. As a result, fewer people were able to attend due to reasons associated with limited numbers to observe social distancing and health reasons, and this made communication to external stakeholders very difficult.

4.2 Lack of Access to Information (Misinformation)

Participants (70%) indicated that it was difficult to pass information and get input from external stakeholders as often they experienced access issues and this resulted in a lack of information and misinformation among other groups. Some groupings also among external stakeholders were adamant that COVID-19 did not exist and believed project managers were trying to exclude them intentionally from participating in projects.

4.3 Access Restrictions

Government offices' opening and closing times changed depending on the rotation system and availability of staff. Further restrictions were imposed on the number of people allowed inside buildings to ensure social distancing was observed. This resulted in delays in obtaining planning permits and affected project delivery. Additionally, when traditional face-to-face meetings were arranged limited numbers of attendees were observed and some stakeholders had to be left out to comply with health restrictions.

4.4 Unintentional Exclusions

Most participants (60%) admitted that at times they excluded external stakeholders as they were focused on balancing cost, time, and quality of projects. There were many delays incurred with trying to include external (communities) stakeholders and most participants decided to exclude them on some aspects of the project so they are not delaying the project. Most participants indicated that these exclusions were beyond their control and were focused on delivering projects on time within the stipulated health restrictions. 60% of participants agreed that other external stakeholders were excluded because they were limiting numbers on site and in face-to-face meetings to comply with health regulations. While other external stakeholders were excluded in face-to-face meetings as they did not believe COVID-19 existed and did not want to comply with health protocols citing that project managers were intentionally trying to exclude them so they do not ensure their constituencies get opportunities on the project. One participant (CPM 10), explained in detail that fewer people were getting employed from the community as site numbers were restricted and some external stakeholders who were misinformed believed and complained that this was a strategy to try to exclude them from participating in the project and such issues created conflict in some projects.

4.5 Lack of Connectivity (Power, Fibre/ Wifi, or Data Issues)

100% of internal stakeholders were working from home and connecting on virtual platforms. 90% of participants indicated that external stakeholders failed to attend meetings due to a range of issues such as power cuts (load shedding) in their areas, no availability of fibre/ wifi, or other data-related issues. These issues were related to costs or unavailability of service.

4.6 Inadequate Infrastructure to Support Compliance with Health Protocols

Some participants (55%) indicated that some external stakeholders did not have hardware (computers/smartphones) to enable connection to virtual platforms. A further (40%) indicated that some external stakeholders were unable in some communities to have water in their homes for washing hands and observing health protocols and relied on water tankers and street taps to obtain water. Therefore some of the stakeholders who were also community leaders invested most of their efforts in organizing and co-ordinating systems to aid communities to deal with local issues related to water and sanitation and a lesser focus was on the project.

It can be deduced from the results above that construction project managers were faced with many challenges in engaging external stakeholders during the COVID-19 pandemic period. Most of the challenges encountered were sudden, unexpected, and not traditionally project-related challenges, however, these had an impact on the project and adversely affected project stakeholders. This finding agrees with Aigbavboa *et al.* (2021), on the fact that engaging external stakeholders, with no information and communications technology tools available, connection to the right virtual private platforms and internet protocol address and no hardware proved difficult for project managers to engage with them. In contrast to Aigbavboa *et al.* (2021) who found that some industries had a smooth transition to the virtual world when COVID-19 hit and admits the construction industry had challenges, this study explains the nature of the challenges. Traditionally the construction industry is not a technology-savvy industry therefore transitioning to the virtual world was highly unlikely.

Most construction project managers indicated that their main priority during COVID-19 was to find a balance between delivering projects on time, cost, and quality and within stipulated health restrictions to save lives. This balance proved difficult as most external stakeholders had multiple challenges that were not traditionally the responsibility of the project but affected the project. The exclusion from site activities, meetings, and lack of access to information due to adherence to health restrictions frustrated some external stakeholders who did not have sufficient information or relied on misinformation and viewed such practices as exclusions. During this period, jobs were scarce as projected by Phuravhathu *et al.* (2020), a 62% decline in construction activity, with further effects on supply chains supplying materials and cancellation of some contracts (Deloitte 2020). These measures are likely to cause a deterioration in business activity that impacts on job losses (Cokayne, 2020). Most external stakeholders in community development projects relied on jobs from the projects, and exclusion and lack of information created frustration and dissent.

Projects that involve internal and external stakeholders working together to achieve project goals have a better chance of success. Lack of coordination and exclusion of stakeholders on projects creates friction and delays projects and may incur additional time and cost. Engaging external stakeholders in community development projects during the COVID-19 pandemic period was a challenging process for construction project managers. They introduced mechanisms to ensure project progress and adherence to health restrictions to save lives.

However, engaging external stakeholders in community development projects without resources and an emerging unequal country presented additional challenges that made it difficult to work.

These challenges were a result of the strategies implemented by construction project managers to respond to the COVID-19 pandemic to save lives. However, the implemented measures disadvantaged and limited the inclusion of external stakeholders in the project. As a result, project managers were unable to adequately involve external stakeholders in community projects during the pandemic. This suggests that these community projects lacked external stakeholder influence. This deficiency had a bearing on how project managers met project outcomes to create value for stakeholders during extraordinary times of the COVID-19 pandemic. Construction project managers in community development projects prioritized adherence to health restrictions to save stakeholders' lives whilst risking unintentionally excluding external (community) stakeholders without resources to drive completion of the project.

5 Conclusion and Further Research

This paper explored the engagement of external stakeholders during the COVID-19 pandemic period. It looked at how construction project managers adjusted to COVID-19 demands and engaged external (community) stakeholders in community development projects. The study identified challenges experienced by project managers and grouped these challenges into six themes namely communication difficulties, lack of access to information (misinformation), access restrictions, unintentional exclusions, lack of connectivity, and inadequate infrastructure to support compliance with health protocols. Secondly, the study agreed with the literature that external stakeholders play a key role and have the potential to affect the projects if not engaged in the project. Thirdly the COVID-19 pandemic was unexpected and switching from traditional face-to-face to virtual mode resulted in the unintentional exclusion of most external stakeholders and additional frustration.

External stakeholder engagement is key to ensuring project success and minimizing conflict within projects. Their engagement minimizes the chances of conflicts and delays that result in cost, quality, and time implications that are detrimental to project success. Enhancing the engagement of external stakeholders and identifying support mechanisms to include them in projects during difficult periods will improve the achievement of project goals.

A reorientation of external stakeholders and further education and induction into a new context are recommended as ways to handle the engagement of external stakeholders in crisis environments. More support (education and resources) is recommended to be offered to external stakeholders to facilitate progress on projects.

This study contributes to the body of knowledge by assessing external stakeholders' engagement in community projects during the COVID-19 period. It assessed the challenges that were experienced by construction project managers in engaging and integrating external stakeholders during COVID-19 period considering the issues of access and lack of resources external stakeholders (communities) have in a developing and unequal country. It also contributes to and highlights the notion that some solutions do not fit other contexts as these external stakeholders could not switch easily to virtual modes like others in other industries and developed countries. The findings are however limited to external stakeholders who are in communities that are disadvantaged and lack resources in developing countries such as South

Africa. A further study focusing on the perspectives of external stakeholders and the difficulties they endured in participating in projects during the COVID-19 period is recommended.

6 Acknowledgment

The authors would like to acknowledge a group of three BSc Honours in Construction Management students namely Mary Riba, Pamela Magagula, and Modjadji Ramaila who worked on the project and assisted in data collection.

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Exploring the Factors Affecting the Cost of Quality (COQ) in Construction Industry: A Systematic Literature Review

Nandini Sharma[1] *, Boeing Laishram[1]

[1]Department of Civil Engineering, Indian Institute of Technology Guwahati, Guwahati, 781039, Assam, INDIA

nandini.sharma@iitg.ac.in; boeing@iitg.ac.in

* Corresponding author

Abstract

In the construction industry, one of the most important concerns is how to establish the optimal balance between the desired standard of quality and the cost incurred. The evaluation of the cost of quality (COQ) can help achieve this balance. Understanding the factors that influence the cost of quality in the construction industry (CI) may assist in identifying cost-saving methods without compromising quality. Even while manufacturing has a well-developed understanding of the components and theories of cost of quality, there is a lack of data accessible from the construction industry for multiple reasons. The study aims to review and analyse literature to identify the factors affecting the cost of quality in construction industry and group them into respective themes. The study is performed utilising 55 peer-reviewed publications on COQ extracted from three databases, i.e., EBSCO Host, Scopus & Web of science. Using the Systematic Literature Review (SLR) strategy, the publications are organised according to the technologies employed so that new directions may be discovered in the existing literature. Thus, this study contributes to the body of knowledge by developing an integration framework of factors that can help industry practitioners, policy makers, and researchers promote COQ & Quality Management in the construction industry. Directions for future research are proposed to address the gaps in literature and enhance effective research towards promoting COQ.

Keywords

CI, Cost of quality, Framework, SLR, Themes

1 Introduction

Construction projects are difficult to manage, and they are carried out under unpredictable circumstances (Lee et al., 2005). Sometimes building projects fail to meet their pre-determined goals in their predetermined goals in regards to budget, schedule, quality, and scope of work, which may lead to problems including cost overruns, delays, unsatisfactory work, and scope creep (Shafiei *et al.*, 2020). Given the construction industry's considerable linkages to other economic sectors and to the development of a country's economy, operating expenses for construction projects must be carefully monitored and regulated (Hoonakker et al., 2010).In such Scenario, competition among the construction firms increases and to stay competitive under such circumstances, it is essential to minimize the cost of construction projects while maintaining the specified level of quality. The use of cost of quality analysis in a project provides for the quantification and documentation of project quality in order to make better and more efficient use of resources and invest in preventative and assessment activities to reduce project costs (Omar et al., 2014). The majority of research have discovered that the ideas, techniques, and procedures of TQM in manufacturing need to be interpreted and decoded before they can be implemented to the construction industry (Hoonakker et al., 2010). Apart from maximizing profits, COQ calculations enable a company in identifying obstacles in achieving quality objectives, monitoring the efficacy of existing systems and production, and making cost-effective, fact-based strategic choices (Garg et al., 2021). In developing countries where infrastructure development is a top priority, the subject assumes a much greater level of significance. For example, the Indian government plans to spend INR 39 trillion on urban infrastructure by 2022-23, and it is projected that the construction sector would be worth US$ one trillion by 2025 (KPMG 2016). Given the constraint of resources, the importance of a clearer understanding of issues relating to quality, including cost and its components and its relation to defects, cannot be overstated.

Of the information available also, most of the studies focuses on rework or only direct cost as most of factors are missing to calculate the cost of entire COQ (Abdul-Rahman et al., 1996; Barber *et al.*, 2000; Love et al., 2005). According to the existing research, a large number of construction organisations exclusively consider failure costs rather than the other two cost categories, preventative and appraisal costs. In the USA, the Building Industry Institute (CII, 1989) investigated the rework costs of rectifying quality deviations in nine construction projects. The deviation costs averaged 12.4% of the overall project cost. A minor decrease in deviation costs might lead to significant savings. This requires identifying and assessing quality expenses. This highlights the need of understanding how and where quality expenditures have been expended to avoid their recurrence, decreasing building costs for contractors, customers, and end-users. Nearly 60% of survey respondents indicated they had not even measured defects-related expenses. Those who measured claimed defects cost 5% of total construction expenditures. Significant results (about 5–6%) were also identified by Abdul & Rahman (Abdul-Rahman et al., 1995).

Although it has been observed that there is a lack of research on COQ, however none of the above-mentioned literature review publications focused significantly on future research recommendations. Hence, there is a window of opportunity to focus on the future research agenda in the field of COQ and proper comprehensive framework to reduce the workload of quality managers & contractors for the analysis of COQ.

The objective of this study is to identify the most important factors contributing to COQ and to categorise these factors into respective themes of COQ that may assist cost estimators in arriving at a more precise calculation of the projected cost of quality for any construction project. This study is expected to help project managers, contractors, quality managers and other construction professionals figure out about the major factors contributing in increased cost of quality so that these factors can help further in developing the frame work for COQ model in future.

2 Methodology

The SLR methodology used in the present study follows the guidelines suggested by (Tranfield, 2003). A review is "systematic" if it is based on explicitly articulated questions, discovers relevant research, evaluates their quality, and summarizes the data using an explicit approach (Khan *et al.*, 2003).Unlike the traditional review, a systematic literature review is a method that locates existing studies, selects and analyses in such a manner that reasonably clear judgments about what is and is not known may be obtained. According to author, three-step process must be developed to perform a systematic and well-defined research of the literature that can be replicated by other researchers (Chelliah *et al.*, 2021).Therefore, in this study, the following three-stage procedure was adopted:

1. Stage I: Planning the review
2. Stage II: Conducting the review

3. Stage III: Analysing the review

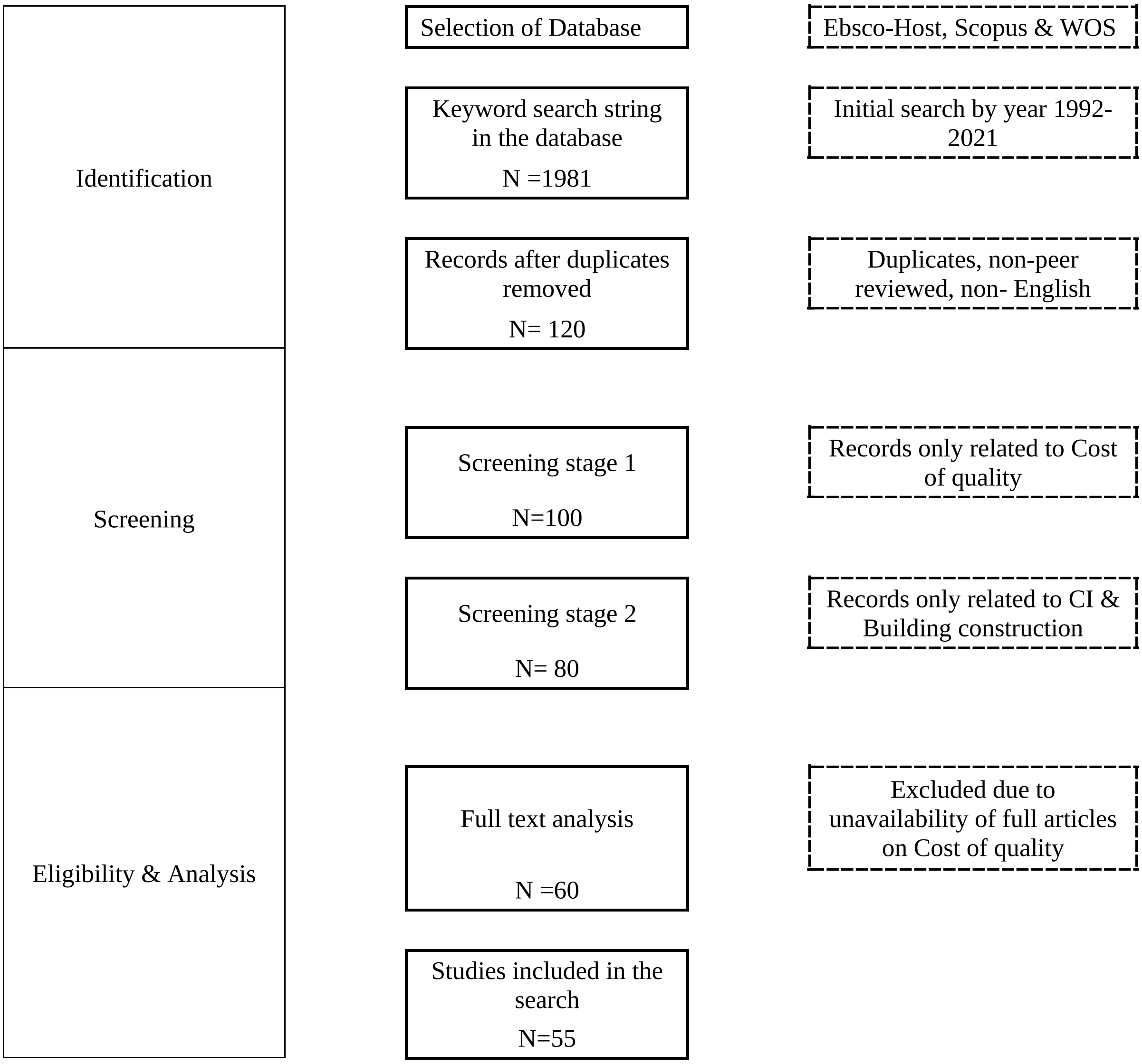

Figure 1. Literature search and selection process

2.1 Planning the Review

The First step in SLR involves the research problem or defining the subject of literature review. The Review starts with identifying the relevant articles, specific keywords and main databases to find the right set of publications. For the literature search, three databases were used: Web of Science, EBSCO-host, and Scopus. These databases were chosen due to their flexibility, accessibility, and the scope and quality of their journal coverage in the management and construction sector. Before initiating the literature search, it is necessary to identify every potential keyword, including duplicates and alternative phrases. As a result, the search was conducted using building blocks, which is one of the most often used search techniques by literature reviewers (de Araújo et al., 2017). Thus, the research area is broken into distinct words that are connected using Boolean operators such as AND and OR. The keywords for the present research problem were selected via a process of snowballing and trial-and-error search, which included the following: "Cost of quality," "Cost of Poor Quality," "Quality costing," "Quality-related costs," "Quality costs," "Prevention cost," "Appraisal cost," and "Failure cost."

As proposed by Kuhrmann, Fernandez, and Daneva, using a combination of snowballing and trial-and-error methods, keywords were determined (Kuhrmann et al., 2017).

2.2 Conducting the Review

Using the keywords identified in the prior section, the following phase involves choosing the most relevant articles for further review. This process is broken down into three distinct phases. In the first stage, keyword search was introduced in the three databases. To preserve the comprehensiveness of the acquired literature, the initial date for the publication search was not specified. All the articles until July 2021, when the search activity was undertaken, were covered and generated 1981 publications. The search results were narrowed down to 120 publications after excluding those that were not written in English, did not undergo peer review, and were considered to be duplicates. The titles and abstracts of publications were thoroughly assessed in the databases adopting pre-defined filtering and selection criteria (Fu Jiaa et al., 2018). When it was uncertain from the abstract whether it should be retained or not, the whole publication was read. The publications were assessed concurrently by the authors of the present research, and any questions or discrepancies were settled by reaching a consensus (Roeser et al., 2014).

Table 1. Inclusion and exclusion criteria for SLRs

Inclusion Criteria	Exclusion Criteria
Publications until July 2021	Publications after 2021
Fully accessed publications	Non–fully accessed publications
Only peer-reviewed publications	Publications that were not peer reviewed
Studies concentrating on factors of COQ	Studies concentrating on any other area of COQ
Publications written in English	Publications written in any language

The criteria included the inclusion and exclusion of papers is mentioned in table 1. Following this regressive screening, 80 publications were chosen for additional review. In the third phase, once the articles had been exported and initially filtered, a full-text manual analysis was performed, and 55 publications were chosen for the systematic review study (Kuhrmann et al., 2017).

2.3 Analysing and Reporting Review

In this step, a descriptive analysis of the publications was undertaken to obtain year-wise and infrastructure sector-wise publications. These results are shown using charts and tables in following section. Furthermore, inductive content analysis was undertaken to determine the factors of cost of quality and how these factors are divided into various themes. Each of the articles was read numerous times, back and forth, to extract and group codes, and eventually, classify them (Seuring et al., 2012).

3 Analysis and Results

3.1 Descriptive Analysis

The descriptive analysis, as shown in Figure 2, includes the publication distributions in various years starting in 1992. This descriptive analysis consists of two phases: the first phase began with infrequent publications between 1997 and 2005, and the second phase is between 2008 and 2021. Initially, publishing in the area of COQ was limited, but the overall number of publications published on the subject of COQ has risen dramatically over the past decade, with the largest numbers seen in 2014, 2008, and 2021, followed by 1998, 2009, 2010, 2013, 2017,

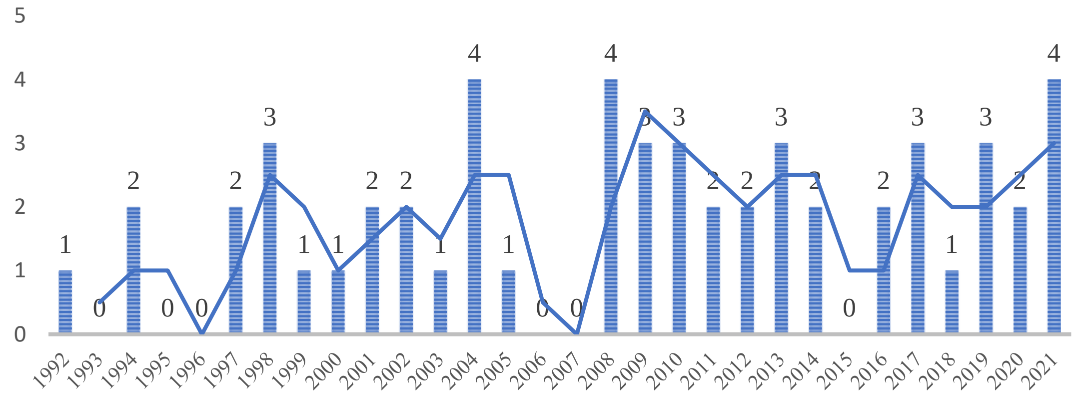

Figure 2. Number of publications within the selected period

and 2019. For the years 2011, 2014, 2016, 2012, and 2020, fewer publications were reported. Additionally, the list of publications is classified according to the methods used to acquire the data. There were four distinct methods for data collection: conceptual research, case study, survey/questionnaire, and literature review. The conceptual study was the often used strategy for data collection (21 publications). Furthermore, a considerable number of researchers used the case study methodology (15 publications) to collect data. The other techniques of data collecting include survey/questionnaire (12 publications) and literature review (7 publications).

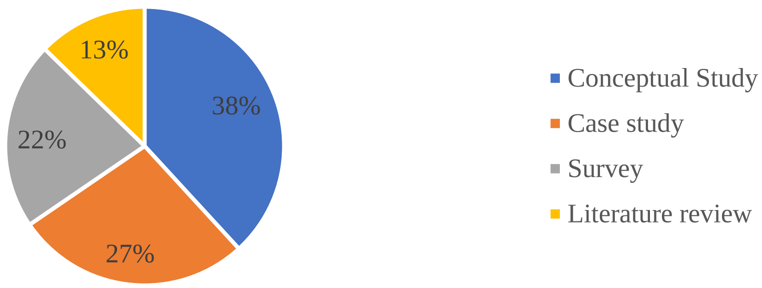

Figure 3. Overview of research methodologies on data collection

3.2 Content Analysis

The content analysis results from the study of all the research articles are presented in this section. This section discusses the core concept of cost of quality (COQ), the cost of quality in the construction industry, the analysis of the factors that affect the COQ and the approach used to calculate the COQ.

Understanding cost of quality system – the core concept:

In the construction sector, quality is defined as the ability to adhere to contractual obligations with clients. One of the most crucial tools used for quality management process is Cost of quality (COQ). The concept of COQ was first introduced in the "Quality Control Handbook" by Dr. Juran and discussed the use of COQ tool in calculating the cost (Schiffauerova et al., 2018). The cost of quality is commonly defined as the sum of the cost of conformity and the price of non-conformity. The cost of conformance is defined as the cost spent to prevent poor quality, while the cost of non- conformance is the cost of poor quality caused by product and service failure (Schiffauerova and Thomson, 2006). According to the American Society for Quality (ASQ), COQ is used to determine the expenses associated with achieving or failing to attain product or service quality (Campanella 2003). The Basic themes for Cost of quality is well defined by British Institute for the identifying and analysing the factors which are contributing the cost of quality(Llanos, 2002). After quality guru Feigenbaum defined quality costs as Prevention-Appraisal-Failure (PAF), the PAF methodology became almost universally acknowledged for estimating quality. The failure costs in this methodology can be further divided into two subcategories: internal failure and external failure costs (Feigenbaum, 1956).

Under this PAF approach, following are the themes:

Prevention costs: This comprises all expenditures needed to avoid non - conformance, such as obtaining the specified quality in a building project without the need for rework and repair. Author described preventive cost as "cost associated with activities necessary to ensure a process produces high-quality goods or services" (Abdul-Rahman et al., 1996; Barber *et al.*, 2000; Love et al., 2005).

Appraisal costs: These expenditures are associated with the supplier's and customer's evaluation of purchased materials, processes, intermediates, products and services to assure conformance with the specified requirements (Kazaz rt al., 2005; Thomson et al., 2006).

Internal failure costs: These expenditures occur when the results of work fail to reach designed quality standards and are detected before transfer to customer takes place(Soriano, 1999).

External failure costs: These expenditures occur when products or services fail to reach design quality standards but are not detected until after transfer to the customer (Soriano, 1999).

Cost of quality factors in construction industry:

There were 24 factors that were found by coding and classification, and they were organized into four primary groups (as shown in Table 2).

A considerable number of authors have highlighted *strategic planning* as the tool for quality improvement. In order to achieve a project's goal, strategic planning must take place early on in the project(Tawfek et al., 2012). Creating powerful, well-intentioned ventures that never get off the ground is possible when strategy is strong and tactics are poor. Projects that experience "errors of inaction" can result in cost and schedule overruns.

Table 2. Summary for identified factors for cost of quality

Themes	Factors	Example Papers
Prevention	Strategic planning	(Tawfek et al., 2012)
	Equipment maintenance and calibration	(Kazaz et al., 2005; Abdelsalam et al., 2009; Rosenfeld, 2009; Heravi et al., 2014; Mahmoudi et al., 2020; Garg et al., 2021)
	Evaluating & verifying designs	(Aoieong et al., 2002; Forcada *et al.*, 2017)
	Employee training	(Kazaz et al., 2005b; Abdelsalam et al., 2009; Tawfek et al., 2012; Heravi et al., 2014; Shafiei *et al.*, 2020; Garg et al., 2021)

Themes	Factors	Example Papers
	Quality improvement programs	(Kazaz et al., 2005; Tawfek et al., 2012)
Appraisal	Design evaluation by reviews	(Kazaz and Birgonul, 2005; Heravi et al., 2014; Shafiei *et al.*, 2020)
	Material consumed during inspection & testing	(Kazaz et al., 2005a; Rosenfeld, 2009; Balouchi et al., 2019)
	Third Party quality auditing	(Llanos, 2002; Rosenfeld, 2009; Tawfek et al., 2012; Garg et al., 2021)
Internal Failure	Repair, rework, or replacement	(Hall et al., 2001; Kazaz et al., 2005; Rosenfeld, 2009; Mahmood *et al.*, 2014; Balouchi et al., 2019; Shafiei *et al.*, 2020)
	Re-test, Re -inspection	(Rosenfeld, 2009; Mahmood *et al.*, 2014; Shafiei *et al.*, 2020; Garg et al., 2021)
	Downgrading	(Mahmood *et al.*, 2014)
External Failure	Complaints	(Kazaz et al., 2005; Heravi et al., 2014; Mahmood *et al.*, 2014; Shafiei *et al.*, 2020)
	Compensations claims	(Rosenfeld, 2009; Mahmood *et al.*, 2014; Shafiei *et al.*, 2020)
	Arbitration and litigation	(Shafiei *et al.*, 2020; Garg et al., 2021)

The *calibration and maintenance of equipment* is considered by numerous authors. The calibration and maintenance of equipment used in all inspection activities. Failure to calibrate equipment correctly might result in low-quality output and slow down the construction. Equipment that hasn't been calibrated properly can't sustain consistent temperatures, which may cause damages and increases the cost and time (Soriano, 1999). Numerous authors also have highlighted one of the factor is *employee training* for the prevention phase. It is essential for the employees to attend training classes tailored to the particular responsibilities, nature, and size of the project they are working on (Tawfek et al., 2012). As the employee experience differs, and as some of the workforce has no prior experience with some of the project's construction operations, therefore training of the QC employees is critical to assisting the inexperienced QC employees in becoming familiar with the project specification, techniques, engineering drawings, and quality standards (Abdelsalam et al., 2009). According to the majority of authors, investing money on employee training is not reasonable or economical for businesses due to lack of necessary job stability and employees may quit the organization shortly after training and transfer to another (Heravi et al., 2014). In addition to prevention Phase, most of the expenses are spent on *quality improvement programs*. Quality improvement programs is one of the influential factor for the prevention phase. Various quality improvement programs like Six Sigma, Just-in–time, Lean, Quality function deployment, PDCA cycle etc., are adopted by the construction firms in order to maintain the quality throughout the project. Quality improvement incurs its own expenses. Consequently, quantifying the cost of quality is crucial since it offers information on the cost of quality improvement activities.

In the conventional prevention, appraisal and failure approach, major expenditure may be recognized as either prevention cost or appraisal cost. *Design appraisal by reviews*, for example, may be regarded as a preventive cost; yet, they are fundamentally a checking phase and, as such, may be termed as an appraisal cost (Tang, Aoieong and Ahmed, 2004). The first step towards reducing the significant influence of errors is to conduct design reviews and verifications, although these procedures will not eliminate them from occurring. In light of this, it has to be thought about hiring a community advisor who is knowledgeable and skilled enough in construction to establish specifications as well as modifying the procurement process to provide all contracting parties a larger portion of the responsibility (Love at el., 2004; Palaneeswaran *et al.*, 2008). Thus, errors and rework may be avoided via design reviews and verifications, as well as the selection of companies based on the actual skill level and expertise of the employees who will handle the design process of the project. Due to the fact that minimizing construction costs is the primary objective of contractors in the construction industry, they are unwilling to engage in establishing a fully-equipped laboratory on the construction site and would rather select a reliable supplier for ensuring the quality of the materials, i.e. a *third party for quality auditing.* These are the inspection fees paid by the contractor and his subcontractor. This covers the cost of the inspection equipment as well as any third-party costs paid to examine any particular activity (Soriano, 1999). Third-party audits performed by independent organisations to offer present and potential clients with confidence about the product or service (Love at el., 2004; Palaneeswaran *et al.*, 2008).

Whereas under internal failure cost, many authors highlighted the *rework* factor. Rework is described as "repetition of an activity or task that was performed incorrectly the first time." According to previous studies, rework expenditures might account for up to 23% of contract values (Ma *et al.*, 2021). According to various authors, internal failure costs are the costs spent by an organisation as a consequence of non-conformities or defects at any point in the quality cycle, requiring *re-testing or re-inspection* of the particular activity. Also, construction equipment that is functional but does not satisfy criteria may be downgraded and offered at a discounted rate as 'second hand quality' (Manatos *et al.*, 2015).

In addition, external failure costs are costs incurred after the project has been handed over to the client. These include costs for adjustments of *complaints, compensation claims and litigation costs* (Tang at el., 2004). The reason construction organisations prefer to avoid legal claims is because such legal entanglements may not only easily harm their brand, but also impose substantial expenses on the entity (Kazaz et al., 2005). Direct expenses are easily measured, often mentioned in assessing workmanship quality, and account for a considerable amount of overall project expenditures. Indirect costs, which include delayed schedule and productivity, litigation and claims, and poor operational efficiency, are not clearly quantified (Tang at el., 2004).

4 Conclusion and the Way Forward

The findings of a thorough review of the literature on the factors influencing cost of quality have been given in this study. This systematic study concluded that there is still a significant gap in existing cost control research and methods owing to the complexity of project implementation circumstances and the fact that most projects do not accomplish their cost and quality targets. One of the gaps along this path is the control of cost of quality in construction projects. Under the four themes of cost COQ, it was found that *maintenance & calibration of test and measuring equipment & staff training* from the prevention phase were the most discussed factors in the literature review. The findings of the study indicated that investing in training and hiring experienced workers may minimise failure costs and enhance preventative costs, hence reducing the COQ of construction projects. Whereas, under appraisal phase, *design appraisal by reviews, material consumed during inspection & testing & third party quality audit* were discussed by the authors. With this in mind, the findings of the study indicated that investing in training and hiring experienced workers may minimise failure costs and enhance preventative costs, hence reducing the COQ of construction projects. Under internal failure phase, *rework & defects* were contributing to the internal failure cost. It has been observed that rework arises as a consequence of a lack of coordination between the project's stakeholders, and that errors or defects on construction sites are common and expensive for contractors and owners of built facilities. Whereas, under external failure phase, *complaints & liability claims* were the factors which are increasing the cost of external failure cost. Addressing client concerns has been proven to escalate failure costs, and external failure costs can only be reduced by concentrating more on prevention and appraisal costs.

The paper provides a systematic review of literature on cost of quality factors. The insights gained from this study provide a holistic view of a quality's classifications and measures. Researchers may utilise this expertise as a knowledge basis to analyse the building's cost and quality. Since these indicators are key drivers of the cost of quality and architects and engineers may include them throughout the design and construction phases to reduce the cost of quality management and enhance the quality of the building. The identified quality measures can also assist contractors and project manager in making informed decisions during budgeting of the project. Furthermore, governments may use these measures to analyse budgets to set cost-of-quality guidelines.

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Towards Developing a Conceptual Megaproject Management (MPM) System

Jery Johnson[1*], Mohan Siriwardena[2] and Suranga Jayasena[3]

[1]ABAC Pty Ltd, Melbourne, AUSTRALIA
[2]Liverpool John Moores University, UNITED KINGDOM
[3]University of Moratuwa, SRI LANKA

antony@abacau.com.au; m.l.siriwardena@ljmu.ac.uk; suranga@becon.mrt.ac.lk
* Corresponding author

Abstract:
The importance of an effective Megaproject Management (MPM) system has been strongly emphasized in the literature, with UK advocating for the necessary reforms, and Australia following suit. However, no comprehensive system has been forthcoming to date. Traditionally Megaprojects had been affected by poor performance in terms of cost, time, benefits etc. The literature indicates that project size, number, and investments in Megaprojects are growing globally. Thus, ensuring better performance through adopting MPM best practices is currently a very important task for Project Managers. With current level of awareness about the poor performance of Megaprojects and several challenges related to MPM, there is an urgent need to find suitable practical solutions to overcome the relevant practical and pressing issues. This paper reports on the results of a systematic literature review carried out to develop a conceptual MPM system. The presented MPM framework comprises 18 main elements with each having a number of key points/sub-elements for consideration. Once validated, the system could also be used for the evaluation of MPM practices especially during its development stage to provide actionable insights for the management team, and even used at the post-completion evaluation stage to facilitate learning. The need for such a forward-looking performance evaluation system has been highlighted in the literature. As a next step, the derived conceptual MPM system could be validated through field research involving case studies and subsequently applied across Megaprojects consistently to improve MPM practices, and increase the likelihood and predictability of their success.

Keywords:
Development, Evaluation, Management, Megaprojects, System

1 Introduction

Megaprojects are delivered to accelerate developments to contribute to the advancement of economic, social & cultural, transportation, energy, technological etc updating (Yuan *et al.*, 2021) Due to substantial resource consumption, they have to be delivered effectively and operated successfully. Megaprojects are managed as a single project or program or part of a large portfolio of projects. Building standard processes on leading practices increases the chances of repeating successes across the program/portfolio (Accenture, 2012). To achieve predictably good results, Megaproject managers could apply tested and proven PM methods and tools & techniques together with the associated professional insights and lessons learned in a more disciplined and structured manner. This paper attempts to develop a framework of MPM best practices as a starting point to achieve the same objective.

There are four Management components in a Megaproject, such as (Yuan *et al.*, 2021):

During Development stage:
1) Business Management (BM) (Client-side),

2) Project Management (PM) (Client-side),
3) Construction Management (CM) (Contractor's delivery-side), and

During Operational Stage:

4) Asset Management (AM) (Operation and Maintenance-side).

This article mostly focuses on the 2nd Project Management (Client-side) component, while touching upon the essential interfacing MPM practices with other three components (especially the BM & CM components). The key development phases of a Mega Construction project could be identified as Pre-contract (Front-end), Tender & Procurement, and Post-Contract / Construction / Execution Stage. Accenture (2012) insists that comprehensive approaches are needed to cope with the increasing scale and complexity of Megaprojects. Thus, all three main phases are critical. When striving for achieving success and designing suitable MPM systems, it is important to develop and implement 'strategies for addressing reasons for poor performance' (Jaselskis, 2018). This article is written in two steps, with first step being the critical analysis of the selected core literature based on a selection of valid and useful literature by the practitioner that reflect the real-life practice knowledge. The second step is the addition of practice knowledge based on lessons and learnings from both successful and less successful Megaprojects for sense-making and sharing practice insights. The project size, number, and investments in Megaprojects costing over US$1 Billion are growing globally (Flyvbjerg, 2019; ACA, 2019) and unfortunately, they have a higher rate of failure with 95% fail to deliver cost & schedule targets (Jaselskis, 2018), and of a sample of 3022 projects, only 0.2% of projects were on budget, on time, and on benefits (Flyvbjerg, 2019). This requires PMs and researchers to systematically study the Megaprojects, issues, risks and best/leading practices adopted on them to learn and apply the knowledge gained to improve performance on the parts of the same, parallel, and future projects. Due to page restrictions, we have omitted the detailed analysis of the literature and reflections related to the Stage 2 & 3 components.

Theoretical and Practical approaches to MPM and Steps taken to Develop this Comprehensive Framework

The derived conceptual framework follows and complies with the MPM elements considered in the recent research paper of Denicol *et al.*, (2020). The paper was based on a wider and systematic literature review related to Megaproject Success and Failure. The elements have also been re-confirmed and verified through a review of the published Megaproject Case studies covering over 200 Megaprojects. The MPM framework is also generally in line with NAO's publications which is a UK's Centre of Excellence for MPM. In addition, publications of HMT, IPA UK and FHWA (USA) have been considered and quoted. Further, steps had been taken to capture and incorporate valid practitioners' reflections which makes the MPM system more industry relevant. The proposed conceptual MPM Framework is provided in Figure 1.

2 Research Methodology

Therefore, the research methodologies adopted are: 1) critical analysis of the selected literature including published case studies which are judged to be of high quality and reflect industry practice by the practitioners with domain knowledge, 2) and systematic recording and reflections of practice knowledge to come up with a best practice framework. The proposed framework is the final output of a detailed review of Megaproject Management reports and practices across approximately 65 real cases supported by the research works of various leading Megaproject delivery and auditing authorities and professional institutes, such as NAO, IPA, HMT, FHWA, Infrastructure Australia, ICE, etc. The framework incorporates results of over 200 (approximate) published case studies.

3 Findings and Discussion

Under each of the three (3) key development stages, six best practices have been recorded leading to a total 18 MPM best practices being identified in this conceptual MPM model. A number of key sub-elements of Stages 1 & 2 have also been discussed in detail below. This paper has been written to highlight a series of MPM best practices and essential supporting evidence that will be sought when evaluating a MPM system from a MPM practitioner's point of view.

Stage 1 - Front end Planning & Feasibility Studies	Stage 2 - Tendering & Procurement	Stage 3 - Post-Contract
• Effective Business Management [E1] • Project Planning, Initiation & Set-up [E2] • Value-based procurement & assembling the right team [E3] • Design & Design Development [E4] • Risks & Opportunities Management [E5] • Relistic Project Baselines & Management of Changes & Progress [E6]	• Procurement, contractual & commercial arrangements [E7] • Packaging strategy & sequence of works [E8] • Tender Evaluations & Risk Management [E9] • Updating baselines and business case [E10] • Due Diligence & Project Assurance [E11] • Robust contract design & contract clauses review [E12]	• PM, Oversight, Contract Management & reporting [E13] • Progress & Performance Management [E14] • Proactive Claims & Disputes Management [E15] • Project Controls & Risk Management [E16] • Scope & Design Management [E17] • Client's side risks and opportunities management [E18]

Figure 1. Conceptual Megaproject Management Framework for Construction Developments

STAGE 1 - FRONT-END LOADING - MEGAPROJECTS PLANNING AND FEASIBILITY STUDIES

Element No 1: Effective Business Management by the Client Team

1.1 Strategic Business and Project Management

1.1.1 An Enterprise Model

Once the project's purpose and strategic need have been identified, the leadership team will have first thoughts about the project (ICE, 2017) and select a project that meets its business priorities, after confirming it is the right project to meet business needs (NAO, 2021). Subsequently, an **Enterprise Model** needs to be defined in connection with a project/program including its vision and objectives; policies; PM, procurement, and commercial strategies; and delivery model (Deloitte, 2021). The enterprise model and governance processes need to be flexible on Megaprojects (ACA, 2019). Large capital project delivery team need to move to agile, efficient, and well-balanced operating model to be high performers (Accenture, 2012).

1.1.2 Governance & Assurance (G&A)

Instigating an efficient and timely client decision-making process while holistically looking at wider and long-term development success perspectives is the focus of G&A. Robust design of a **G&A** strategy is important (NAO's, 2021 and IPA, 2020). G&A function aims at the alignment of business and project objectives with effective PM strategies (Accenture, 2012b).

Implementation of a robust business management system with wider performance measures and back-to-back reporting mechanism from the Project Delivery team help implement an effective G&A process within client organisations.

1.1.3 Gateway / Stage Gate Process

The **Gateway / Stage Gates** (Deloitte, 2016) **process** is an integral part of G&A (ICE, 2017). G&A is about achieving development objectives, and sustainable operational success and achievement of planned benefits (ICE, 2017).

Additionally best MPM practices are:

- Avoid 'premature' public commitment about the project (ICE, 2017).
- Adopting a central program/portfolio management system (NAO, 2021).
- A continuous authority liaison for understanding new regulations.
- Tracking of all necessary authority approvals within a Master Schedule.
- 'Future-proofing' of the Megaproject and its design (ICE, 2022).
- Implementing a *'system based'* governance (Denicol *et al.*, 2020) and PM models (e.g., Work Breakdown Structure - WBS) (Fluor, 2012).

1.1.4 Acting Intelligently and Capitalising on Experience (Knowledge management & learnings)

Clients have to be '**Intelligent and Experienced Clients**' (ICE, 2022; IPA, 2020; CCG, 2020) while leading Megaprojects as a business, follow best practices, working collaboratively, taking full ownership of outcomes, making the contractor/supply chain successful (McKinsey, 2017), and deploying adequate client resources (CCG, 2013).

1.2 Quality & Robust Business Case (BC)

We need a well-researched, top quality and comprehensive BC. A Megaproject BC report must contain information pertaining to the Business Strategy, Financial Appraisal (FA), Economics (CBA), Commercial, and Management (HMT, 2018). Demonstration of a better investment management and benefits realisation plans are also essential (HMT, 2013). Clients must consider full outcomes and benefits (IPA, 2020; McKinsey, 2017 and ICE, 2022) which drive management decisions during the project's cycle.

1.3 Business Policies and Project Organisation (PMF/PMP)

The Project Management Framework (PMF) together with Plan (PMP) is a key element of Australian Megaproject delivery and Business Cases (e.g., MMP, 2016). The project execution strategy and supply chain (including consultants, contractors, and operators) selection and management will be aligned to the PMF & PMP.

1.4 Adopting Best Practices

Clients need to implement **'Best Practices'** to improve delivery efficiencies (CCG, 2013; ICE, 2022; McKinsey, 2017), and construction excellence. Megaproject Client's adoption of matured approach to procurement (e.g., innovative supplier engagement strategy – HMT, 2013) and RM will improve productivity and VfM (AIP, 2021).

1.4.1 Master Planning (MP)

A **MP** duly informs and sit at the core of a BC. MP by construction specialists will usually explore and analyse all feasible project & design options, establish realistic project baselines (budget, schedule, design, etc.), and inform various development strategies. Ensure that the selected project option will drive early income streams and have 'flexibility' of functions to some extent.

1.4.2 Agile PM Methodologies and Authentic Leadership

Literature suggests adopting an appropriate, authentic, and agile '**Project Leadership'** with necessary authority and influence (NAO, 2021; ICE (2022; Accenture, 2012a) for successful project control and outcomes.

1.4.3 Performance Culture and Innovative Approaches

Clients also need to build a 'performance culture' upfront and embrace 'creative innovations' (ACA, 2019) such as innovative designs, procurement (HMT, 2013), technological use (design, construction, operational or PM) and risk management models (ACA, 2019). A wider performance Measurement & Management (M&M) is important.

1.4.4 A range of Feasibility Studies (FSs)

Various important **FSs** (e.g., Infrastructure, Financial and Market, Authority approvals, engineering, technology, etc.) are to be conducted to inform the BC, FA, and MP.

1.5 Establishing an Operating and Functional System

1.5.1 Financial Appraisal (FA)

Project's FA is a key document as clear financial objectives are prerequisites (CCG, 2013). They must be validated to gain confidence (ICE, 2017) including by independent experts. FA will be updated regularly as the project progresses.

1.5.2 Management of Finance

Finance Management is a CSF (FHWA, 2015) on large and complex projects. It includes *preparing a Finance Plan* and cashflow forecast (FHWA, 2015). Evaluating flexible financing is an important task (FWHA, 2015). The project budget that appears in the Loan Agreement (LA), must include sufficient Contingency Allowance to cover possible risks and scope changes / contract variations. Best RM practice is to seek a 'syndicate' financing to increase the project's finance pool.

1.5.3 Proactive and continuous Stakeholder Management and Creating the right culture & mindsets

Thinking about (ICE, 2022) and working hard on relationships with stakeholders are best practices (McKinsey, 2017). Accenture (2012a) and NAO (2021) found that effective stakeholder analysis, early and continuous engagement, communication and management are prerequisites (ICE, 2021; ACA, 2019). It is important to proactively manage authorities (Brookes, 2015) and *sustainability issues* (Accenture, 2012b; UCL, 2011) for a smooth delivery.

1.5.4 Data Management, Management Information System (MIS), and Knowledge sharing

Clients need an effective **data management system (DMS)** including a **MIS** (ICE, 2022). Project teams must effectively collaborate and share data (ICE, 2022 and NAO, 2011) and information. Regular weekly/fortnightly knowledge sharing is a kay part of MPM.

1.5.5 Risk & Opportunity, Complexity and Uncertainty Management (see Element No 5).

Essential Evidence Sought (E1):

Access to distinctive capabilities, joint and comprehensive risk assessment and RM plan, adoption of best practices and tools, central program/portfolio management, MP, MS, authority approvals tracker, FSs, options appraisal, VfM assessment, project G&A arrangements (e.g. Gateway process), performance M&M, robust and well-researched BC (sound FA & CBA with accurate forecasts), finance plan, Cost models, benefits realisation plan, DMS, MIS, etc.

Element No 2: Project Planning, Initiation / Set-up

The evidence shows that the best way to ensure successful delivery is by '*setting up projects correctly*' in the first place (IPA, 2017) and thus, planning component of MPM is critical. The project planning shall be realistic (IPA, 2020). High performers followed a **comprehensive and rigorous up-front planning** (Accenture, 2012a). A clear and unambiguous definition of the client's requirements and project's **SoW** and preferably including a '*reference concept design*' is required.

2.1 Learning from past projects & knowledge management

Learning across Megaprojects is a critical driver of their performance (Brookes, 2015). The most common causes of Megaproject failures are linked to early PM tasks and activities such as: lack of clear project objectives (and priorities), insufficient resources, over-ambitious cost and schedule (IPA, 2017) and quality requirements, optimism bias (Flyvbjerg, 2020) or lack of planning, forecasting, and RM (Brookes *et al.*, 2014 & ICE, 2017). Therefore, having robust strategies for addressing each root causes for poor performance issues mentioned above is important (Jaselskis, 2018). IPA (2020) reinforces that '*experience gained and learning from past similar projects'* could enormously help successful project initiation (e.g., from data models and benchmarks).

2.2 Exploring Alternative and Shovel Worthy Projects

NAO (2011) indicates that the project team must explore alternative ways to achieve the intended outcomes and consider flexibility of solutions. NAO (2021) and ICE (2013 & 2017) recommend options appraisal (involving alternative projects and designs) to be carried out systematically using wider criteria with appropriate weightings (ICE, 2017) and scoring of each project option against the others. The clients and PMs need to think of 'shovel worthy' projects, not focusing purely on shovel ready projects (ICE, 2022) which requires adequate forecasting, planning and assessment.

2.3 Project Set-up and Available Project Management Methodologies

Different methodologies that are discussed in the literature can be summarised as follows:

NAO's (2022) Program/Project set-up consists of elements such as G&A (plus planning/options appraisals), Leadership & Culture, Resources Management, Deliverability checks, and **RM**. NAO (2021 & 2016) reinforce on the RM which is a key element of setting up a Megaproject and its Procurement Strategy and Contracts (refer to Elements No 5 and 11 for details).

According to IEC (2022), when initiating a project, a system thinking (e.g., WBSs) is necessary leading to RM. Key questions to ask at the initiation stage - whether project is being set-up in accordance with best / matured practices (including due diligence, procurement & risk management – AIP, 2021) and are risks being well-managed? (NAO, 2021).

IPA (2020) identified few set-up factors associated with project success, such as focus on outcomes, realistic planning, prioritising people, and transparency (tell it like it is) (e.g., reporting).

The IPA's (2016 and 2022) Project Initiation Route-map deals with three steps in project initiation and planning such as (understanding – ICE, 2017, and) assessing complexity, assessing capabilities and gaps, and align for success (i.e., total alignment and adapting to complexity – S&H, 2017).

Essential Evidence Sought (E2):

Achieving realistic and comprehensive project planning, following best practices/methodologies, project charter, cost/schedule benchmarking, risk/complexity/uncertainty management strategies, resources allocations (staff & money), funding & finance plan, etc.), contract/procurement strategy, cashflows/cost models, assembling project teams including whole supply chain, knowledge management, etc.

Element No 3: Value-based Procurement, Selection and Assembling the right team

3.1 Value based selection of Consultants (DM, PMC, Designers etc) and Main Contractor
Value-based procurement and selection using a weighted multi-criteria analysis is highly critical for Megaprojects (UCL, 2011 and NAO, 2021). The criteria is to include wider performance perspectives, values, and quality attributes of the suppliers. It must be applied to the selection of the teams representing all parties (FHWA, 2015). AIPM and KPMG (2021) research finds that two main ingredients of complex project or program success highlighted by overwhelming responses are: *strong and active leadership with a clear vision, and strong relationship and stakeholder management and collaboration among project teams*.

3.2 Assembling the right team
HMT (2020) recommends that people/team selection (such as client/consultants/contractor) shall be based on relevant functional expertise and experience (right mix of both). The supplier with exposure to complex RM and hands-on experience in successfully managing inherent risks on Megaprojects is a core capability (UCL, 2011). The search is for people with skills, competencies, relationships, attributes, holistic views (seeing the project over the entire lifecycle), and verified experience/past-track records (UCL, 2011). The supplier's experience in successfully working as part of an integrated team (CCG, 2013) (and past working experience) is also a prerequisite. Thus, the above are the qualities to check and explore when selecting and assembling project and supply chain members.

The team selection methodology considering PM & CM expertise & experience on a Maga Hotel & Resort project is explained in Figure 2 below.

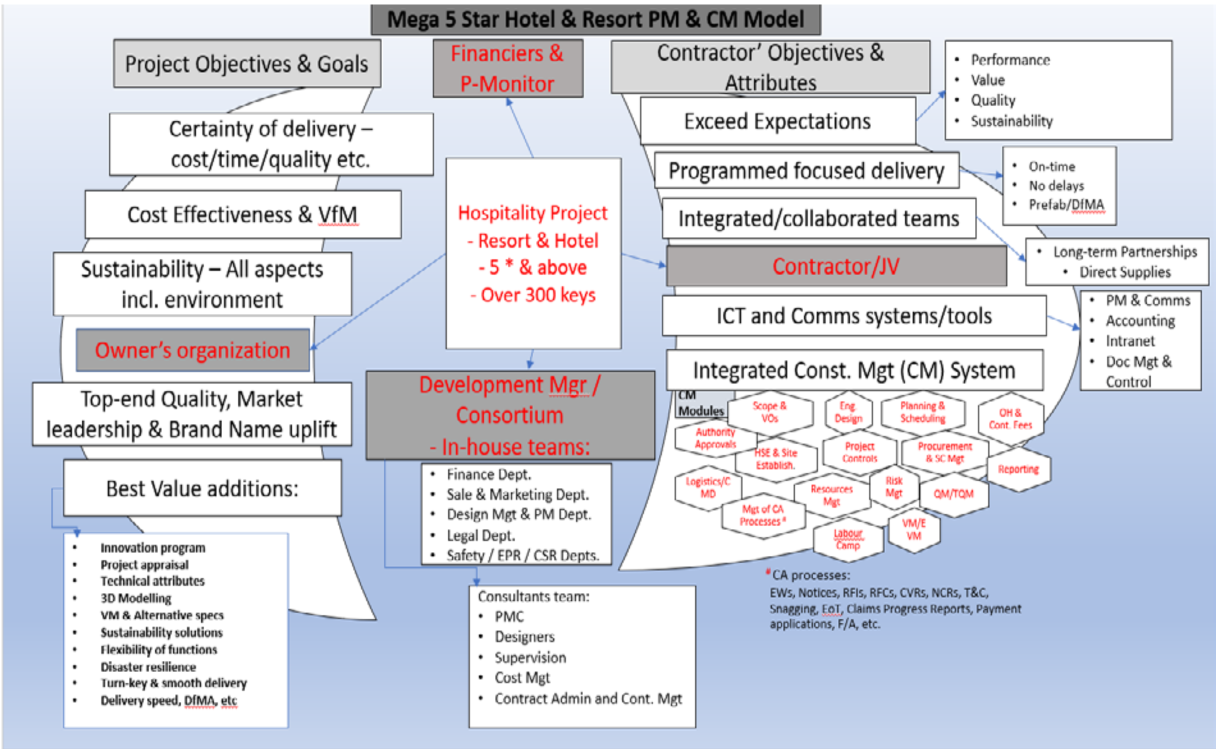

Figure 2. Team Selection methodology

Essential Evidence Sought (E3):
Conducting tender evaluations based on a weighted multi-criteria comprising wider performance and success factors, assembling the right team with the required KSAEs; main contractor's response to client's risk register detailing his planned RM strategies, two-stage tender evaluation, etc.

Element No 4: Design and Design Development (Architectural, Engineering, and other specialties)

This element covers the Design and Design Development including design/scope definition (Flour, 2014), design quality and aesthetics (CCG, 2013), VM, and performance/outcome specifications (ACA, 2019). From the Megaproject design point of view, the following are critical:

- A clear scope of work and approved reference 'Concept Design'.
- Planning and authority approvals (including disbursements) for the MP & concept design.
- Completion of design deliverables prior to construction contract award and/or providing design deliverables as per Master and construction schedules.
- Buildability of the design and Early Contractor Involvement (ECI)/Pre Construction Services (PCS).
- Design to facilitate fast-tracking of the construction (effective designer-contractor co-ordination and integration) and D&C overlaps.
- Design competition to select a preferred design from the market
- Design to budget, adopt a flexible design criteria and application of off-site manufacturing techniques (FHWA, 2015).
- Adopts platform DfMA (IPA, 2021)/pods/off-site manufacturing techniques.
- Engage all stakeholders early including end-users and operators (HMT, 2020) to gain design inputs.

- Standardise the design and pursue ESD (HMT, 2020).
- Make Megaprojects design more modular (HMT, 2021).
- Future-proof the (design and) projects (ICE, 2022) and in building projects, consider flexibility of functions.
- Sustainability of construction and operation – energy efficiency & renewable energy use (CCG, 2013).
- Disaster risk resiliency of the design.
- Benchmarking of design economics against other similar projects to try to cut down unnecessary costs and achieve value for money.

Essential Evidence Sought (E4):
SoW and Concept Design, flexible design and performance specifications, design to budget, innovations, sustainability considerations, disaster risk resilience, future-proofing of design, design deliverables programme, etc.

Element No 5 - Risks (including complexity, uncertainty, baselines etc.) and Opportunity (R&O) Management

Brooks et al. (2015) identified front-end RM as a core element of European MPM function that sets the project on a sounder ground. The RM on a Megaproject is a continuous process (HMG, 2022) and an experience business. NAO's (2021) guide to review programs has also identified RM is to be carried out throughout the pre and post-contract stages. A main task of any PM working on a Megaproject is to manage a full range of risks.

Some Project and Risks management best practices that come to mind here are:

1. Clients developing building projects must select mixed-use developments to reduce and manage demand risks, and '*putting eggs in different baskets*'.
2. Due diligence - AIP (2021) recommends to consistently adopt appropriate best practice front-end Due Diligence (DD) on all Major Infrastructure projects to reduce risks and improve value.
3. Clients need to consider early engagement of the contractors (and operators) via ECI for effective RM capturing its PM experience and expertise (Denicol *et al.*, 2020).
4. It is important to clearly understand the inherent risks and level of risks, consequences, and see whether they match the risk appetite, current capabilities, and past experience of the project team (NAO, 2011 & HMT, 2013).
5. The RM plan is to be a live and up to date document based on an operational Early warning system (EWS).
6. At the selection of procurement strategy and contract type, client's requirements must be clearly understood, and risks and rewards must be balanced appropriately with the supply chains preferably using a RAM (IPA, 2016 p.25 & HMT, 2013).
7. NAO (2011) emphasises on equitable risk allocation – i.e., risk is allocated to the party best placed to manage the particular risks and a joint RM approach.
8. PMs need to develop benchmarking tools and processes to scrutinise and prevent biases (Brookes *et al.*, 2014) in estimating cost, time and benefits baselines (Denicol *et al.*, 2020).
9. As a best practice, project baselines including cost and schedule should include necessary risk and preferably itemised contingency allowances based on a set of assumptions (HMT, 2020). These allowances shall be regularly updated based over time on latest information.
10. The clients must also mitigate the risks from skills shortfalls which may affect its ability to act as an intelligent client (NAO, 2011). The turn-over of key staff (especially with

substantial knowledge of the project history and agreements) tends to affect the project management function badly from both client and contractor sides.
11. Environmental risk (a show-stopper) management plan and proactive actions and authority liaison.
12. Finance RM Plan including seeking a syndicate finance to increase the finance pool to fund any variations and continuous engagement with financiers.

Essential Evidence Sought (E5):
Early RM (e.g., ECI), EWS, joint RM, appropriate risk allocation (and RAM) and selection of contract type, RM Plans, contingency plans (e.g., DfMA, off-site manufacturing, multi contractor/sub-contractor appointment, etc.), contingency allowances, syndicate finance, mixed-use building projects, etc.

Element No 6 – Realistic Project Baselines and Management of Changes and Progress

Fluor’s (2014) emphasised on Baseline Centric execution. The ECI, MP exercise, and studies conducted as part of the feasibility studies inform parts of a project’s baselines. It is important to setting up realistic and accurate project baselines from the start of a Megaproject (IPA, 2021 & Clayton, 2018). In establishing project baselines, we need to plan for contingencies and be aware of optimism bias (IPA, 2020). A Project’s baselines typically include BC, financial appraisal, scope, design, budget/cost, cashflow forecast, schedule, quality, safety, finance, cost benefit analysis (and CBR), etc. HMT (2020) and PMI (2013) articles deal with benchmarking of baselines, using RCF (Flyvbjerg, 2014) which benchmarks a Megaproject against other similar projects. It encourages ‘*learning across Megaprojects*’ (Brookes, 2015).

Essential Evidence Sought (E6):
ECI, PCS, Scoping exercise, baselines and benchmarking of baselines, Monte Carlo Simulation (MCS), Initial Development Budget (IDB), Cost Models, FA, FSs, Finance Plan and Expenditure Model, etc.

STAGE 2 – TENDERING AND PROCUREMENT

Due to page restrictions, for elements 7 to 12, only the **essential evidence to be sought by the MPM DD service provider or MPM practitioner have been summarized below**.

Element No 7: Procurement set-up and contractual & commercial arrangements
Co-ordinated and robust tender documents, procurement strategy selection and analysis, market engagement, JV main contractor request, contract administration manual, request for alternative bids with VE/VM proposals, standard contract and Ts&Cs, robust special conditions, appropriate risk allocation (RAM), dispute resolution plan, VM, contract management (including supervision & QM) & operational model, collaboration and joint RM, supplier relationship and performance management, contractual requirement for progress and close-out report, execution & RM plan, Key Performance indicators (KPIs), reporting, etc.

Element No 8: Packaging Strategy and Sequence of works
Robust D&C and programme co-ordination, forecasting and effective interfaces management between contracts, letting of early works packages, brainstorming with the main contractor and extended supply chain, fast-tracking mechanism, etc.

Element No 9: Tender Evaluation including relevant Risks Management

Technical tender evaluation and scoring of the suppliers to invite the selected suppliers only for commercial tender submission, combined scoring of the tenders, weighted wider criteria use, value-based selection, use of a standard templates for tender evaluation, compulsory reference checking, checking proposed sub-contractors of key packages, conducting tender interviews, and following Probity Rules and record keeping arrangements are recommended, contractor's response to risks, probity arrangements, etc.

Element No 10: Updated Business Case and Project Baselines as the project evolves
Updating of the baselines regularly (monthly basis) and as needed, Updating the BC and Project Baselines based on the selected tender and received tender information from the market, etc.

Element No 11: Due Diligence (DD) and Project Assurance (PA) review prior to Contract Award
Appointment of an experienced consultant for DD&PA review, risk management review, tender and other documents co-ordination review, full Gateway documentation review, procurement of long-lead items and lock-in prices of key materials, scrutiny of tender evaluation reports and bids of at least five (5) lowest bidders, review of requested contract clauses by tenderers and consultation with Legal Experts, flagging risks & issues within the selected tender for attention during the post-contract, consideration of contractor's current and future workloads, reference checking, proposed contract management & operational models, progress & performance management (KPIs), etc.

Element No 12: Robust Design of Contract and Contract Clauses Reviews
Identification of potential risks and issues and proposing mitigation measures, balancing risks and rewards, review of all key contract conditions especially Special Conditions of Contract, introducing best practice clauses, co-ordination of the review comments with the team and actioning before going to tender, etc.

STAGE 3 – POST-CONTRACT – CONSTRUCTION AND EXECUTION STAGE

(Note: Detailed analysis of the Elements from 13 to 18 are not covered due to page restrictions – refer to Figure 1 for relevant elements).

4 Conclusion and Further Research

To date, no comprehensive MPM framework has emerged despite the existence of a vast collection and pipeline of Megaprojects and experienced professionals with domain knowledge. MPM research tend to cover single perspectives (such as risk management, governance etc). The proposed MPM framework is based on a focused review of quality literature and practitioners' reflections. The conceptual framework includes three key stages including Front-end Planning & Feasibility studies, Tendering & Procurement, and Post-contract. Each stage has six (6) best practices, sub-elements, and essential evidence. The core literature includes those published by leading organisations in UK and USA (such as NAO, IPA, HMT, FHWA, ICE, UCL etc.) and over 200 published case studies. The framework aligns with PMI's PMBOK. Further, some practical and useful domain knowledge have also been shared in this article to benefit the readers and further enrich the model. Next step is to validate the proposed MPM Framework via field research exercise, and also use the validated system to evaluate MPM system deployed on Megaprojects. The main limitations of the current study are that this framework is more suitable for Megaprojects in the construction industry and the framework is based on practice reflections of a small group of practitioners (still has potential to capture more pertinent knowledge from a large group of professionals with domain experience).

5 Acknowledgement

Authors acknowledge the Australian Government RTP Support (Fee Offset) Scholarship provided to Jery Johnson (2020-2024).

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Development of Conceptual Motivational Framework to Improve Construction Labour Productivity in the U.K.

John Kojo Tawiah Hayford[1*], Timothy Eccles[1], Daniel Fong[1] and John Obas Ebohon[1]

[1]Centre of Integrated Delivery of the Built Environment, School of Built Environment and Architecture, London South Bank University, UNITED KINGDOM

hayforj2@lsbu.ac.uk; ecclest@lsbu.ac.uk; fongd@lsbu.ac.uk; ebohono@lsbu.ac.uk
* Corresponding author

Abstract:
The theoretical study presents vital motivational factors influencing labour productivity and understanding the relationship between motivation, social compliance, and labour productivity for decision-making. Labour motivation is essential because the quality of labour performance depends upon motivation. Labour who put forth more effort makes a big difference in company productivity. The construction industry in the U.K. is to become Europe's largest construction market by 2030. However, the trend of construction industry productivity in the U.K. has been low relative to other industries resulting in a skilled labour shortage, project delays, high construction costs, and low productivity growth as foreign migrants execute most projects. The U.K. serves as a security for the concerns of Middle Eastern and other war-torn countries, including the effects of the Ukraine war. It is the largest market for U.S.A. service exports, thus accepting more migrants. Therefore, demands for housing projects are ever-increasing, leading to a rise in construction projects that present opportunities for research to improve productivity through motivation by enhancing social compliance. The findings indicate that motivation mediates social compliance and labour productivity and that the essential way to motivate labour is by upholding social compliance. The present study conducts a comprehensive literature review to identify motivational factors influencing labour productivity. The findings developed a conceptual motivational framework that indicates a positive relationship between motivation, social compliance, and labour productivity. The next level is to test the framework on construction sites empirically through pragmatism philosophy with quantitative and qualitative approaches.

Keywords:
Construction productivity, Motivational factors, Motivation framework, Productivity, Social compliance

1 Introduction

The effective management of labour is key to achieving higher labour productivity. The bond between motivation and labour productivity is widely accepted and highly significant. Enhancing labour motivation is vital to maximising labour productivity (Kazaz *et al*., 2008; Khan *et al*., 2011). To effectively manage and ensure that labour is productive enough, it is imperative to understand factors which have an edge on motivating labour. The essential way to motivate labour is safeguarding social compliance (Razzaue and Eusuf, 2007). The construction industry is essential and affects every country's GDP. The industry contributes about 6–10% of many countries' economies (Naoum, 2016; Alaghbari *et al*., 2019). In 2018 the industry contributed 6% of the U.K.'s total economic output (Rhodes, 2019). The U.K. is to become Europe's largest construction market by 2030 (Hairstans and Smith, 2018). To achieve this, the government has called to cut the cost of construction by 33% and to deliver 50% faster projects by 2025 (Rhodes, 2019; Noruwa, 2020). However, the U.K. serves as a security and greener pasture for the Middle East and other war-torn countries. It serves as the largest market for U.S.A. service exports. Thus, accepting more migrants over the years; therefore, demands for housing and investment projects are ever-increasing, leading to a rise in construction which presents significant opportunity to study to improve construction labour productivity.

Previous studies identified many factors influencing productivity; few considered motivational factors and how social compliance drives labour productivity. The automation of construction tasks which could potentially increase productivity has yet to become a reality on construction sites. In the mean term, this seems unlikely except for prefabrication and powered tools due to a lack of capital investments. However, the trend of construction industry productivity in the U.K. has been consistently low relative to other industries resulting in a skilled labour shortage, project delays, high construction costs, and low productivity growth as foreign migrants execute most projects (Abdel-Wahab *et al.*, 2008; Jarkas and Radosavljevic, 2013). To assess the challenges faced by the industry, several researchers targeted many challenges and classified them as information technology (El-Mashaleh et al., 2007; El-Mashaleh 2007), project delays (Sweis et al. 2008) and health and safety (El-Mashaleh et al. 2010; Alkilani et al. 2013)**.** The studies on productivity focused mainly on external factors such as health and safety issues, weather conditions, material availability, and technology (Sweis *et al.*, 2008; Sweist *et al.*, 2013). There are many solutions to improve labour productivity, such as enhancing social compliance. Therefore, the proposed study attempts to fill the above knowledge gap by identifying the motivational factors that influence labour productivity to develop a conceptual motivational framework to improve construction labour productivity in the U.K. To identify the motivational factors which influence labour productivity in the U.K. construction industry, to examine and understand the relationship between motivation, social compliance, and labour productivity, and to examine the motivational factors that could improve labour productivity. Essentially part of projects, these factors are worth researching because they may lead to a deep understanding of improving skilled labour shortage, project delays, high construction costs, and low productivity growth.

2 Social Compliance

Often, vital motivational factors identified by construction industry researchers are yet to make them socially compliant with company policies and practices to enhance motivation and higher labour productivity. Social compliance ensures labour rights prescribed by U.K. labour rights and practices and the international labour organisation labour rights convention (Fukunishi and Yamagata, 2013). It is defined as looking at wages and benefits, labour rights, discrimination against gender or vulnerable groups, health, and emergency planning. Social compliance refers to the policies and practices of the company connected to the psychological and physiological well-being of labour. Social compliance in this study refers to the motivation factors incorporated into company policies and practices to address concerns about working conditions, labour rights, fair labour practices, labour standards, environmental protection issues, and health and safety (Alam *et al.*, 2018). Upholding social compliance has been contemplated as one of the significant factors for competitiveness (Moazzem and Sehrin, 2016). Regulated companies from other industries have a compliance unit led by a compliance officer, who implements policy and ensures practices that guarantee compliance. However, compliance with motivational factors that could enhance motivation and lead to higher productivity has yet to become a reality on construction sites. Implementing social compliance policy and code of practices by practitioners could improve skilled labour shortage, project delays, high construction costs, and low productivity growth and upgrade the global image (Rahman and Hossain, 2010; Alam and Alias, 2018). Despite many advantages, construction practitioners place less importance on implementing social compliance policies and codes of practice on sites. This study addresses how compliance with motivational factors establishes positive relationships with motivation and labour productivity to influence management decision-making leading to higher productivity in the construction industry.

2.1 Compliance and Non-compliance

Compliance in this study is an aspect of company management concerned with the extent to which a company operates by the terms and conditions of labour motivation policy and practices. The degree to which an employer has the right to monitor labour compliance is written as the parties' right or duty to ensure that the contractors adhere to legal and other mandatory obligations. This study's compliance with motivational factors can be understood as a process that concomitantly improves skilled labour shortage, project delays, high construction costs, and low productivity growth. The process of assessing compliance may involve verifying during pre-qualification assessment that any new labour meets the qualification standards specified. The contract compliance process includes employers creating an organised framework that enables contractors to report their activities in a manageable manner. Third-party Consultants may also look for potentially undiscovered lapses, find potential compliance gaps and ensure compliance. Noncompliance refers to failure to comply with the motivational factors incorporated into the company policies, rules and regulations by the authority having jurisdiction, the standards put forth by industry-recognised quality management, or rules presented by a particular company that controls workplace motivation. Noncompliance is the failure of individual labour to observe motivational requirements or the failure of individual managers to enforce adequate motivation behaviour. A company may be noncompliant with regulatory or quality standards if it fails to institute required motivation provisions as part of its corporate policies and practices. There are two types of compliance issues (1) recognition, which occurs as a result of compliance, and (2) penalisation, which occurs as a result of noncompliance. In the construction industry, some form of recognition of motivation compliance is necessary before a company is allowed to work. Companies also require that their suppliers and business partners hold recognised motivation compliance certifications as a prerequisite to contracting them. Certifications and other formal recognition types may be revoked if an individual or company becomes noncompliant. Individuals or companies that have become non-compliant will incur penalties. For labour, this likely means disciplinary action from a supervisor. For companies, this can result in an enforceable stop-work order. Failure to comply with the motivational standards can be part of motivation lawsuits brought by labour against their employer. Social compliance requires the implementation of codes of practice and policies that ensure the regulations on a day-to-day basis. If a company, wittingly or unwittingly, fails to adhere to a motivation regulation, it may be subject to punishment.

2.2 Proposed Conceptual Motivation Framework

The objective of motivation is to enhance labour productivity. It has been established from the theoretical review with an adequate discussion of labour productivity detailed in 2.3 to 2.8 that motivation influences labour productivity and motivated labour puts enough effort at work to improve productivity. According to the review, social compliance enhances motivation and improves labour productivity. Therefore, the construction industry may emphasise improving motivation by implementing social compliance policies and practices to enhance motivation and improves labour productivity. The developed framework is a conceptual motivational framework to improve construction labour productivity in the U.K. The previous studies in the construction industry failed to establish that socially compliance with the motivational factors in company policies and practices enhances motivation and improves labour productivity and understanding of the relationship between social compliance, motivation, and productivity. In this study, 49 motivational factors influencing labour productivity from construction and other industries articles are examined by bringing them together in four groups based on the motivation theories, and the past studies' classifications constituted organisational, economic, physical, and physiological / socio-psychological factors. The grouping is to determine the most influential group among them statistically later on-site and determine which factors most significantly influence labour productivity. Each of these groupings interacts and influences one another, providing a harmonised compliance which enhances motivation and productivity. The factor groupings can be used separately to enhance motivation; together, will increase productivity. The groupings for this framework in Figure 1 below, adapted from Kazaz et al. (2008), are the most cited groupings that relate to the current research work derived by Vroom (1964).

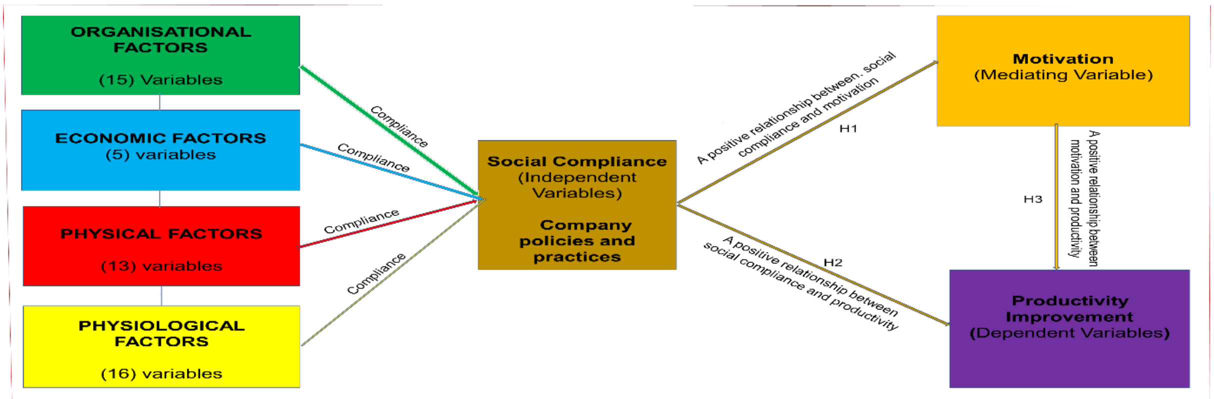

Figure 1. Proposed Conceptual Motivational and Productivity Framework

2.2.1 Organisational factors

An organisational environment refers to how work is organised, the culture of the organisation, and the nature of the leadership (Hoel and Salin, 2003). Productivity improvement has a link with the quality of management. What dictates a site to be productive is to what degree the management understands labour productivity and how it can positively influence it. The organisational factors have been explored to understand the role of organisations and their effect on motivation. There is much evidence in the past on the importance of motivation and its impact on labour productivity. The study identified 15 organisational motivation factors from previous articles. Socially compliance by incorporating these factors into company policies and practices will enhance motivation, as indicated in the framework. Combining these factors with economic, physical, and physiological factors will enhance motivation leading to high productivity. Table 1 detailed organisational motivation factors to be tested later on site.

Table 1. Organizational Motivational Factors

Item	Organisational motivation factors	Articles
1	Motivating workplace climates work environment away from physical distractions)	(Aiyetan and Olotuah, 2006; Ogunlana and Chang, 1998; Alaghbari *et al.* , 2019;Doloi, 2007; Eze *et al.* , 2020; Ohueri et al., 2018; Venkatesan et al., 2009; Borcherding and Garner, 1981; Norbu and Wetprasit, 2021; Chandrasekar, 2011; Cherian and Jacob, 2013; Vavra *et al* ., 2021; Liu *et al.* , 2021; Njambi, 2014; Andrew-Martin, 2005; Lindner, 1998; Olcer, 2005)
2	Supervision approach / supportive environment	(Kazaz *et al* ., 2008; Ogunlana and Chang, 998; Jarkas and Radosavljevic, 2013; AlAbbadi, 2020; Eze *et al.* , 2020; Hamza et al., 2019; Ailabouni et al., 2007; Hickson and Ellis, 2014; Jarkas et al., 2015; Mahamid et al., 2013; Ghate et al., 2016; Rakib *et al* ., 2020; Afolabi *et al* ., 2018; Chandrasekar, 2011; Abukhait and Pillai, 2017; Lorincová *et a* l., 2019)
3	Training and employee well-being (orientation programme, learning environment, growth in job)	(Kazaz *et al.* , 2008;Ogunlana and Chang, 1998;Khan *et al.* , 2013;AlAbbadi and Agyekum-Mensah,2019;Eze *et al* ., 2020; Ohueri *et al.*, 2018; Chandrasekar,2011;Cherian and Jacob, 2013;Pratheepkanth,2011;Abukhait and Pillai, 2017;Suryani *et al* .,2020;Lorincová *et al* .,2019;Olcer, 2005)
4	Material management (availability/shortage)	(Kazaz *et al* ., 2008; Jarkas and Radosavljevic, 2013; Alaghbari *et al* ., 2019; AlAbbadi, 2020; Jarkas *et al* ., 2014; Eze *et al* ., 2020; Hamza et al., 2019; Shan *et al* ., 2016; Dai and Goodrum, 2011; Borcherding and Garner, 1981; Ghate *et a* l., 2016; Ugulu *et al* ., 2019; Rakib *et al* ., 2020; Afolabi *et al* ., 2018; Chandrasekar, 2011)
5	Schedule and requests delays /clear work schedule	(Hiyassat *et al* ., 2016; AlAbbadi, 2020; Jarkas *et al* ., 2014; Jalal and Shoar, 2019; Shan *et al* ., 2016; Dai and Goodrum, 2011; Hickson and Ellis, 2014; Mahamid *et al* ., 2013; Jarkas et al., 2015; Rakib *et a* l., 2020; Afolabi *et al* ., 2018; Lorincová *et al* ., 2019)
6	Clear communication between workers and management, motivational communication	(Ogunlana and Chang, 1998; Hiyassat *et al* ., 2016; Jesumoroti and Draai 2021; Eze *et al* ., 2020; Venkatesan *et al* ., 2009; Hamza *et al* ., 2019; Naoum, 2016; Hickson and Ellis, 2014; Mahamid *et al* ., 2013; Noah and Steve, 2012; Lorincová *et al* ., 2019)
7	Leadership style of site managt / Authoritarian versus authoritative style,positive leadership)	(Alaghbari *et al* ., 2019; Eze *et al* ., 2020; Shan *et al* ., 2016; Dai and Goodrum, 2011; Hickson and Ellis, 2014; Mahamid *et al* ., 2013; Ameh and Shokumbi, 2013; Noah and Steve, 2012; Nasr *et al* ., 2020; Andrew-Martin, 2005)
8	Appropraite welfare facilities	(Kazaz and Acıkara, 2015; Ugulu *et al* ., 2019; Afolabi *et al* ., 2018; Chandrasekar, 2011)
9	Company's policy, corporate image, name/mission	(Aiyetan and Olotuah, 2006; Venkatesan *et al* ., 2009; Vavra *et al* ., 2021; Lorincová *et al* ., 2019)
10	Change order's / reduction of instruction changes	(Ogunlana and Chang, 1998;Jarkas and Radosavljevic, 2013; Jarkas *et al* ., 2014; Jarkas *et al* ., 2015; Mahamid *et al* ., 2013)
11	Availability of tools/equipment to carry out the work	(Shan *et al.* , 2016; Dai and Goodrum, 2011; Borcherding and Garner, 198;Rakib *et al* ., 2020; Afolabi *et al* ., 2018)
12	Availability of logistics, Job aids and templates	(Alaghbari *et al* ., 2019; Eze *et al* ., 2020; Chandrasekar, 2011; Hossain and Roy, 2016)
13	Weather conditions / climate	(Hiyassat *et al* ., 2016; Hickson and Ellis, 2014; Jarkas *et al* ., 2015)
14	Site Conditions / layout	(Khan *et al* ., 2013; Ghate *et al* ., 2016; Chandrasekar, 2011)
15	Clarity and completeness of technical spec	(Alaghbari *et al* ., 2019; Jarkas *et al* ., 2014; Jarkas *et al* ., 2015)

2.2.2 Economic factors

The construction industry plays a vital role and affects every country's GDP. The industry contributes to the economy by about 6–10% on averagely in many countries, promotes growth employment, and acts as a linkage between other industries and the economy (Dixit *et al.*, 2017; Alaghbari *et al.*, 2019; AlAbbadi, 2020). The construction industry in 2018 contributed £117 billion to the U.K. economy, representing 6% of the total economic output (Rhodes, 2019). Productivity improvement is the need of the hour which in this study leads to improved skilled labour shortage, project delays, high construction costs, and low productivity growth. The study identified four major economic motivation factors from previous articles. Socially compliance by incorporating these factors into company policies and practices could enhance motivation. Combining these factors with the organisational, physical, and socio-psychological factors will give higher motivation leading to high productivity. Table 2 details economic motivation factors that influence labour productivity to be tested later on the construction site.

Table 2. Economic Motivational Factors

Item	Economic Motivational Factors	Articles
1	Financial package (Incentive payments / Pay on time / Payment delay / Lack of income / salary-related,payment method, contractor's financial condition, Overtime Payment, Commision / sharing profit,Bonus / Holiday abroad with pay	(Aiyetan and Olotuah, 2006; Kazaz *et al.*, 2008; Jarkas and Radosavljevic, 2013; Khan *et al*., 2013; Zakeri *et al*., 1997;Kaming *et al*., 1998; Hiyassat *et al*., 2016; AlAbbadi and Agyekum-Mensah, 2019; AlAbbadi, 2020; Jarkas e*t al*., 2014; Eze *et al*., 2020; Gichunge and Musungu, 2010; Widanagamachchi, 2015; Ohueri *et al*., 2018; Kazaz and Acıkara, 2015; Ailabouni *et al*., 2007; Jarkas *et al*., 2015; Hickson and Ellis, 2014; Mahamid *et al.*, 2013; Afolabi *et al*., 2018; Ameh and Shokumbi, 2013; Norbu and Wetprasit, 2021; Chandrasekar, 2011; Zameer *et al*., 2014; Noah and Steve, 2012; Samuel and Chipunza, 2009; Pratheepkanth, 2011; Abukhait and Pillai, 2017; Sanpakdee *et al*., 2019; Vavra *et al*., 2021; Lorincová *et al*., 2019; Nasr *et al*., 2020; Njambi, 2014; Hossain and Roy, 2016; Parvin and Kabir, 2011; Lindner, 1998; Olcer, 2005)
2	Fringe Benefits (non-wage or salary), provision of transport, telephone services, social Insurance and free medical facilities	(Aiyetan and Olotuah, 2006; Ogunlana and Chang, 1998; Gichunge and Musungu, 2010; Kazaz and Acıkara, 2015; Shan *et al*., 2016; Dai and Goodrum, 2011; Afolabi *et al*., 2018; Ameh and Shokumbi, 2013; Lorincová *et al*., 2019; Njambi, 2014; Hossain and Roy, 2016)
3	Job security	(Ogunlana and Chang, 1998; Eze *et al*., 2020; Gichunge and Musungu, 2010; Zameer *et al*., 2014; Samuel and Chipunza, 2009; Lorincová *et al*., 2019; Lindner, 1998; Olcer, 2005; Hossain and Roy, 2016)
4	Promotions	(Aiyetan and Olotuah, 2006; Zakeri *et al*.,1997; Eze *et al*., 2020; Ugulu *et al*., 2019; Lindner, 1998; Samuel and Chipunza, 2009; Pratheepkanth, 2011)
5	Retirement benefits	(Widanagamachchi, 2015; Samuel and Chipunza, 2009; Vavra *et al.* , 2021)

2.2.3 Physical factors

The physical factors refer to the work itself, decent and respectful job, interest in work and many others detailed in Table 3. The study identified 13 physical motivation factors from previous articles. As indicated in the framework, socially compliance by incorporating these factors into company policies and practices will enhance motivation. Combining these factors with the organisational, economic, and socio-psychological factors will give higher motivation leading to higher productivity. Table 3 details physical motivation factors that influence labour productivity to be tested later on the construction site.

Table 3. Physical Motivational Factors

Item	Physical Motivational Factors	Articles
1	Work Itself, interest in work / Decent and respectful job / type of work	(Aiyetan and Olotuah, 2006; Zakeri *et al*., 1997; AlAbbadi and Agyekum-Mensah, 2019; Venkatesan *et al*., 2009; Momade and Hainin, 2019; Pratheepkanth, 2011; Lorincová *et al*., 2019; Njambi, 2014; Lindner, 1998)
2	Less repetition of work-reduced rework	(Ogunlana and Chang, 1998; Jarkas et al., 2014; Eze et al., 2020; Borcherding and Garner, 1981; Jarkas et al., 2015)
3	Flexible working arrangement or hours / Shift systems	(Chandrasekar, 2011; Samuel and Chipunza, 2009; Abukhait and Pillai, 2017; Lorincová *et al*., 2019; Parvin and Kabir, 2011)
4	Job enlargement and work rotation	(Kazaz *et al*., 2008; Khan *et al*., 2013; Andrew-Martin, 2005; Alam and Alias, 2018; Hossain and Roy, 2016)
5	Temporary nature of the job	(Doloi, 2007; Widanagamachchi, 2015; Jang *et al*., 2011)
6	Work discipline (Early quit and unscheduled breaks)	(Kazaz *et al*., 2008; Hickson and Ellis, 2014; Lindner, 1998)
7	Hard work or physical effort at work / and personal bests	(Widanagamachchi, 2015; Lorincová *et al*., 2019; Andrew-Martin, 2005)
8	Fatique / Under utilisations of skill	(Ogunlana and Chang, 1998; Jalal and Shoar, 2019; Jarkas *et al*., 2015)
9	Exact definitions of tasks / Job content / job assignment	(Chandrasekar, 2011; Cherian and Jacob, 2013; Abukhait and Pillai, 2017)
10	Commitment and loyalty	(Hiyassat et al., 2016; Noah and Steve, 2012; Lindner, 1998)
11	Appropriate works with labour skills / context of task	(Cherian and Jacob, 2013; Olcer, 2005)
12	Performance feedback information	(Chandrasekar 2011; Lorincová *et al*., (2019)
13	Working at similar activities	(Kazaz *et al*., 2008)

2.2.4 Physiological / Socio-psychological factors

Psychosocial factors, such as stress, have been linked to specific outcomes related to performance and health, such as job dissatisfaction, anxiety and depression among management and labour. The physiological needs include the basic needs required for any person's survival (Maslow, 1943). In this framework, the psychosocial factors refer to the relationship between workmates and management, work recognition, participation in decision-making, and many others, detailed in Table 4. The study identified 16 psychosocial motivation factors from previous articles. Socially compliance by incorporating these factors into company policies and practices will enhance motivation. Combining these factors with organisational, economic, and physical factors will give higher motivation leading to high productivity. Table 4 detailed psychosocial motivation factors that influence labour productivity to be tested later on site.

Since the construction industry in the U.K. is labour-intensive, developing a motivational framework to enhance labour productivity is imperative. The theoretical review has led to understanding these factors that have led to the development of the conceptual motivational framework to enhance labour motivation and improve labour productivity. The motivational factor groupings such as organisational, economic, physical, and physiological / socio-psychological factors (social compliance) work as an independent variable, labour productivity as the dependent variable and motivation as mediating variable. From the theoretical development of the existing articles, it has been established that motivation mediates the relationship between social compliance and labour productivity. The next level is to empirically test the framework on construction sites to establish whether this is the case or otherwise to provide a better understanding of these variables for practising in the construction industry during decision-making to improve labour productivity by the management.

Table 4. Socio-Psychological Motivational Factors

Item	Socio-psychological Motivation Factors	Articles
1	Relationship among workmates and management	(Aiyetan and Olotuah, 2006; Ogunlana and Chang, 1998; Zakeri *et al*., 1997; Yisa *et al*., 2000; Kaming *et al*., 1998; AlAbbadi and Agyekum-Mensah, 2019; Venkatesan *et al*., 2009; Jarkas *et al*., 2015; Mahamid *et al*., 2013; Afolabi *et al*., 2018; Samuel and Chipunza, 2009; Olcer, 2005)
2	Work Recognition	Aiyetan and Olotuah, 2006; Ogunlana and Chang, 1998; Zakeri et al., 1997; Yisa et al., 2000; Eze et al., 2020;Widanagamachchi, 2015; Momade and Hainin, 2019; Norbu and Wetprasit, 2021; Samuel and Chipunza, 2009; Lorincová *et al*., 2019; Njambi, 2014; Hossain and Roy, 2016)
3	Health and safety conditions (health care / personal protective equipment/Good safety regulations)	(Aiyetan and Olotuah, 2006; Ogunlana and Chang, 1998;Kaming *et al*., 1998; Eze *et al*., 2020; Kazaz and Acıkara, 2015; Jang *et al*., 2011; Ghate et al., 2016; Ugulu *et al*., 2019; Ameh and Shokumbi, 2013; Chandrasekar, 2011; Samuel and Chipunza, 2009; Vavra *et al*., 2021)
4	Participation in decision making, love and sense of belonging	(Ogunlana and Chang, 1998;Yisa *et al*., 2000; AlAbbadi and Agyekum-Mensah, 2019; Jarkas *et al*., 2014; Momade and Hainin 2019; Ameh and Shokumbi, 2013; Samuel and Chipunza, 2009; Sanpakdee *et al*., 2019; Lorincová *et al*., 2019)
5	Challenging tasks / Job enrichment	(Ogunlana and Chang, 1998; AlAbbadi and Agyekum-Mensah, 2019; Eze *et al*., 2020; Cherian and Jacob, 2013; Zameer *et a* l., 2014; Samuel and Chipunza, 2009; Pratheepkanth, 2011; Alam and Alias 2018; Hossain and Roy, 2016)
6	Level of skill availability, experience, and competence	(Ogunlana and Chang, 1998; Alaghbari *et al*., 2019; Eze *et al*., 2020; Hamza *et al*., 2019; Naoum, 2016; Ailabouni *et al*., 2007; Mahamid *et al*., 2013; Ghate *et al*., 2016; Rakib *et al*., 2020)
7	Achievement / feelings of accomplishment	(Aiyetan and Olotuah, 2006; AlAbbadi, 2020; Ohueri *et al*., 2018; Johari and Jha, 2020; Venkatesan *et al*., 2009; Momade and Hainin, 2019; Nasr *et al*., 2020; Njambi, 2014)
8	High responsibility job / empowerment	(Aiyetan and Olotuah, 2006; Yisa *et al*., 2000; AlAbbadi and Agyekum-Mensah, 2019; Norbu and Wetprasit, 2021; Pratheepkanth, 2011; Njambi, 2014;)
9	Fair treatment / equal opportunity	(Venkatesan *et al*., 2009; Vavra *et al*., 2021; Parvin and Kabir, 2011; Lorincová *et al*., (2019; Hossain and Roy, 2016)
10	Team Spirit / teamwork	(Hiyassat *et al*., 2016; Eze *et al*., 2020; Cherian and Jacob, 2013; Lorincová *et al*., 2019; Olcer, 2005)
11	Gaining respect / Prestige / Status	(Johari and Jha, 2020; Pratheepkanth, 2011; Lorincová *et al*., (2019)
12	Work appreciation	(AlAbbadi and Agyekum-Mensah, 2019; Njambi, 2014; Lindner,1998; Olcer, 2005)
13	Work autonomy / freedom for innovative thinking	(Samuel and Chipunza, 2009; Vavra *et al*., 2021)
14	Psychological stress /Negative thoughts	(Cherian and Jacob, 2013)
15	Work satisfaction (role congruity - agreement or harmony)	(Chandrasekar, 2011; Nasr *et al*., 2020)
16	Setting job performance target	(Samuel and Chipunza, 2009; Lorincová *et al*., 2019)

2.3 Motivation

Motivation is a process which activates productivity. Motivated labour is highly productive and enhances additional value to the company. Griffin and Moorhead (2011), cited in AlAbbadi (2020), describe motivation as a force that causes a person to engage in a particular behaviour. Motivational factors differ; therefore, labour is motivated by different motivators (Lunsford, 2009). There are two types of motivation, intrinsic and extrinsic. Intrinsic motivation is by performing tasks that lead to a feeling of satisfaction, as detailed in Herzberg's two-factor motivation-hygiene theory (1966 cited in AlAbbadi, 2020). Conversely, effective incentives achieve extrinsic motivation (Herzberg, 1966; Deci and Ryan, 1975). Extrinsic motivators consist of financial reward-salary, bonuses, and benefits. Labour is extrinsically motivated when involved in achieving goals apart from work itself. Labour is intrinsically motivated when seeking self-expression, satisfaction, challenging work, enjoyment, or exciting work. It can be a driving force or desire that performs a job without external incentive (Herzberg, 1966; Islam *et al*., 2018). Identifying motivational factors to incorporate them into company policy and practices for compliance could be challenging where many factors are involved. What motivates one labour will not necessarily motivate the other; hence, this study focused on motivational factors that influence labour productivity on construction sites in the U.K. to establish the link that motivation has with social compliance and labour productivity.

2.4 Labour Productivity

There are many definitions for productivity; however, they all broadly say the same thing. It is the input and output, where output implies the product produced and input implies resources such as capital, labour and materials consumed to produce the outputs (Saha and Mazumder, 2015). Productivity is the efficient use of resources in manufacturing goods. An empirical technique, productivity, is an economic concept defined as a ratio of the volume measure of outputs to a ratio volume measure of inputs (Yi and Chan, 2014; Hiyassat *et al*., 2016). Construction companies depend on both inputs and outputs to complete projects successfully. The industry needs various inputs to generate a value-driven output (Too and Weaver, 2014). The combination of labour, material, equipment, capital, and technology are the inputs that drive construction companies to generate outputs (Saha and Mazumder, 2015; Ying, 2004). The primary resource or input for producing the optimum value of productivity in the construction industry is labour (Jarkas, 2010; Kisi *et al*., 2017). labour input is one of the fundamental inputs practitioners of labour-intensive industries use to generate an efficient and value-driven output (Jarkas, 2012; Swies *et al*., 2013). Despite the advancement of technology in order industries, the construction industry remains labour-intensive (Jarkas et al., 2014). The construction industry is naturally labour-intensive (Yi and Chan, 2014; Ghoddousi et al., 2014). Because of the labour-intensive nature of the industry, labour is an essential productive resource. However, the measurement of labour productivity is one way to evaluate and assess the overall performance of the construction industry (Hwang and Soh, 2013). The study shows the value of gross output per work, referred to as man-hour or work hour (Yates and Guhathakurta, 1993). The simplest way to measure construction productivity is to compare the estimated labour per hour and cost per hour. In many countries, construction labour costs account for about 30% to 60% of the total project costs (Fayek, 2011; Jarkas and Radosavljevic, 2013). Because the construction industry is labour-intensive, labour productivity is vital to the industry's success. Therefore, focusing on labour productivity is essential for higher levels of successful project completion (Jarkas, 2012). For these reasons, coupled with the lack of capital investment for the automation of construction activities, the study focuses on labour productivity to improve skilled labour shortage, project delays, high construction costs, and low productivity growth. The developed framework establishes how social compliance and motivation improve construction labour productivity.

2.5 Assessing the Relationship between Social Compliance and Motivation

Motivated labour is highly productive and enhances value to the company. The motivational factors that could improve the companies' value differ in many countries, and individuals are motivated by different motivators (Lunsford, 2009; Vroom, 1964 cited in Alabbadi, 2020). The essential way to motivate labour is to uphold social compliance (Razzaue and Eusuf, 2007; Alam and Alias, 2018). Social compliance in this study is the motivational factor incorporated into company policy and practices. Labour is motivated by social compliance factors such as better wages, timely payment, non-discrimination, hygienic welfare facilities, medical facilities, and a suitable working environment (Baral, 2010; Ferdous, 2015). Implementing social compliance policy of motivational factors could motivate labour on construction sites. And that enhancement of social compliance could lead to higher motivation. From the theoretical review, motivation is dependent on social compliance and hypothesised that:

H1: There is a positive relationship between social compliance and labour motivation.

2.6 Assessing the Relationship between Social Compliance and Labour Productivity

In the construction industry, labour is likely to feel associated when supported by the company. Labour involves themselves intensely with their company when associated with welfare facilities (Glavas and Godwin, 2013). Companies engaged in social compliance policies and practices earn a positive image and attract skilled labour (Umeokafor *et al*., 2014). Therefore, a company can improve its trustworthiness amongst labour, reflected in higher productivity through better social compliance. Previous studies have provided theoretical claims for positive relationships between social compliance and labour productivity (Siegel, 2009). Social compliance contributes to the foundation by positively influencing a company's associations with its labour (Perrini *et al*., 2009). Therefore, improved social compliance enhances trustworthiness and reinforces the relationships with labour which could improve skilled labour shortages, project delays, high construction costs, and low productivity growth. Implementing social compliance in the construction industry may have expenses; it could enhance motivation and labour productivity. Furthermore, the enhancement of social compliance could lead to higher productivity. Thus, from the theoretical development, it is hypothesised that:

H2: There is a positive relationship between labour productivity and social compliance.

2.7 Assessing the Relationship between Motivation and Labour Productivity

The relationship between motivation and labour productivity has been established. However, the earlier studies could not confirm a direct connection. Motivation and labour productivity are related, and motivation is the cause of the performance of labour (Petty *et al*., 1984; Olusadum and Anulika, 2018). Satisfaction occurs when motivators exist at work that increases motivation (Herzberg,1959). Therefore, labour productivity depends on motivation (Khan *et al*., 2012; Dina and Olowosoke, 2018). Lack of motivation negatively influenced productivity (Jalal and Shoar, 2019). If labour is motivated, they perform with higher determination, which increases productivity (Ajalie, 2017). Labour's level of motivation can be intrinsically and extrinsically based. Positive job characteristics are essential in forming the relationship between motivation and labour productivity (Hackman and Oldham, 1976). For instance, when specific work features are present in the company, labour is well-motivated to improve productivity. Job characteristics involve particular attributes and dimensions that explain various tasks (Griffin *et al*., 1981). The five job characteristics are from (Maslow's 1943, Alderfer's 1972) self-actualisation and growth need theories, and Two-Factor Theory from Herzberg 1959 (Hackman and Oldham, 1976). These job characteristics are feedback, skill variety, identity, task significance, and job autonomy. The labour scoring high on the five characteristics shows high work motivation, satisfaction, and productivity (Brass, 1981). Therefore, the theoretical development confirmed that motivation is linked with productivity (Jalal and Shoar, 2019; Johari and Jha, 2020). The enhancement of motivation leads to higher productivity. From the theoretical review, productivity is dependent on motivation and hypothesised that:

H3: There is a positive relationship between labour motivation and labour productivity.

2.8 Relationship between Motivation, Social Compliance and Labour Productivity

Good social compliance motivates labour towards higher productivity. The availability of social compliance could intensify motivation and increase labour productivity (Alam and Alias, 2018). A strong relationship between a positive work environment and labour productivity has been established (Battisti and Iona, 2006). Labour become motivated when they find their rights are protected. Social compliance ensures that all labour rights and practices are adhered to (Fukunishi and Yamagata, 2013). Improving labour productivity and high wages raised living standards, motivating labour to work more (Fukunishi and Yamagata, 2013). Enhancement of social compliance leads to higher motivation and productivity. Social compliance, motivation, and labour productivity are related. Motivation and productivity depend on social compliance, while motivation mediates social compliance and productivity. Thus, it hypothesised that:

H4: Motivation mediates the relationship between social compliance and labour productivity.

3 Research Methodology

This research study adopts pragmatism philosophy because pragmatism recognises that there are several methods of interpreting reality and conducting research and that no single view could give the whole picture. This study is essential for a pragmatistic philosophy combining positivism and interpretivism (Farrell, 2016). Unlike positivism, critical realism or interpretivism, pragmatism philosophy combined quantitative and qualitative methodology in this study to achieve the desired outcome (Bryman and Bell, 2013; Creswell and Clark, 2011).

3.1 Research Design

The research design consists of four main stages; 1) the literature review to gain secondary data on motivational factors that influence labour productivity, 2) a questionnaire survey to get opinions on motivational factors that influence labour productivity in the UK construction sites, 3) conceptual motivation framework is tested based on the opinions of the respondents and 4) semi-structured interview to validate the workability of the conceptual framework. The study developed a thorough flow diagram Figure 2 that describes the research process. The review process was governed by search and selection criteria adopted by Sadiq et al. (2021) that helped arrive at the most pertinent research works and established the gap. The data collection methods for this study include quantitative and qualitative techniques.

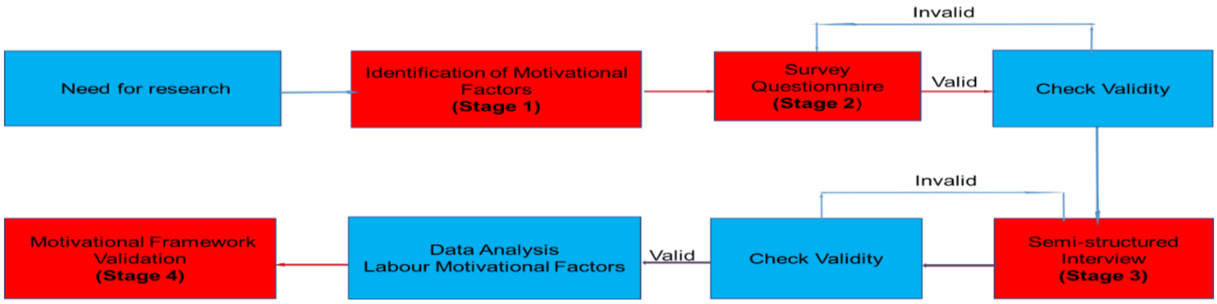

Figure 2. Proposed Research Flow Diagram

The U.K. projects use minimal advanced technologies with a variety of skilled labour intensive, which account for the accuracy of data collection for this study. The sampled population are skilled and unskilled labours: Labour is because they are physically and directly involved in executing works on site. Additional samples are the experience site management who oversee the labour tasks. This set of workers plays a supervisory role in skilled and unskilled labour. A mixed research design method is proposed for this study, using quantitative and qualitative data collection to understand the depth and breadth of motivation and productivity (Patton, 2002; Creswell and Clark, 2011). The study proposed a survey questionnaire for quantitative and semi-structured interviews for qualitative data collection. The semi-structured interview is proposed to gather data from experienced site management teams to validate the framework's workability. A web and a self-administered survey for skilled and unskilled labours are proposed for quantitative data collection. Criteria for selecting respondents are set to ensure quality data and reduce bias. The respondents must have at least 5years of work experience, have been involved in the execution of at least two projects and be currently involved in an active site (Spradley, 1979; Eze *et al.*, 2020). A pilot study tests the research instruments to ensure internal reliability and consistency. A Cronbach's alpha is proposed for all factors identified (Ohueri *et al.*, 2018). Factor analysis is a relatively straightforward technique and is psychometrically appropriate to adopt. Factor analysis will examine how the variables would group into related factors and reduce data (Pallant, 2007; Eze *et al*., 2020).

4 Findings and Discussion

The theoretical review findings are that upholding social compliance is essential to motivate labour. And that motivation influences labour productivity (Kazzaz *et al.*, 2008). Social compliance positively influences motivation (Van-Woerkom and Meyers, 2015). The conceptual framework provides a clear understanding of motivation and the relationship between social compliance and labour productivity. The theoretical development suggests a positive relationship between motivation, social compliance, and labour productivity and that motivation mediates the relationship between social compliance and labour productivity.

5 Conclusion and Further Research

The theoretical review developed a conceptual motivational framework to improve labour productivity which will be tested later on the construction site. The framework shows the importance of social compliance and how compliance drives motivation, which drives productivity. The framework explains labour motivation and how it mediates between social compliance and labour productivity. This framework will encourage the construction management team to implement social compliance in the workplace to improve labour productivity. Implementation of social compliance could lead to improved skilled labour shortage, project delays, high construction costs, and low productivity growth. The improvement in labour productivity allows more money for labour. Improving labour productivity and high wages raised living standards, motivating labour to work more. The framework will give a tremendous advantage to U.K. construction companies when competing against others in practice for decision-making. The study critically examined the role of motivation in the relationship between social compliance and labour productivity. The next stage in this study is to empirically test the framework on the construction site in the U.K.

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Understanding the Relevance and Impact of Systems Thinking in the Construction Industry: A Bibliometric Analysis

Natalia Ortega[1*], Daniel Paes[1], Tak Wing Yiu[1] and Monty Sutrisna[1]

[1]School of Built Environment, Massey University
Auckland, 0632, NEW ZEALAND

n.ortega@massey.ac.nz, d.paes@massey.ac.nz, t.yiu@massey.ac.nz, m.sutrisna@massey.ac.nz
* Corresponding author

Abstract
The construction industry has been considered a complex system, and the need to better address this complexity through innovative systemic approaches has been coined. Therefore, this study conducts a bibliometric and thematic analysis-based literature review on Systemic or Systems Thinking (ST) and its contributions to the construction industry, identifying research trends, dissemination, implications, and future research directions. This research addresses the knowledge gap using a scientific mapping approach, including systematic bibliometric analysis of the Scopus database and thematic analysis. Findings indicate that while ST research has been growing exponentially in other areas such as Social Science, Business, Management, and Accounting, it is not the case with the construction discipline and industry. The studies examined mainly focus on ST applied to accidents, human factors, safety management, site safety, and performance management. This study describes the characteristics of ST research in other fields and discusses why this topic is underrepresented in the construction domain.

Keywords
Construction industry, Decision-making, Disruptions, Management, Pandemic, Systems thinking, Systemic thinking

1 Introduction

The construction industry supports jobs to approximately 7% of the world workforce; however, it is accountable for 30 to 40% of fatalities (Rafindadi et al., 2022; Umeokafor et al., 2022). Covid-19 has set new and drastic challenges for the construction industry worldwide, such as making timely decisions, producing different procedures to reopen businesses helping staff to return to the workplace safely, and applying techniques to future-proof companies against future pandemics (Stride et al., 2022). In New Zealand, a recent Covid-19 Impacts Survey revealed that the impact on staff is one of the main concerns of construction firms (BDO New Zealand, 2021). The lack of health and safety competencies is one of the reasons that affect skills shortages in the industry, impacting the retention of young workers (Musonda & Okoro, 2021). It has been attributed to the weakness of management, exposing their lack of flexibility and experience to deal with such disruptions and risks (BDO New Zealand, 2021). However, the industry already experienced some of these issues pre-pandemic. The main factors affecting productivity in the construction sector in New Zealand have been identified as slow decision-making at the management level (Nguyen & Bosch, 2013), inadequate supervision and coordination, and rework (Hasan et al., 2018). Another variable in New Zealand causing disruptions is poor contract management that generates unsafe working conditions or other safety issues, which greatly impact productivity (Gibson, 2015).

Disruptions are considered endemic in the construction industry worldwide; their impacts on the sector are associated with extra time, costs and risks, loss of productivity, and delays in making accurate decisions (Gibson, 2015). Systemic Thinking, interchangeably also known as

Systems Thinking (ST) is a framework of thinking that highlights connectedness and helps decision-makers see the bigger picture to identify and address systemic failures (Boardman & Sauser, 2013). The urgency for ST to cope with Covid-19 has been highlighted recently by the Organization for Economic Cooperation and Development (OECD), as it allows stakeholders to recognise the crucial drivers and interactions during a crisis and facilitates anticipation and adaptation when massive disruptions happen with a wide array of systemic threats (OECD, 2020).

ST holds the potential to improve decision-making if well understood and implemented (Ackoff, 1997). Thus, it is argued that this new thinking approach helps identify mistakes and corrective actions, promoting a shift of thought patterns and innovative solutions. It can improve problem-solving, and the earlier it is implemented, the higher the likelihood of achieving changes, particularly in repetitive patterns (Johanessen et al., 1999). ST can facilitate decision-making through principles, methods, and tools (Ackoff, 1997) and has been proven successful in technical problems and could be used by managers handling the unexpected complexities of organisational life (Checkland, 1999).

The need for a discussion about a new systemic approach to better tackle the complexity of the construction industry has been anticipated, and further research has been recommended for a better understanding of ST benefits in the construction sector (Boton & Forgues, 2017). Furthermore, to overcome the challenges of implementing a safety culture among contractors, it has been suggested to use ST tools in other sectors (Goh et al., 2010). ST could provide efficient tools to tackle complex situations such as Covid-19 (Haley et al., 2021). In this direction, this study examines ST research in the past 20 years in the Scopus database. The objective of this study is to characterise the main topics, focus, and trends of ST research in construction compared to other fields based on research output. The ultimate aim is to provide insights into research needs and opportunities in ST applications in the construction sector.

2 Literature Review

ST is considered a particular framework of thinking that can help decision-makers identify and address systemic failures (Boardman & Sauser, 2013). Systems Thinking (used interchangeably with Systemic Thinking in this study) aims to tackle problems by exploring the context of the systems in which the problems happens, dealing with wholes instead of their parts separately (Paucar-Caceres et al., 2022). Basic Systems Thinking skills include exploring part-whole systems, realising multiple perspectives, analysing interrelationships, and considering alternative boundary characteristics, concerning thinking ‘outside the box’ (Foote et al., 2021). Systems Thinking has been widely applied in many disciplines, typically in organisational settings where complex or uncertain situations or “messes” are most recurrent. It has been reported to yield effective and positive results (Vilchez et al., 2021).

Exploratory studies in different disciplines, such as healthcare, sports, and transport, found ST tools beneficial for preventing risks, improving communication, and facilitating decision-making (Butler et al., 2022; Hulme et al., 2021; Newnam et al., 2021). In the healthcare sector in Australia, an ST toolkit based on ST principles was developed and applied to enhance staff safety; the findings showed that participants could better interact with several stakeholders and understand the factors contributing to injuries (Newnam et al., 2021). In the sports sector, researchers applied ST-based risk assessment (RA) methods to improve performance, resulting in successfully minimising risks and preventing accidents (Hulme et al., 2021). In the transport sector, other researchers found significant benefits in implementing ST to minimise maritime incidents during pilotage in Australia and highlighted the need for developing long-term strategies based on ST (Butler et al., 2022).

3 Research Methodology

This study conducts a literature review applying the scientific mapping approach. It involves a bibliometric analysis of the Scopus database. Scopus has been recognised as one of the main and most popular research databases (Guz & Rushchitsky, 2009), covering various scientific fields. It has one of the broader journal coverage in all disciplines (Mongeon & Paul-Hus, 2016) and 20% more accuracy on citations than other databases (Belter, 2015; Falagas et al., 2008).

Thematic analysis (Braun & Clarke, 2006) was developed based on factors limiting knowledge management among construction small and medium enterprises (Egwunatum & Oboreh, 2022) and used next to contextualise and identify patterns across qualitative data in a) the sixteen papers selected from Scopus on ST research in construction and b) in the two most cited papers of the top five authors in ST research in other fields. A qualitative discussion and the overall process of the research are summarised.

This study employs two groups of keywords, one to explore ST research in construction and another to explore ST research in all disciplines combined.

3.1. Bibliometric Analysis of ST in Construction

A bibliometric search on Scopus for publications on ST in the construction industry yielded 33 documents – TITLE-ABS-KEY (system* AND thinking) AND TITLE-ABS-KEY (systemic AND thinking) AND TITLE-ABS-KEY (construction AND industry OR sector). Next, the search was limited by titles and abstracts, resulting in 16 papers related to ST in construction for the last 20 years. The United Kingdom published 5 articles, Hong Kong around 4, and Australia about 3, followed by Norway with 2, China, Iran, and New Zealand with 1 publication each. Therefore, Australasian countries, followed by European countries, are more active in ST research in the construction discipline. The University of Hong Kong supports research on this topic, followed by Loughborough University in the United Kingdom. Top journals (Q1) that have published research on ST in construction include: ‘Safety Science’, which published 2 papers, followed by ‘Accident Analysis and Prevention’, ‘Built Environment Project and Asset Management’, ‘Engineering Construction and Architectural Management’, and ‘Journal of Construction Engineering and Management’, with 1 publication each. They started publishing ST research after 2015 (see Figure 1), and publications have increased rapidly, suggesting that only in the last seven years has ST become a relevant topic for these journals. Figure 1 shows that no ST research in construction was published before 1999. ST studies were published mainly through journal and conference papers, representing around 80% of publications (56% and 25%, respectively), and 20% are found in books or book chapters.

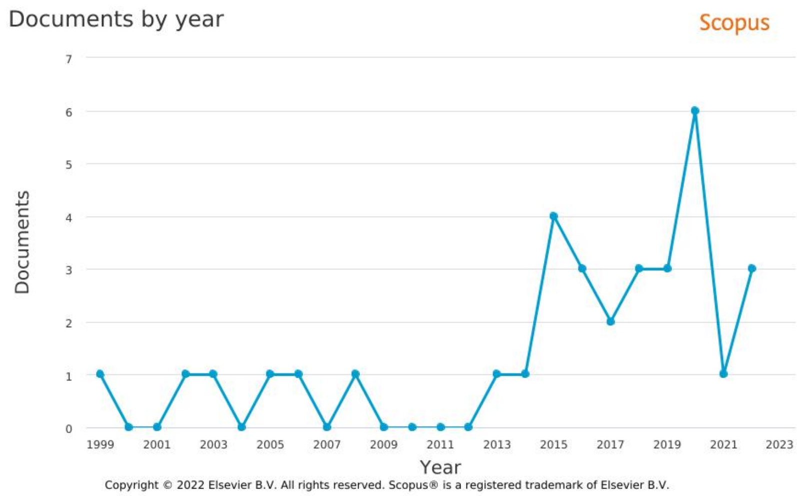

Figure 1. ST research in construction by year. Source: Scopus

Next, the 16 articles are grouped into themes, and their methods and main findings are summarised (see Table 1). Mohammadi and Tavakolan (2020), Harvey et al. (2019), Rowlinson and Jia (2015), and Guo et al. (2015) discuss ST as a tool for safety management and preventing/coping with accidents. Zhan et al. (2020), Lingard and Wakefield (2019), Jennings and Kenley (2002), Atkinson (1999), Javed et al. (2018), Orstavik and Harty (2017), and Belay et al. (2016) investigate ST as a tool to support management. The selected themes to group the publications were safety management, management, innovation, project level, and organisation strategy. Findings indicate that ST could be a crucial driver for efficiently dealing with the complexity of construction activities and projects by facilitating decision-making. The primary methods of investigation adopted by those authors were mainly interviews and case studies, which enables further possibilities for future research through other techniques.

Table 1. Summary of publications on ST in construction.

Main Theme	Authors	Title	Year, Source Title, DOI			Method	Findings
Safety Management	(Mohammadi & Tavakolan, 2020)	Identifying safety archetypes of construction workers using system dynamics and content analysis	2020	Safety Science	10.1016/j.ssci.2020.104831	Interview conducted with experts in the field of construction health and safety	By identifying systematic patterns responsible for the occurrence of accidents, systemic thinking through system dynamics tools helps project managers understand the dynamic complexity of construction safety management and make better decisions.
	(Harvey et al., 2019)	Impact of the 'contributing factors in construction accidents' (ConCA) model	2019	Advances in Intelligent Systems and Computing	10.1007/978-3-319-96071-5_33	An expert panel of participants	Construction challenges are to face the negative perceptions of workers and embrace the empowerment and collaboration between them.
	(Rowlinson & Jia, 2015)	Construction accident causality: An institutional analysis of heat illness incidents on site	2015	Safety Science	10.1016/j.ssci.2015.04.021	Cases + interviews with managers	Systemic thinking effectively develops interventions and identifies improvement opportunities for stakeholders at different levels of systems related to a construction project.
	(Guo et al., 2015)	Identifying behaviour patterns of construction safety using system archetypes	2015	Accident Analysis and Prevention	10.1016/j.aap.2015.04.008	Interview decision-makers	By providing systemic insights to deal with complexity, safety management saw improvements.
Management	(Zhan et al., 2020)	Construction project productivity evaluation framework with expanded system boundaries	2020	Engineering, Construction, and Architectural Management	10.1108/ECAM-12-2019-0691	Semi-structured interviews with senior industry experts and exploratory case studies	Systems thinking facilitated industry stakeholders to formulate holistic strategies for the long-term to improve construction project productivity.
	(Lingard & Wakefield, 2019)	Integrating work health and safety into construction project management	2019	Integrating Work Health and Safety into Construction Project Management	10.1002/9781119159933	Full text not available, only abstract	Construction project management produced sustained and significant health and safety (H&S) improvements by applying new and non-traditional ways of thinking.
	(Jennings & Kenley, 2002)	Integrating complexity	2002	The Organization and Management of Construction: Shaping Theory and Practice: Volume Two: Managing the Construction Project and Managing Risk	10.4324/9780203477090	Case studies	Systems thinking facilitates the integration of specialists in construction.

	(Atkinson, 1999)	The role of human error in construction defects	1999	Structural Survey	10.1108/02630809910303006	Statistical study + Unstructured interviews with managers	Applying systems thinking to the problem of avoiding construction defects.
	(Javed et al., 2018)	A systemic exploration of drivers for and constraints on construction productivity enhancement	2018	Built Environment Project and Asset Management	10.1108/BEPAM-10-2017-0099	Case study	The study conceptualises construction productivity from a systemic perspective – systems thinking of industry stakeholders in formulating holistic strategies for long-term construction industry productivity enhancement.
	(Orstavik & Harty, 2017)	The unexplored brutality of performance recipes	2017	Proceedings – Association of Researchers in Construction Management, ARCOM – 33rd Annual Conference 2017		Full text not available, only abstract	Systems thinking is a possible lens to fill the gap between the persuasiveness of reductionist thinking and linear diffusion models, on the one hand, and the realities of complex, messy, and fragmented construction activities.
	(Belay et al., 2016)	Managing Concurrent Construction Projects Using Knowledge Management and Set-based Thinking	2016	Procedia Engineering	10.1016/j.proeng.2016.11.615	Case study	Knowledge management includes new concepts like systems thinking, where firms manage concurrent projects effectively and obtain benefits in current project management.
Innovation	(Kralj, 2008)	Dialectal system approach supporting environmental innovation for sustainable development	2008	Kybernetes	10.1108/03684920810907850	Literature review	Systemic thinking is an engine for novel social, economic, and political changes in construction companies and other organisations.
Project level	(Shafaat et al., 2016)	Developing a systematic framework to enhance construction procedure design	2016	Proceedings – Frontiers in Education Conference, FIE	10.1109/FIE.2016.7757591	Workshop	Systems thinking not only helps students understand components of the construction process but also assists them in dealing with uncertainty, its sources, and its impacts.
Organisation strategy	(Oner & Saritas, 2005)	A systems approach to policy analysis and development planning: Construction sector in the Turkish 5-year development plans	2005	Technological Forecasting and Social Change	10.1016/j.techfore.2004.11.002	Case study	Systems thinking supports a developing plan with *claritas-unitas-integritas-consonantia* between the management level and components.
	(Powell & Newland, 2003)	An integrating interface to data	2003	Integrated Construction Information	10.4324/9780203475782	Full text not available, only abstract	Systems thinking enables value integration between the builder and the buyer or consumer.

3.2. Bibliometric Analysis of ST in All Fields

In order to understand the trends of ST research in all knowledge fields combined, a search for publications on Scopus was performed – TITLE-ABS-KEY ([systemic AND thinking] OR [system* AND thinking]). The search was not limited to subject areas or documents, which resulted in 4089 documents. Records show that not many papers were published before 1988, when the topic started taking relevance until the present date, reaching a peak of 373 publications in 2020 (see Figure 2). Before 2002, there were less than 50 publications yearly, and between 51 to just over 250 publications from 2002 to 2016. Between 2016-2021, there have been over 300 publications yearly. Journal articles represent 63% of publications, and conference papers 13%. The 'Journal of Family Therapy' was the first source to mention the topic in 1982, followed by 'Systemic Practice and Action Research' and 'Kybernetes' around 1996 (see Figure 3). 'Sustainability Switzerland' started publishing on the theme only around 2017 but published over 20 documents in 2020. In contrast, other sources only published around 5 to 10 documents.

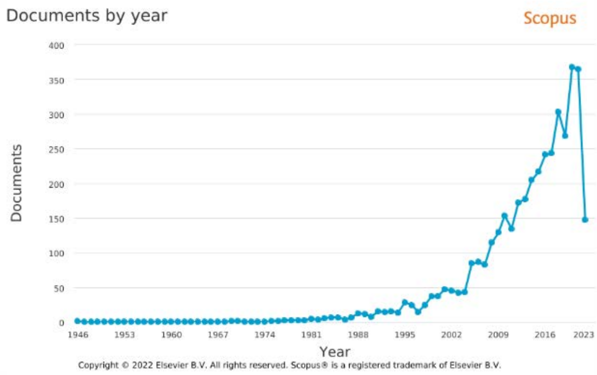

Figure 2. ST research in all fields by year. Source: Scopus

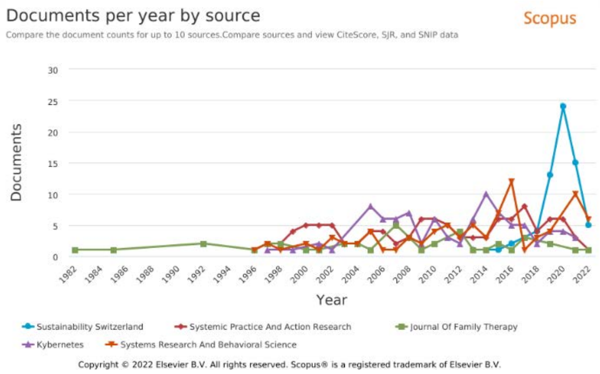

Figure 3. ST research per year by source. Source: Scopus

Grouping documents by authorship, both Mulej and Midgley published over 20 documents on the topic, and Johannessen, Nguyen, Pauar-Caceres, Bosh, and Ison produced between 15 to 20 publications. Hester, Salmon, and Adams published less than 10 papers each (see Figure 4). To date, there are no prominent authors on ST in construction; some authors, such as Boton and Forgues (2017) and Lingard and Wakefield (2019), highlight the importance of adopting ST in the building sector. Universities worldwide are promoting ST research. The Open University (UK), University of Hull (UK), and The University of Queensland (AU) have published over 40 documents, followed by Univerza V Mariboru (Slovenia), Old Dominion University (USA), and Universidade de Sao Paulo (Brazil) with between 25 to 35 documents, (see Figure 5). The United States published over 900 documents where systemic/systems thinking is mentioned, followed by the United Kingdom with 600 and Australia with 300. Germany, Italy, Canada, Brazil, France, China, and the Netherlands have published less than 200 each (see Figure 6).

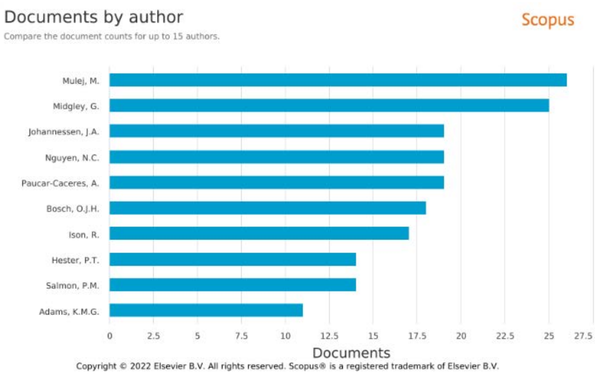

Figure 4. ST research by authorship. Source: Scopus

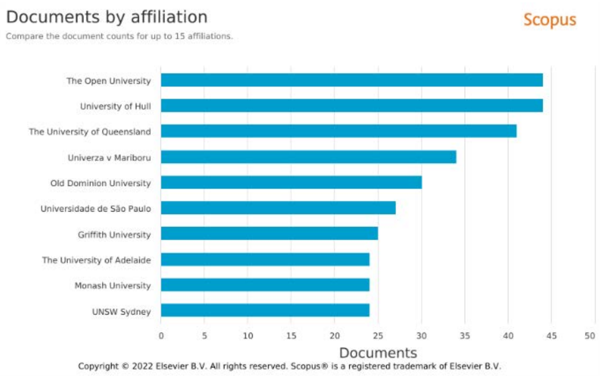

Figure 5. ST research by affiliation. Source: Scopus

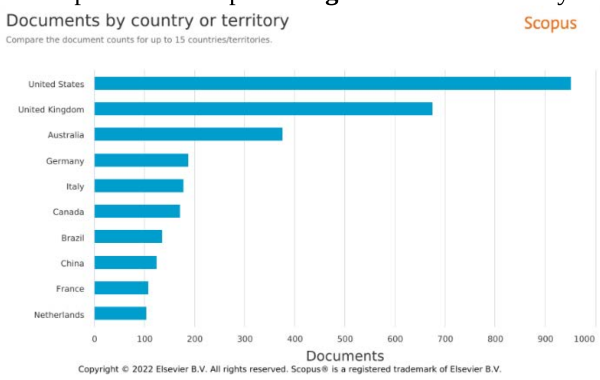

Figure 6. ST research by country/territory. Source: Scopus

Next, the two most cited documents of the top 5 authors have been grouped into themes, as shown in Table 2.

Table 2. Overview of publications on ST in all fields: the two most cited documents of top 5 authors grouped into themes.

Main Theme	Authors	Title	Year	Source Title	DOI	Method
Project	(Midgley, 2003)	Science as Systemic Intervention: Some Implications of Systems Thinking and Complexity for the Philosophy of Science	2003	Systemic Practice and Action Research	10.1023/A:1022833409353	Observation
	Findings: Observation should be viewed as just one type of intervention, which could be a methodology of systemic intervention.					
	(Nguyen & Bosch, 2013)	A Systems Thinking Approach to identify Leverage Points for Sustainability: A Case Study in the Cat Ba Biosphere Reserve, Vietnam	2013	Systems Research and Behavioral Science	10.1002/sres.2145	Application of causal loop diagram tool modelling
	Findings: The research demonstrated the application of systems thinking by using Causal loop diagram modelling and modelling as a fundamental framework to address and integrate the numerous dimensions of sustainability.					
Organisation strategy	(Johannessen, 2009)	A systemic approach to innovation: The interactive innovation model	2009	Kybernetes	10.1108/03684920910930330	Application of interactive model
	Findings: ST facilitates the management act in the face of innovation.					
	(Mulej et al., 2003)	Informal systems thinking or systems theory	2003	Cybernetics and Systems	10.1080/01969720302868	Case study and survey

	Findings: Good business depends a lot on systems thinking. Executives at companies in transition find the concepts in Built to Last to help bring about productive change without destroying the bedrock foundation of a great company.					
	(Knez-Riedl et al., 2006)	Corporate social responsibility from the viewpoint of systems thinking	2006	Kybernetes	10.1108/03684920610653737	Empirical
	Findings: ST helps people to think, decide, and act on a very broad/systemic/holistic basis rather than focusing only on profits.					
Management	(Midgley et al., 2013)	Towards a new framework for evaluating systemic problem structuring methods	2013	European Journal of Operational Research	10.1016/j.ejor.2013.01.047	Questionnaires, workshops, case study
	Findings: Evaluating participative methods is a problem-structuring method that improves stakeholders' decision-making.					
	(Rodriguez-Ulloa & Paucar-Caceres, 2005)	Soft System Dynamics Methodology (SSDM): Combining Soft Systems Methodology (SSM) and System Dynamics (SD)	2005	Systemic Practice and Action Research	10.1007/s11213-005-4816-7	Systems Dynamics and Soft Systems
	Findings: A combination of ST tools improves the communication between the directors.					

4 Findings and Discussion

The difference between the number of publications on ST in construction and ST in other fields indicates that the construction community has yet to explore the benefits of ST reported in other fields. Studies peaked over two decades ago in many knowledge fields, whereas in construction-related ones, this has only happened to a limited extent in the last seven years. This study also identified a large difference in the number of publications among authors. The most cited authors (all fields combined) have over 19 publications; however, when it comes to publications in the construction field alone, authors typically published around 3 papers only. These trends indicate the need and an opportunity for academics in construction-related fields to explore new research areas in ST, given its demonstrated potential to solve issues in other contexts. Future ST research in construction may explore whether findings and solutions from other fields apply to the construction context, similar to when the concept of Lean Production (Singh & Kumar, 2020) was adapted from the manufacturing industry into Lean Construction (Aslam et al., 2020).

Findings from ST research in other fields provide insights into the value of ST in addressing systemic issues in the construction sector by facilitating the integration of numerous parties, enabling managers to introduce innovations quickly, improving business through the executives at companies, and providing a mindset to think, decide, and act on a holistic way, offering a different way to address the problem, and providing tools to improve the communication among decision-makers. All these are challenges that the construction industry is facing to improve productivity (BDO New Zealand, 2021; Hasan et al., 2018; Nguyen & Bosch, 2013). Previous studies discussed in this paper suggest that ST could be a valuable tool to guide a team in identifying safety risks, integrating stakeholders, and making decisions that improve safety. In the construction industry, accurate decisions under disruptive situations could reduce their impact associated with extra time, costs and risks, loss of productivity, and delays.

The theme analysis showed that ST research in construction is similar to research in other fields; there is room, however, to use different methods other than surveys and case studies. Research in other fields presented alternative methods such as empirical and modelling approaches to verify and demonstrate the efficiency of ST. Top journals are starting to publish papers on potential ST implications in the construction sector. Still, it does not match the frequency and volume of papers that journals publish about ST in other fields. Over 900 documents on ST (all fields combined) were published in the United States, followed by the United Kingdom, with 600 in the last 20 years. In the construction field, nearly 5 papers have been published in the United Kingdom and 4 in Hong Kong over the last seven years. Therefore, there is space to explore and transfer insights from ST research findings in other fields into construction disciplines.

5 Conclusion

This study examined the characteristics of published ST research in construction-related disciplines and other fields indexed in Scopus. The publications examined mainly focus on ST applied to accident prevention, human factors, safety management, site safety, and performance management. Through bibliometric and thematic analyses, it became evident that there is a gap and hence opportunities for construction disciplines to explore ST approaches to address the industry's current safety issues. Attention to accident prevention will continue to increase in the construction industry, and poor contract management is one of the main factors to be addressed. Transferring research findings from other fields into the construction sector through applied research could possibly improve management approaches by adding more flexibility to deal with disruptive situations such as Covid-19, introduce innovation quickly, and make better decisions. The proposed future directions could benefit the construction industry in various ways. For example, ST could facilitate the identification and prevention of risks and hazards, promoting safer working conditions in construction. Nevertheless, researchers have yet to observe, quantify, and document such benefits. ST may add value to management, offering an alternative and potentially more effective way to tackle a crisis.

The limitations of this study are that it has only used the Scopus database and did not assess the bibliographic coupling of co-authors, co-citations, and documents. Further studies may do so to expand the findings reported here and provide additional insights. Nonetheless, this study detected a critical gap between ST research in construction and other fields, evidenced by the difference in the number of publications over the years and the discrepancy in the number of publications by authors. Further studies may address these gaps by following the trends in the topic and investigating the suitability and applicability of ST in the various dimensions of the construction industry.

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Establishing the Symbolic Meaning of Buildability: Construction Practitioners' Point of View

PLI Wimalaratne[1*] and U Kulathunga[1]

[1]Department of Building Economics, University of Moratuwa, Bandaranayake Mawatha, Moratuwa 10400, SRI LANKA

indraniw@uom.lk; ukulatunga@uom.lk

* Corresponding author

Abstract:
Lack of buildability is identified as one of the reasons for poor performance in the construction industry. Construction Industry Research and Information Association (CIRIA) in the UK in 1983 first defined buildability as "the extent to which the design of a building facilitates ease of construction, subject to the overall requirements for the completed building". Since then, numerous studies have focused on various phases and aspects of construction projects to strive for better project performance through improving buildability. To date, the buildability discourse on various definitions, generic explanations, and guidelines are loosely focused around aspects that can improve construction performance. However, a detailed interpretation of buildability concept as to its in-depth meaning and how the construction professionals experience this concept is not adequately explored. Buildability is a concept that is born and brought up within the construction industry and continues to serve the industry itself. Therefore, exploring the industry view on this concept to understand what is being represented or implied through this term can help establish clear mechanisms that could improve construction project performance. Accordingly, the aim of this paper is to establish a discourse on symbolic meaning of buildability from the industry practitioners' point of view. This research explores the lived experience of industry practitioners on buildability perceptions. Expert interviews using a phenomenological approach is used as the data collection technique. The term buildability is deconstructed from construction practitioners' point of view. This deconstruction facilitates further research on establishing a clear set of guidance that can improve buildability throughout the construction project stages to improve performance.

Keywords:
Buildability, Construction, Lived experiences, Performance, Phenomenology

1 Introduction

The construction industry is a key player in a country's national economy (Ibrahim *et al.*, 2010). One of the reasons for its prominence in national economy is the high multiplier effect generated by the construction industry through its extensive backward and forward linkages with other sectors of the economy (Oladinrin et al., 2012). For example, the construction industry is a prime source of employment generation offering job opportunities to lots of unskilled, semi-skilled and skilled workforce (Zhao *et al.*, 2022). Therefore, improving performance in the construction industry is vital. A construction project is commonly acknowledged as a successful project when the aim of the project is achieved in terms of its predetermined objectives of completing the project on time, within budget, and to the required quality standards (Kesavan, G *et al.*, 2015; Naoum and Egbu, 2015). To achieve this goal, construction companies should complete the projects within their anticipated budgets and durations, and expected quality targets (Polat *et al.*, 2014). However, in most construction projects severe time and cost overruns occur due to various factors (Habibi and Kermanshachi, 2018; Ogbu and Adindu, 2019; Johnson and Babu, 2020). Poor quality in construction projects has also become a common phenomenon in the world (Eriksson *et al.*, 2019; Buba *et al.*, 2020).

Lack of buildability has been identified as one of the root causes of this poor performance in construction (Farrell and Sunindijo, 2020; Jelodar *et al.*, 2020). This is because buildability impacts throughout the construction projects, starting from conceptual planning, through the procurement processes, construction methods, and also involving stakeholders in the decision-making to achieve their satisfaction (Ansyorie, 2019; Al-Fadhli, 2020; Samimpey and Saghatforoush, 2020). Past research proves that buildability and its further improvements, could contribute to early completion of projects, a saving in project costs and costs of change orders (variations), enhance quality, improve safety performance, and achieve a high level of productivity rate (Samimpey and Saghatforoush, 2020). Therefore, various research has been carried out seeking ways of incorporating buildability into construction projects. oFor example, adopting an assessment tool such as the Singapore Buildable Design Appraisal System (BDAS) published by the Building Construction Authority (BCA) in Singapore, which covers the three areas of structural works, Architectural, Mechanical, Electrical and Plumbing (AMEP) works and good industry practices (BCA, 2022), or by incorporating buildability with modern technologies such as Integrated Project Delivery (IPD) (Leoto and Lizarralde, 2019), Building Information Model (BIM) (Govender *et al.*, 2018), 3D Drawings (Liau and Lin, 2017), Off-Site Manufacturing (OSM) technology, Design for Manufacture and Assembly (DfMA), or by adopting different procurement strategies such as Project Management (PM), Early Contractor Involvement (ECI) (Finnie, *et al.*, 2018; Wondimu *et al.*, 2018; Farrell and Sunindijo, 2020), or in connection with another concept such as Lean Construction Triangle (LCT) (Wondimu *et al.*, 2018; Ballard and Tommelein, 2021), sustainability (Singhaputtangkul *et al.*, 2014). There are also various buildability practices published in view of improving the construction project performance. Among these, ten (10) principles published by Adams (1989), twelve (12) principles published by (CIIA, 1996), twenty three (23) buildability concepts published by (Nima *et al.*, 2001) can be highlighted. Although these studies introduce various methods to incorporate buildability into construction, these methods are mostly focused on the early stages of construction projects. However, it is evident from existing knowledge domain that buildability could improve construction project performance not only during the early stages but also throughout the different work stages.

As discussed above, even though the existing knowledge domain suggests various buildability guidelines, appraisal systems, principles and concepts targeting different phases or different elements of construction, there is no established set of practices or directives that can be incorporated into any construction project throughout its entire works stages to improve construction project performance. This is mainly due to the absence of clear identification of the deep meaning of the key drivers of the buildability concept. A recent study revealed that the most frequently used keywords in buildability discourse were “optimal integration of construction expertise and experience”, “ease of construction”, “design that facilitates building construction”, “construct efficiently, economically and to agreed quality levels”, “project quality improvement technique”, and “design and detailing” (Wimalaratne *et al.*, 2021). However, these keywords are very generic when it comes to their practice. Therefore, it is important to obtain a clear picture of the key drivers of this concept. Provided that buildability is a concept born and brought up within the construction industry and continues to serve the industry itself, obtaining an industry practitioners’ point of view on this concept is seen as the best place to start. This challenge may be handled by obtaining perceptions from industry practitioners with regard to their lived experience concerning buildability (Wimalaratne and Kulatunga, 2022). Accordingly, this study aims to uncover the symbolic meaning of buildability from the construction industry practitioners' point of view. Therefore, this research takes phenomenological research philosophy. The study discussed in this paper is a part of an ongoing research. Research techniques adopted in this portion of the study include literature review, in-depth interviews and Interpretative Phenomenological Analysis (IPA).

2 Buildability Discourse in the Existing Knowledge Domain

2.1 History of Buildability

Although the term 'buildability' had not been framed until early 1980s, the concerns with regard to buildability concept can be traced back to early 1960s. For instance, the studies conducted from 1960 to 1970, indicated that lack of integration of knowledge and experience in the framework of design and construction was the origin of many complex problems in the construction industry (Jadidoleslami *et al.*, 2021). Interestingly, a significant contribution in relation to buildability research is made by various industry research institutes such as Construction Industry Research and Information Association (CIRIA) in the UK, Construction Industry Institute Australia (CIIA) and Construction Industry Institute in United States (CIIUS).

2.2 Various Interpretations Emerged

CIRIA in 1983 first defined buildability as "the extent to which the design of a building facilitates ease of construction, subject to the overall requirements for the completed building". This definition was criticised for its narrowness in scope as it confines to the design process only (Wong *et al.*, 2007) as buildability impacts throughout the various work stages of a construction project aiming to accomplish the ultimate project goals (CIIUS, 1986). Since then, numerous studies have been conducted to strive for better project performance through improving buildability. Accordingly, numerous researchers have interpreted buildability based on their conceptual assumptions. For example, Illingworth (1984) stated that buildability is, "Design and detailing which recognize the assembly process in achieving the desired result safely and at least cost to the client". This statement was further elaborated by Ferguson (1989) providing a new definition for buildability as, "the ability to construct a building efficiently, economically and to agreed quality levels from its constituent materials, components and sub-assemblies". Ferguson's definition emphasised the optimum management and structuring of project activities and building process to achieve project goals. Adding to these, Moore (1996) stated that buildability is, "a philosophy, which recognizes and addresses the problems of the assembly process in achieving the construction of the design, safely as well as without resorting to standardization or project-level simplification". An extended clarity of buildability was introduced by CIIA deviating its traditional focus on "lack of knowledge" but emphasizing that buildability is about "lack of management of information" rather than "lack of information" (CIIA, 1996). BCA code of practice who have given deeper thoughts on buildability and its influence on productivity defined buildability as, "the extent to which the design of a building facilitates ease of construction, as well as the extent to which the adoption of construction techniques and processes affects the productivity level of building, works" (BCA, 2022).

The review of the literature indicates that the term "constructability" has been used interchangeably for buildability (Kalsaas *et al.*, 2018; Ansyorie, 2019; Ding, Salleh and Kho, 2019; Finnie, Ali and Park, 2019). Lam *et al.* (2007) stated that these two terms are referring to similar concepts except in some instances the term "constructability" had been used to explain broader management implications which embrace both design and management functions of construction projects. According to the CIIUS and CIIA, the key components of constructability include the application of construction knowledge in different work stages to achieve the overall project objectives, which are similar to the concept of buildability as well. Hence, some researchers argued that constructability and buildability are two identical concepts, used in different parts of the world (Kalsaas *et al.,* 2018; Finnie, Ali, & Park, 2018; Ansyorie, 2019; Ding *et al.,* 2019; Finnie *et al.,* 2019). However, BCA in Singapore, which has pioneered buildability research has used both buildability and constructability terms in their latest publications on BDAS in which they referred to buildability as a responsibility of the professional team and constructability as the responsibility of the builder (BCA, 2022). Therefore, although there is no clear demarcation between these two terms, most researchers agreed that both terms carry similar meanings for enhancement of construction project performance (Wimalaratne *et al.*, 2021). Therefore, the term "buildability" is used in this study to interpret both "constructability" and "buildability" terms. Below Table 1 represents a summary of emerged interpretations and definitions of buildability over time.

Table 1. Interpretations and definitions of buildability emerged over time.

Reference	Buildability Interpretations
CIRIA (1983) "Buildability"	"The extent to which the design of a building facilitates ease of construction, subject to the overall requirements for the completed building".
Illingworth (1984) "Buildability"	"Design and detailing which recognize the assembly process in achieving the desired result safely and at least cost to the client".
CIIUS (1986) "Constructability"	"The optimal use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives"
Ferguson (1989) "Buildability"	"The ability to construct a building efficiently, economically and to agree quality levels from its constituent materials, components and sub-assemblies".
CIIA (1996) "Constructability"	"The integration of construction knowledge in the project delivery process and balancing the various project and environmental constraints to achieve project goals and building performance at an optimum level"
Moor (1996) "Buildability"	"a design philosophy, which recognizes and address the problems of the assembly process in achieving the construction of the design, safely as well as without resorting to standardization or project level simplification"
Griffith and Sidwell (1997) "Constructability"	"a system for achieving optimum integration of construction knowledge in the building process and balancing the various project and environmental constraints to achieve maximisation of project goals and building performance"
Arditi et al. (2002) "Constructability"	"Constructability programs aimed at integrating engineering, construction, and operation knowledge and experience to better achieve project objectives"
Capone et al. (2014) "Constructability"	"Constructability interacts with the project management techniques that utilize optimally knowledge and experiences on building effective, to improve the achievement of the project objectives".
Mohammed (2014) "Buildability"	"Integrating construction knowledge, resources, technology and experience into the engineering and design of a project"

BCA (2011-2022) "Buildability"	"The extent to which the design of a building facilitates ease of construction as well as the extent to which the adoption of construction techniques and processes affects the productivity level of building works"

It has to be noted that buildability definition is not evolved a great deal over time. The latest definition has been introduced by BCA, Singapore. These various interpretations, generic explanations and definitions are loosely focused around aspects that can improve construction performance. A previous study conducted specifically on various definitions of buildability and its key constructs has illustrated the numerous definitions that emerged over three decades and concluded that the key constructs of buildability include "integrate construction knowledge and experience", "throughout the project delivery process" to "achieve overall project objectives" (Wimalaratne *et al.*, 2021). However, much deeper insight is necessary in relation to these key constructs for further investigating this concept and to develop a practical application that was found profoundly missing in the existing knowledge domain. Provided buildability is a concept that emerged within the construction industry (Griffith and Sidwell, 1997), exploring the industry view on this concept to understand what is being represented or implied through this term can help establish a clear discourse on the symbolic meaning of this concept. Thereby a clear mechanism could be developed to improve construction project performance.

2.3 Key Constructs of Buildability

Past research covering indexed publications from 2011-2021 conducted following a Systematic Literature Review (SLR) technique revealed that the most frequently cited definition of buildability was the definition published by the CIRIA in 1983 (Wimalaratne, *et al.*, 2021). The same study revealed that the most common definitions for constructability were the definitions published by CIIUS (1986) and CIIA (1996). The following Figure 1 shows these three definitions and their composition.

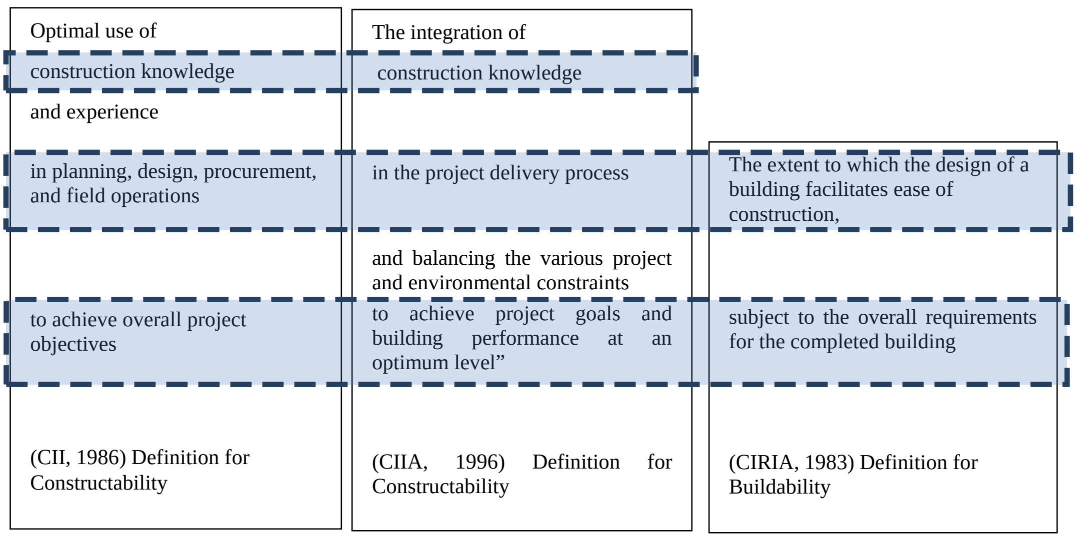

Figure 1. Widely Used Industry Interpretations of Buildability

All the above definitions focus on the issue that the benefits of buildability can solely be achieved by the integration of the construction knowledge and experience into each phase of the project delivery process (Jergeas and Put, 2001), which shall enhance the project performance towards its overall project goals.

Accordingly, the concept of buildability shares the following three (03) common themes:

1. Integrate construction knowledge and experience
2. Throughout the project delivery process
3. To achieve overall project objectives

3 Research Methodology

This study aims to uncover the symbolic meaning of buildability from the construction industry practitioners' point of view. Phenomenology is concerned with the systematic reflection and analysis of phenomena associated with conscious experiences, such as human judgment, perceptions, and actions, with the goal of; (1) appreciating and describing social reality from the diverse subjective perspectives of the participants involved, and (2) understanding the symbolic meanings ("deep structure") underlying these subjective experiences (Bhattacherjee, 2012). Therefore, this research takes phenomenological research philosophy.

In this study, literature review identified various interpretations of the phenomena being studied (buildability). However, further investigation is required through data collection to further explore the phenomena being studied. A deep identification and interpretation of the lived experiences gathered from the data collection will facilitate uncovering the buildability concept from industry practitioners' point of view. Therefore, this research will take abductive approach instead of deductive or inductive research approaches where the study attempts to collect data to explore a phenomenon. In Abductive studies, the researchers analyse collected data to identify themes and explain patterns, to generate a new or modify an existing theory (Saunders *et al.*, 2019). This particular study takes mono-method qualitative methodological choice with exploratory survey strategy. Research techniques adopted in this portion of the study include literature review, in-depth interviews and IPA. Refer to Figure 2 for a detailed illustration of the research methodology.

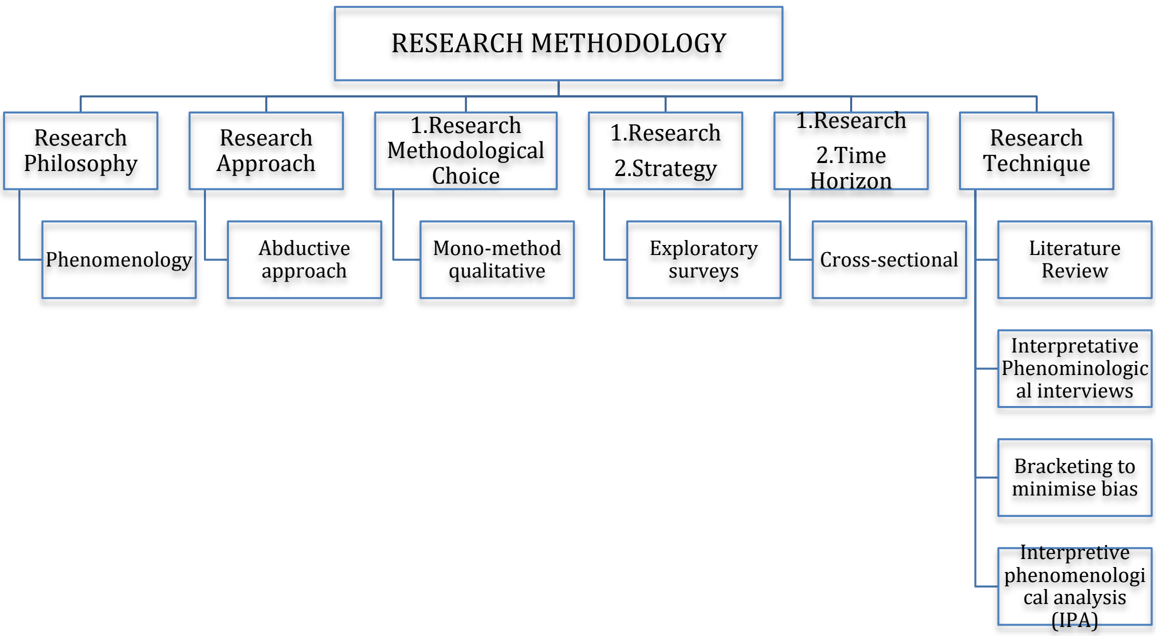

Figure 2. Research Methodology

Participants were selected based on the convenience sampling method as it lead to identify the sample that actually have experienced buildability. Semi-structured interviews were carried out to ensure that only the relevant data is collected and that expected outcomes are in line with answering the research question. Targeted participants were professionals currently working in the construction industry with significant years of experience in various construction projects and playing management roles from both contractor and consultant perspectives. Ideal participants had been involved in buildability of construction projects and could provide input into their experience in that area. Data collection was carried out via web interface (Zoom) and in-depth interviews were carried out following the phenomenological interview approach. NVivo software is used for coding. IPA was followed to carry out the qualitative data analysis (Smith, *et al.*, 2009). The following table represents the profile of the participants who participated in the data collection.

Table 2: Participants' Profile

Ref	Discipline of Services	Years of Experience
R1	Project Manager/ Consultant	30
R2	Project Manager/ Consultant	30
R3	Project Manager/ Contractor/Construction Manager	28
R4	Project Manager/ Contractor/Construction Manager	30

This study followed an interpretative phenomenological approach where the researcher attempts to understand the hidden deeper meanings behind the phenomenon and interpret it using a suitable analytical technique (IPA) to explain the phenomena being studied. Interpretive phenomenological interviews facilitate active listening and non-interruption of participants while gathering data around two broad questions "what have the participant experienced in terms of the phenomenon" and "what contacts or situations have influenced the participant's experiences of the phenomena". During the data collection, the researcher bracketed herself up to a greater extent in collecting rich insights and digging deeper into the meanings while preserving the authenticity of the lived experiences of the participants. There is no 'one best method' of working with data in an IPA study (Smith and Larkin, 2009). Therefore, there is no definitive account of guidelines for conducting IPA analysis. However, eight (8) steps were followed in reaching the conclusions for this study including; (1) preparation of the interview guideline, (2) conducting in-depth interviews following the phenomenological interview approach, (3) transcribing the originally recorded interviews ensuring the adherence to research ethics, (4) refine the verbatim following noise reduction, (5) reading and re-reading the verbatim, (6) codification and assignment of initial nodes ('open coding'), (7) arrangement of data according to dominant emerging themes ('axial coding'), (8) extend the analysis to comparative analysis between interviews to ascertain common themes and irregularities.

4 Findings and Discussion

The key themes derived from the literature namely (1) Integrate construction knowledge and experience, (2) Throughout the project delivery process, (3) To achieve overall project objectives were further analysed to obtain the deeper meaning of buildability from an industry practitioners' point of view. The findings are discussed below under two areas.

1. Meaning of ‘buildability’

Participant 1 (P1) stated that buildability is the “ability to build” which is similar to “ease of construction” as stated in literature. P1 further stated buildability is “ ability to build **without many practical verifications”** highlighting the avoidance of practical verifications which was not found in the literature analysis. Further clarification in this regard revealed that verifications refer to changes to the established methodology of construction which was further clarified as “alternative methods” of carrying out a particular work.

Participant 2 (P2) stated that buildability is improving quality, reducing time and cost. P2 firmly stated that “from my experience, it simply eases the construction activities to deliver the project on time, required quality, and maybe with reduction of the cost” agreeing with literature but with more elaboration on overall project goals.

Participant 3 (P3) agreed with P2 stating “buildability means whether we can construct or, give a design that we can construct, very quickly or with the given time and with the available resources”. P3 further highlighted the need for knowing the “**available resources**” while the design is completed, which was not found in the literature analysis. P3 here is agreeing with P2, highlighting the overall project goals.

Participant 4 (P4) mentioned that their attitude on buildability completely changed after the long industry practice (30 years). P4 highlighted that during the undergraduate period, buildability was more referred to as the building morphology, dimensions, and their relation to cost although later P4 understood that buildability was a much broader concept. P4 stated that “when I study in the university, I studied the spatial requirements, the relationship between the spatial requirements and the cost as buildability studies”. P4 further stated that the industry practice persuaded them to look at buildability from two aspects “spatial aspect” and “construction aspect”. P4 further illustrated this by saying, “when I came to the industry, I looked at those spatial aspects separately, then construction aspects separately”. “In the construction aspect, we looked at whether it is buildable”. P4 illustrated their interpretation of “buildable” stating, “Means, whether we have the required technology.... we have the required skills of the people.... whether the materials are available”. In this instance, P4 agrees with P3 who highlighted the importance of knowing the availability of resources.

Therefore, all the participants agreed with the literature stating that buildability is “making it easier to construct” and “achieving the project objectives – time, cost and quality”. In addition to this, the industry practitioners refer to “building without many verifications”, and “building according to the available resources” addressing the practical aspects of being able to construct as buildability.

2. The participant’s personal experience/feeling on ‘buildability’

P1 have felt buildability as periodical checking on the initial design and during construction. P1 stated that “checks are not being usually done, but it is done once the projects are awarded, and halfway through when the contractor finds difficulties, they usually ask from the consultants whether there are any other design alternatives to make it more buildable”. P1 suggests that buildability should be checked by a separate person other than the designer. P1 states, “designers cannot do that! designers are prejudiced with their design and standards and their codes”.

P2 felt buildability as making it easier to construct while achieving time and quality targets but may be compromising on the cost. P2 illustrated this stating “that will ease the construction work to achieve both time and quality and delivery of the project but, there might be a cost reduction, or else sometimes there will be increased, but we need to decide which part is compromised”. P2 further clarified that buildability changes from one project to another and further stated that “what I want to say is that buildability depends on the expertise of the organisation, who is going to build the project”. P2 continued stating “The organization who has the resources or the technology, might interpret buildability differently to another organization who doesn’t have resources and technology”.

P3 have felt buildability as “knowing what to build on a practical aspect”.

P4 felt buildability as an experienced person’s inspection of the design in terms of practicality of construction limiting their opinion only for the early stages of the construction projects. P4’s thoughts were in agreement with the early interpretations of buildability concept. P4 stated, “Some experienced persons must go through the design, or the project once finished to ensure whether it is buildable. Whether it is constructable”. P4 further illustrated stating that when buildability is present in a project, there is “**no need to look for alternative methods**” which is in the agreement with P1’s statement “without practical verifications”.

All the participants agreed with the three common themes identified in the literature as buildability. For example, all the participants agreed that knowledge sharing is of the highest concern in improving buildability. In this regard, P2 stated, “if you increase knowledge sharing it will definitely improve buildability!”. P1 further suggested that collaboration can improve buildability in construction projects. There were some additional themes which were emerged from this study as shown in Figure 3 below. Therefore, the following can be concluded with regard to the industry practitioners’ point of view on buildability.

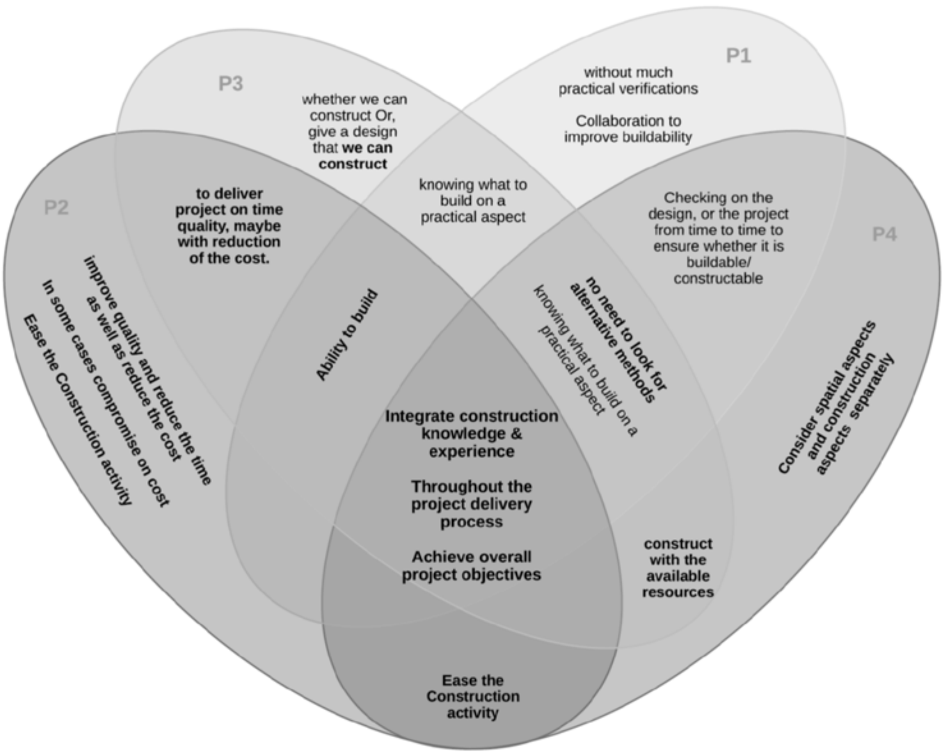

Figure 3. Symbolic Meaning of Buildability: Construction Practitioners' Point of View

5 Conclusion and Further Research

The choice of qualitative approach guided this study to recruit semi-structured in-depth interviews from phenomenological approach as the primary data collection technique. This study intended to capture industry practitioners' point of view on buildability concept. Interviews, therefore, could document research participants' attitudes, feelings, beliefs, experiences and reactions.

This study includes the input of four (04) industry practitioners as this is an ongoing study. All the practitioners agreed with the literature findings on knowledge sharing improves buildability. All the participants agreed that buildability impacts throughout the design and construction phase although one participant focused more on the early phases of the construction project delivery for integrating knowledge. All the participants agreed that buildability is about achieving the project objectives although one participant thought while making a project more buildable there could be a compromise on cost. In addition to literature findings, industry practitioners stated that buildability is being able to build without verifications and without the need of looking for alternative methods. The practitioners highlighted the importance of knowing the level of the available resources.

Further research on this is recommended to obtain a much wider view of this concept which shall then lay a path to research on the integration of buildability throughout the entire project delivery process to improve construction project performance.

6 Acknowledgement

The authors wish to thank Mr. A.A.D.W.V. Udayashantha, Technical officer at the University of Moratuwa, Sri Lanka for his valuable contribution in formatting the paper.

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Recent National Construction Code Changes, Reduced Innovation, and Increased Contractual Risks

Christian van der Pump[1*] and Eric Scheepbouwer[1]

[1] Department of Civil and Natural Resources, University of Canterbury, Private Bag 4800, Christchurch 8140, NEW ZEALAND

christian.vanderpump@pg.canterbury.ac.nz; eric.scheepbouwer@canterbury.ac.nz
* Corresponding author

Abstract:
A new clause recently added to the National Construction Code (A2.2(4)) has fundamentally changed the way performance-based design is developed. Previously, designers could formulate a design that was compliant as long as the applicable performance clauses of the National Construction Code were met. This freedom of design allowed designers to compete freely on innovation grounds as opposed to solely on price. However, on 1 July 2021, the new clause regulated this performance-based design process. Designers can no longer formulate a design that complies with the performance clauses. Now, designers must complete a performance-based design brief to be disclosed and approved by multiple parties, many of whom do not have an approval's role, contractual role, or suitable expertise. This process can represent a significant financial risk to developers since assumptions about how land may be built at the development approval stage may be inefficient if some parties do not agree to the performance-based design methodology for other than safety reasons. This new clause does not, by the authors' research, comply with the statutory Acts under which the National Construction Code is passed.

Keywords:
A2.2(4), Building confidence report, Combustible cladding, National construction code, Performance-based design brief

1 Introduction

Due to numerous building failures in Australia, one of the most notable examples being the 2014 Lacrosse Tower cladding fire, Professor Peter Shergold and Ms. Bronwyn Weir were engaged by the Australian Federal Government to undertake an assessment of the compliance and enforcement systems for the building industry across Australia. This involved looking at reforms, considering strategies for improving compliance and enforcement practices, and making recommendations for best practice models for compliance and enforcement, to strengthen the implementation of the NCC. The result was the Building Confidence Report (BCR), published in February 2018 (Shergold and Weir, 2018).

As a result of this BCR, one of the main changes to the National Construction Code (NCC) was *the introduction of Clause A2.2(4), which states the following:*

Where a Performance Requirement is proposed to be satisfied by a Performance Solution, the following steps must be undertaken:

(a) Prepare a performance-based design brief in consultation with relevant stakeholders.
(b) Carry out analysis, using one or more of the following Assessment Methods: evidence of suitability, verification method, expert judgement, or comparison with the Deemed-to-Satisfy.

(c) Evaluate results from (b) against the acceptance criteria in the performance-based design brief.
(d) Prepare a final report that includes:
  i. All Performance Requirements and/or Deemed-to-Satisfy Provisions as applicable; and
  ii. Identification of all Assessment Methods used; and
  iii. Details of steps (a) to (c); and
  iv. Details of conditions or limitations, if any exist, regarding the Performance Solution.

Performance Requirement, Performance Solution, and Performance-based Design Brief are defined as:

Performance requirement means a requirement which states the level of performance which a performance solution or Deemed-to-Satisfy solution must meet.

Performance solution means a method of complying with the performance requirements other than by a Deemed-to-Satisfy solution.

Performance-based design brief (PBDB) means the process and the associated report that defines the scope of work for the performance-based analysis, the technical basis for analysis, and the criteria for acceptance of any relevant performance solution as agreed by stakeholders.

This new NCC clause was in response to BCR recommendations 8 and 14, namely:

Recommendation 8: *That, consistent with the International Fire Engineering Guidelines, each jurisdiction requires developers, architects, builders, engineers and building surveyors to engage with fire authorities as part of the design process.*

Recommendation 14: *That each jurisdiction sets out the information which must be included in performance solutions, specifying in occupancy certificates the circumstances in which performance solutions have been used and for what purpose.*

Recommendation 8 references the International Fire Engineering Guidelines (IFEG) which is a document produced by the Australian Building Codes Board (Australian Building Codes Board, 2005), with the most current version published in 2005. The IFEG methodology requires a “fire engineering brief” (FEB), described by the IFEG as “the scope of work for the fire engineering analysis and basis of analysis as agreed by stakeholders”. The word “stakeholders” is characterised in the IFEG as being the building consent authority, fire brigade, design fire engineer, peer review fire engineer, architect/designer, and building owner.

However, this paper will show that A2.2(4) of the NCC is of questionable legality and introduces significant contractual risks. Poignantly, it also does not respond to the likely causative factors that have contributed to the prevalence of combustible cladding across Australia (van der Pump and Scheepbouwer, 2022) despite recent cladding fires being the driver of the BCR. To illustrate the legality of A2.2(4) and the potential risks it introduces, the legal context will be detailed in Section 6 Findings and Discussion.

2 Literature Review

The literature reviewed covers legal areas the NCC is bound to by law, not just documents frequently cited within the construction industry, such as the IFEG, as the engineering literature is, by the author's investigation, devoid of any critique of the BCR's findings, whether it be positive or negative, and instead has accepted the outcome of the BCR (e.g., Cadena et al, 2022). The failure to review legislation for any type of (legal) deficiency in the face of significant building failures and conclude the issue is one of either design or workmanship is also reported (Buchanan et al, 2006).

The paper also addresses and references Australian case law, and in particular common law principles and doctrines that are accepted by Australia's state and territory supreme courts such as freedom of contract (Rares, 2013), negligence, and nuisance (Trindade, 2007) as well as the federal circuit and High Court of Australia (Australia's highest court).

It is against these legal references that A2.2(4), a key outcome of the BCR, is critiqued. The BCR recommendation to include A2.2(4), as well as the Regulation Impact Statement (Australian Building Codes Board, 2020) that was conducted by the ABCB, did not address any of the common law principles and doctrines that, as will be discussed, are relevant to A2.2(4)'s legality.

The importance of this research cannot be understated, as the building and construction market is a highly regulated market. And where any type of legal instrument (such as the NCC) that is below a statutory Act is found legally incorrect, the courts in Westminster countries such as the UK, Australia, and New Zealand have the power to rule such legal instruments 'null and void'. Such rulings clearly impact an entire industry.

3 Research Methodology

The methodology adopted in this paper firstly involves describing the structure of Australia's legal system and the different tiers of laws, where each tier has a legal hierarchy over the law beneath it. If the lower tier legal instrument is not legally consistent with the law above it, any of Australia's State and Territory Supreme Courts can find it 'null and void'.

Following an outline of Australia's legal system and its hierarchy, a description of how the courts can review for the legality of many laws, including anything in the NCC. This is based on Australia's most cited legal reference about the legality laws, Delegated Legislation by Prof. Dennis Pearce (AO) (Pearce and Argument, 2017). This type of analysis falls within the area of constitutional and administrative law, which the courts have authority to rule on via what is known as judicial review. Unlike in other sectors of the economy, it is uncommon for practitioners in the construction industry to exercise their constitutional right to challenge the decisions and actions of government departments via the courts to ensure that government officials obey the law and act within their prescribed powers (Australian Law Reform Commission, 2016). This includes A2.2(4).

A2.2(4) is analysed using the legal principles applicable to the NCC (that are arguable under judicial review), as the NCC is not (as it will be shown) supreme law. Therefore, the NCC – including any of its clauses – can be ruled invalid by any of the state and territory's supreme courts if found illegal.

Some of the more basic economic characteristics of A2.2(4) are also analysed, such as what is known as the ‘holdout’ problem, the contractual risks the holdout problem presents, as well as A2.2(4)’s potential to stifle innovation by way of its mandatory requirement to disclose innovative design methods to other parties, including rival companies.

4 Structure of Australia’s Legal System

Australia’s legal system is based on the United Kingdom’s Westminster system, whereby the Government is divided into three separate co-equal arms, namely:

Legislature: The Legislature consists of a lower house where statutory laws are voted on, and, if passed by the lower house, are then voted on by the upper house, where if passed, they become law. Statutory law (Acts) is the supreme law.

Executive: The Executive consists of Ministers and government departments. The Executive’s role is to recommend policy, propose and pass secondary legislation under statutory Acts – known as Delegated Legislation (DL) – and administer laws (whether they be Acts or DL). Typically, DL are regulations, codes, orders, rules, etc. DL cannot be passed into law unless authorised by an Act.

Judiciary: The Judiciary consists of the Courts and their judges, who interpret and apply the law and produce case law, whether it be the interpretation of statutory law, the common law, or both.

The three co-equal arms exist at both federal, state, and territory levels; however, Queensland, the Australian Capital Territory, and the Northern Territory do not have upper houses.

The national Government of Australia is the Australian Federal Government (AFG), but its role in determining the laws each state and territory must comply with is limited by the Australian Constitution. Under the Australian Constitution, the AFG has no authority to pass building Acts that each state and territory (‘jurisdictions’) must comply with. Nevertheless, to facilitate efficient commerce between all jurisdictions, there is an agreement between all jurisdictions that a national building code is produced and introduced as DL under each jurisdiction’s building Act. This DL is known as the NCC, produced by the Australian Building Codes Board (ABCB). The ABCB is funded by the jurisdictions.

The legal status of the NCC being DL is important (Katter *et al*., 2021), since each jurisdiction’s respective building Act adopts it. Therefore, what is written within the NCC must be legally consistent with the statutory law that enables it. This matter is discussed in more detail in the following section.

5 Executive Oversight and Judicial Review

A DL introduced under a parent Act, must be legally consistent with its parent Act. The DL cannot, for example, specify that ‘person A’ has legal authority over a particular matter (e.g., approving building plans) when the parent Act does not grant this power. Nor can it mandate a fee be collected by an Executive entity for something that is not permitted under the parent Act (analogous to an illegal tax). The reasoning behind the importance of DL having legal consistency is simple. The Legislature passes statutory Acts by majority vote, which is the essence of democracy, and therefore Acts are supreme law. DL is not passed by the Legislature but instead by the Executive who comprise of persons who have not been voted in democratically. Therefore DL, whilst important and necessary, is not passed into law by democratic vote. Therefore, if the DL is in any way ‘inconsistent’ with the parent Act, it is illegal.

A mechanism that can be applied to rule DL illegal is via judicial review under the Judiciary, as it is the Judiciary that has the power to oversee the decisions and actions of the Executive, which includes judicial oversight over the content of DL. Each jurisdiction’s supreme court has the power to rule any DL illegal on several legal grounds. Each legal ground is a large subject, and it is well beyond the scope of this paper to describe. However, to analyse A2.2(4) a brief introduction to each of the legal principles and doctrines that determine the legality of any DL follows here (Pearce and Argument, 2017):

1. Simple *ultra vires*: The doctrine of *ultra vires* is one of “beyond the powers” (Latin); it is a broad-ranging doctrine that essentially all other judicial review principles fall under. Simple *ultra vires* has been defined by the Full Federal Court of Australia as:

   “*The general approach to such a challenge was described by Rich J in Footscray Corporation v Maize Products Pty Ltd (1943) 67 CLR 301 at 308; [1943] ALR 221 at 224 (Footscray Corporation) as follows:*

   “Authorities are of little use in determining the validity of a particular by-law. The appropriate steps are to construe the statute under which the by-law is made and then interpret it to ascertain whether it is within the ambit of the statute.”

   Although those observations were directed to a local government by-law, we consider that they apply to any subordinate legislative instrument, including the determination.”

   Examples of simple *ultra vires* include breaches of common law rights such as interference with the right to contract or illegal imposition of a tax (fee).

2. Inconsistency (analogous to Repugnancy): Inconsistency occurs when there is a power to make a regulation under an Act, but the form it takes contradicts the provisions of the parent Act or another law.
3. Improper Purpose: The DL making authority must have addressed the specified purpose, and not for some improper motive or bad faith.
4. Uncertainty: DL cannot be uncertain. To have valid DL (from an uncertainty perspective), it must have two properties – it must be certain, that is, it must contain adequate information as to duties to be met, and it must be reasonable.
5. Unreasonableness: DL cannot be unreasonable; that is, it must not be so oppressive or capricious that no reasonable mind can justify it.
6. Procedural *ultra vires*: Where the Act prescribes specific procedural steps to make in the development of DL and these steps are not followed, the DL is procedurally *ultra vires*.

It can be found that a DL (or any one of its subclauses) breaches more than one of the legal principles identified above.

6 Findings and Discussion

6.1 Analysis of A2.2(4)

The starting point to analyse the legality of A2.2(4) is to establish the characteristics of the statutory Acts that enable A2.2(4) into law (as DL). In all Acts other than the Australian Capital Territory's Building Act 2004, it is stated the purpose/objective of the Act is to create (to the effect of) safe built environments. It is left to DL by prescribing the NCC as the means to produce safe buildings by way of procedural and substantive laws, whether prescriptive or performance based. Moreover, no jurisdiction's statute specifies that any design must be completed in a manner that requires consultation with any parties, whether the private sector or the Executive. Specifically, on the Executive side, the roles are as follows under each Act:

Table 1. Roles of Fire Authorities and Local Authorities (e.g., councils) under each jurisdiction's building Act

Jurisdiction	Fire authority's approval role under jurisdiction's parent building Act	Local authority/council role under jurisdiction's parent building Act
QLD	None under Sustainable Planning Act 2016 or Building Act 1975. Commentary under Sustainable Planning Regulations 2017, only when a design is completed.	None. Private certification, at the end of a design.
NSW	None under the Environmental Planning and Assessment Act 1979.	None. Private certification, at the end of a design.
VIC	Approvals granted by the Building Act 1993 under s 261 (at the end of design).	None. Private certification, at the end of a design.
TAS	None. Commentary role only under the Building Act 2016 s 132 (at the end of the design).	Approval's role under s 138 – 147 of the Building Act 2016, at the end of the design.
SA	Approval's role under s 122 of the Development Act 2016 (at the end of the design).	None. Private certification, at the end of a design.
WA	None under Building Act 2011. Commentary role only under the Building Regulations 2012 (at the end of the design).	Approval's role under s 124 – 127 of the Building Act 2011, at the end of design.
ACT	Approval's role under Section 30A of the Building Act 2004 (at the end of the design).	None. Private certification, at the end of a design.
NT	Commentary role only under s 8 & Schedule 3 of the Building Act 1993 (at the end of design).	None. Private certification, at the end of a design.

Thus, it can be seen from the above table that the Executive has no role in any aspect of design under any building Act; design is preserved for the private sector. Also, on the matter of the role of the Executive, its role, whether it be a commentary role or approval's role, occurs at the end of the design period. No building Act grants the Executive an approval's role to determine how a building can be designed and to have what is effectively a 'veto role' in determining what process, scope of work, technical basis, and acceptance criteria are acceptable. The Chief Justice of the High Court of Australia (Australia's highest court) stated in Plaintiff M47/2012 v Director-General of Security [2012] HCA 46 that '*delegated legislation cannot be repugnant (inconsistent) to the Act which confers the power to make it*'. There is a clear argument that A2.2(4)'s requirement to involve the Executive in the design process, and to grant the Executive an effective veto role on the process, scope of work, etc., is inconsistent with each state and territory's respective building Act.

Where there is silence on a statutory matter, common law doctrines are the law such as the common law doctrine of freedom of contract. The Executive is not permitted to have any control over the private sector's activities. This doctrine is frequently cited by the courts, one example being in the New South Wales Court of Appeal in Biotechnology Australia Pty Ltd v Pace [1988]: "*It is an attribute of a free society, as we know it, that it is generally left to parties themselves to make bargains. It is therefore left to them sometimes to fail to make bargains or to fail to agree on particular terms. Well meaning, paternalistic interference by courts in the marketplace, unless authorised by statute or clear authority, transfers to the courts the economic decisions which our law, properly in my view, normally reserves to parties themselves*". One of the earliest judicial review cases in Australia to strike out a DL for violating freedom of contract was in 1917 where a by-law was passed regulating what could be traded, which was subsequently ruled invalid (*Attorney-General v Metropolitan Meat Industry Board* (1917) 18 SR (NSW) 9). A2.2(4) prohibits freedom of contract, because it mandates design be subject to stakeholder agreement. Thus, there is a clear argument that A2.2(4) is *ultra vires* ('beyond the power of') the common law right to freely contract, as it is not possible to produce a design that complies with the NCC's performance requirements without stakeholder approval.

6.2 Contractual Risks

The contractual risks associated with A2.2(4) are inherently obvious as developments across Australia go through two stages. The first stage is the development approval process, whereby approval is sought from local authorities as to how the land is to be used. In the case of buildings, by-law issues which must be complied with such as built area to land ratios, minimum floor areas for any residential units, recession planes for assessing compliance with shading requirements, number of car parking spaces, aesthetic qualities, noise limitations, are but a few of the myriad of by-law hurdles that developments must comply with. The development approval phase of a project does not assess compliance of the building with the building code and is largely focussed on the effect of the external building envelope on neighbouring property. Therefore, no consideration need be given to compliance with the NCC at this stage. However, the external form a building clearly has impact on how a building is designed internally. A building that is proposed to be built on the long narrow rectangular plot does not have the same floor plate flexibility as a building of equal floor area on a square plot. To elaborate, a residential development on a long narrow plot, to be financially feasible, would require a certain number of units to be built. Issues such as means of escape are not addressed at development phase, and so to make the development feasible, downstream reliance on a trivial fire PBD such as a minor increase in travel distance to avoid the DtS requirement of a stair is commonplace, as an additional stair would require an additional independent corridor to service the second stairwell to which may render a project unviable. This is because an additional corridor consumes ground floor space that reduces available floor area of each unit below that of the minimum thresholds under a by-law. Such 'increase in travel distance' solutions have commonplace in residential developments, especially given the NCC at DtS level is typically limited to 6 m before an additional stairwell is required (c.f. other jurisdictions such as New Zealand where a corridor length of up to 25 m is permitted until an additional stair is required under the same circumstances). Such problems to ground floor space may not occur for a square plot since the degree of ground floor corridor disruption is clearly less, especially where a long narrow rectangular plot can only access the street frontage via narrower width of the plot – a necessary condition for means of escape.

As development approvals and building designs are not mutually independent of each other from the prospective building owner's perspective but are legally independent. Any assumption made at the development approvals stage that cannot be rejected (e.g., an assumption that a commonplace fire PBD will be incorporated) can now fail under A2.2(4) simply because a stakeholder chooses not to agree (i.e., 'holds out'). Such 'holdout' problems are well-known in microeconomic literature and occur when permission of all involved parties must be obtained before an action can be made, with the negotiation process potentially dragging on indefinitely at the expense of a project's feasibility (in this case, the holdout problem can only be avoided if a DtS solution is adopted). Moreover, the holdout problem gives other parties (in this case 'stakeholders') monopoly power (Ogilvie and Carus, 2014), which encourages them to demand the maximum amount of benefits they can receive (e.g., excessive fire precautions, which can lower their exposure to liability in tort (Ehrlich and Becker, 1972)).

A2.2(4) gives rise to the holdout problem, since the building owner, unless they can get all stakeholders to agree to the analysis methodology to justify an extension of travel distance, the PBD will not proceed, regardless of whether the PBD meets the necessary substantive legal thresholds that the NCC prescribe for every performance criterion. Moreover, and as previously mentioned, no party, whether they be an entity of the Executive or the private sector, have a statutory right to effectively cause the holdout problem.

The consequences of the holdout problem are not trivial from the perspective of contractual liability, since to obtain finance for any development, one commonly needs to demonstrate to the financier (usually banks) that certain fiscally related criteria will be met e.g., a building being able to open within a specific timeframe, person(s) who have made a down payment on a residential unit at the development approval phase will receive what they paid for. Such fiscal arrangements occur under contract law, since these are agreements between members of the private sector. With the holdout problem now a characteristic of A2.2(4), breach of contract is a distinct possibility since specific performance may not be possible. And where specific performance is not possible, expectation damages become a legal entitlement for those whose contractual entitlements are breached. Such economic circumstances (e.g., breach of contract), described above, can only be avoided if DtS provisions are the chosen design pathway.

6.3 Reduced Innovation

Innovation, by definition, means doing something rival competitors have not, or are not, doing. The procedure to innovate obviously requires methodologies that have not in any way been repeated in the past (otherwise this would be emulation) with a result that is unique to that design. Innovation cannot occur with DtS solution, as DtS solutions are prescriptive. However, with a PBBC, innovation is obviously possible since a design's only requirement is that it meets or exceeds the relevant legal thresholds that are specified in a PBBC.

A2.2(4) creates the holdout problem, with the risk that any stakeholder may decide not to accept a methodology proposed by the designer for any reason. Any stakeholder may hold out until the cost of the PBD outweighs the cost of the DtS.

With these new procedural risks introduced into the NCC under A2.2(4), the best response to manage this risk is to avoid a PBD wherever possible. This then creates a cost to the developers of sites that were previously able to be developed to their maximum use no longer being able to do so.

Another factor associated with innovation is the right to protect intellectual property rights, often in the form of trade secrets. Trade secret law is not addressed in Australia in statutory law; however, a business's trade secrets can be protected via contract law. As A2.2(4) requires disclosure of the design procedure to all parties (stakeholders), there is no obligation for any stakeholder not under contract to not disclose any type of trade secret to a rival company. As trade secrets can therefore be disclosed to a rival company without the repercussions of breach of contract, any company wishing to see a return on its investment via trade secrets now has to compete with a rival company who can produce the same innovative solution but has not had to incur the cost of innovation. The net result is likely a move away from innovation.

6.4 Other Liability Risks

The purpose of a building code is not complicated. As described by Judge LC Rowe: "*a building code is concerned with the design and construction of buildings to meet specified objectives relating to such matters as the safety, durability, ventilation, sanitation of building to name a few*". The NCC is no different in this regard, where every performance clause in the NCC clearly states design requirements for buildings. Moreover, LC Rowe went on further to say that it is incorrect to suggest compliance with a building code depends to varying degrees on human agency or judgement. All NCC performance criteria reference design requirements for buildings and therefore set substantive legal thresholds that a design must meet. However, after its introduction, A2.2(4) of the NCC requires a PBDB, which, amongst other things, defines the criteria for acceptance of any relevant performance solution (as agreed by stakeholders). The NCC performance criteria does not state that design criteria are based on what stakeholders deem acceptable.

The liability risks here are that when forming a PBDB with stakeholders, even where parties agree to "the scope of work for the performance-based analysis, the technical basis for analysis, and the criteria for acceptance of any relevant performance solution as agreed by stakeholders", this design criterion may not result in a design that complies with the relevant performance clauses of the NCC. It is these performance clauses that must be adhered to.

6.5 Failure to Address Causative Factors

When some type of building failure occurs, as was the case with the Lacrosse Tower fire, it is the common law doctrines of negligence and nuisance that the courts consider, as there must be some type of actionable harm or damage before liability can be assigned. Australia's states and territories have largely adopted statutes that address these common laws (e.g., NSW's Civil Liability Act 2002), but they still closely resemble the common laws of negligence and nuisance.

The BCR report did not investigate any specific case of a building failure to determine causation, for example, defined under s 5D of the NSW Civil Liability Act 2002 as: *that the negligence was a necessary condition of the occurrence of the harm, and, that it is appropriate for the scope of the negligent person's liability to extend to the harm so caused*. It would not have been possible for the BCR's authors to establish causation, as this can only occur where the court sanctions the powers of discovery for one party to obtain the information held by the other party for a civil claim. And since causation is a key step in determining liability, there is no incentive for any party to disclose information that establishes causation, as this opens the door to civil claims. Thus, given the BCR did not have the legal authority to use the powers of discovery, it is difficult to see how A2.2(4) – an outcome of the BCR – in any way mitigates against future actions that may be a causative factor that results in harm. Moreover, the author, in a separate paper, has established that a causative factor that results in problems such as combustible cladding – the likely driver for the BCR – was the NCC itself, with deficiencies that did not adequately address the external vertical spread of fire.

7 Conclusion and Further Research

This paper has shown that National Construction Code clause A2.2(4), based on the IFEG, may be illegal. Not only does A2.2(4) lend itself to having characteristics of uncertainty and ultra vires, but it also allows the 'holdout problem' to operate, resulting in many prospective building owners preferring a DtS option over a PBD. Other issues, such as contractual risks and reduced innovation, are also likely to contribute to avoiding PBD. But perhaps the most concerning aspect of A2.2(4), is that it relies on a "stakeholder consensus" approach to determine what the acceptable design criteria must be, despite being legally defined by the performance criteria of the NCC, a matter that the Judiciary has already echoed its opinion on.

Concluding, as with any study on the legal soundness of delegated legislation, the issue under debate is hypothetical until tested in the courts, and as such theoretical implications are equally as debatable. On the practical front, should the courts be called on to review A2.2(4), in the opinion of the authors, A2.2(4) would be ruled invalid under judicial review. Moreover, an area for further research and publication, are the consequences of false or incorrect (negligent) design information supplied by a "stakeholder" who is not under contract. Under laws such as the Australian Competition and Consumer Act 2010, liability may not reside with the "stakeholder", but with the design consultant that adopts false or incorrect information.

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Perception of Usefulness of Building Price Data for Decision Makers in Australia

Anthony Mills[1*], Argaw Gurmu[1], Citra Ongkowijoyo[1], Wenying Yao[2], Alexia Nalewaik[3] and Imriyas Kamardeen[1]

[1]School of Architecture & Built Environment, Deakin University,
Locked Bag 20001. Geelong VIC 3220, AUSTRALIA
[2]University of Melbourne, AUSTRALIA
[3]American University, UNITED STATES

anthony.mills@deakin.edu.au; argaw.gurmu@deakin.edu.au; citra.ongkowijoyo@deakin.edu.au; w.yao@mbs.edu; dralexia@earthlink.net; imriyas.kamardeen@deakin.edu.au
* Corresponding author

Abstract:
The objective of this research was to develop a deeper understanding of user expectations of cost data published in Australia. The Australian Institute of Quantity Surveyors (AIQS) has been producing building price information for 60 years, in the belief that members find it useful. However, the quality and value of the data has never been examined. The research data was collected from a survey of industry stakeholders. The study revealed the AIQS cost data is perceived to be a robust and reliable indicator of the market. While respondents reported it has been occasionally used for a variety of purposes, including cost planning and benchmarking, the information was not extensively used by industry. The study sought to understand what was valued by users, and how construction cost data was used in business decision-making. The research offers new insight into the interplay between providers and users. The paper offers practical help to those involved in developing or improving construction cost information. It is also a step toward developing new ways of providing information, which creates a platform to promote the role of quantity surveyors (QS's) in the industry.

Keywords:
Building economics, Construction cost, Decision-making, Price indices

1 Introduction

This research was commissioned to review the usefulness of building price information currently published by the Australian Institute of Quantity Surveyors (AIQS). The aim of the project was to examine the value of building price data used by subscribers of the AIQS magazine. This included a review of price data produced in the past.

In 1971, AIQS was formed by a merger of two quantity surveyor professional institutions. Prior to merging, both the Institute of Quantity Surveyors of Australia (IQSA) and the Australian Institute of Quantity Surveyors Incorporated (AIQS Inc.) realised the importance of producing regular publications to promote the interests of the profession. (AIQS, 2008) . The Building Cost Index (BCI) and Current Construction Cost that currently appear in the AIQS journal have their origins in the earlier journals produced by both former QS (quantity surveying) institutions (AIQS, 2008).

The current AIQS Building Cost Index (BCI) includes data for five Australian cities, and an average weighted index (AWA) and covers the period from 1971 to the present. The index also includes a forecast for one-year ahead, based on "expert" opinions of local AIQS state representatives. AIQS states that the index is produced as a matter of interest to readers and subscribers, and is not intended to be relied upon for costing any building project. The research team were asked to consider how useful the information is to subscribers of the AIQS magazine. In addition, the research brief also required insight into how the data can be improved.

2 Literature Review

The outlook for construction price has a significant impact on investment decisions in construction projects (Wang et al., 2013). The accurate prediction of building prices facilitates more accurate bids and helps prevent under or over-estimation (Ashuri and Lu, 2010). Even a small improvement in the accuracy of forecasting building prices can have a large impact on multimillion-dollar projects (Shahandashti and Ashuri, 2013). Moreover, predicting construction prices as accurately as possible is essential, considering the low-profit margin in construction budgets.

Building price data is essential information used in the construction industry by both owners and contractors, and has several elements of importance. Firstly, building price information supports contractors and their supply chains by generating price information used to guide construction budgets for the client (Robson et al., 2016). Secondly, it is used by various stakeholders (e.g., builders, contractors, and owners) during preliminary costing practices to understand the trends of building pricing, which then supports pricing and cost control in rational decision-making. Thirdly, building pricing is an important aspect in controlling supply and demand within the industry. Fourthly, a building price index can be used to mitigate unnecessary economic losses from speculation by developers and builders.

In Australia, commercial building price is one of the most direct and scientific reflections of construction industry conditions. As such, building price fluctuates with the impact of the domestic economy, the degree of competition in the market, and other factors. Approximately one-third of contractors believe that variability in construction price is one of the most important risks that impact their profits (Ervin, 2007). Moreover, construction price movements have adverse impacts on both public and private owners (Shahandashti and Ashuri, 2013).

Construction worldwide is criticized for its high price and low predictability (Best and Meikle, 2015). Further, this issue is exacerbated by the frequent fluctuation of building prices, which is often difficult to forecast (Wang et al., 2013). Therefore, the development of a robust scientific forecasting model of building price is needed. The construction of an accurate and reliable building price index is critically important for practitioners to understand the movement in the construction market, as well as in the broader economy, in order to limit exposure to risk (Liang et al., 2018).

According to (Yu and Ive, 2008) the reasons for utilising construction price data are fourfold:

- deflation of building sector components of the nominal national product;
- capturing relative price change and inflation in the building industry for assessments and forecasting of market conditions
- updating historical cost data for cost planning and estimating

- international or intersectoral comparisons of the level and growth of price, real output and productivity.

The inability to predict building price in a timely manner can undermine the value of capital investments. Indeed, owners and contractors make key strategic decisions about individual projects and capital investment programs based on forecasted prices. Therefore, the ability to have timely and accurately forecast of building price is fundamental for efficient construction industry (Flyvbjerg et al., 2002, Grau et al., 2014, Oberlender and Trost, 2001, Isidore and Back, 2002, Mulva and Dai, 2012, Back and Grau, 2013, Kim and Reinschmidt, 2011).

2.1 Other Sources of Building Price Data

AIQS has been publishing cost information for many decades; however, in that time, many other firms have also commenced producing similar information, both in Australia and overseas. As a result, the market has expanded with many organisations producing building price information as an advisory service or for promotion of the firm. This appears to be an international trend. Many organisations prepare and publish construction cost data for a variety of reasons.

A desktop study was undertaken to understand the rationale and context of each provider, this was then used to classify into a particular category. The Provider information collected included; a brief history of each publication, their objectives, types of information published, publication frequency, and other relevant information (Table 1).

Table 1. Characteristics of Providers

Provider Type	Data produced	Data source	Provider Examples
National Statistics Agencies	Official statistics used by government for guiding economic policy	National surveys of industry.	• Australian Bureau of Statistics • Office of National Statistics, UK. • US Bureau of Census, USA
Professional Societies and Institutes	Cost and price data of interest to clients and industry players	Building prices and Forecasts based on sentiment surveys	• Australian Institute of Quantity Surveyors (AIQS) • Building Cost Information Services (BCIS), UK
Industry Associations	Cost and price data of interest to clients and industry players	Forecasts of official government statistics, eg ABS	• Australian Construction Industry Forum
Subscription-based Providers	Comprehensive data information service providers comprising Building Unit costs, Cost per area by building type, and Price Indices,	Internal database from network of QS professional offices	• Rawlinsons (Australia) • RS Means (USA) • Marshall and Swift (USA)
Marketing-based providers	Cost and price data of general interest to clients and the general public	Internal database from network of QS professional offices	• Rider Levett Bucknall (International Consultants) • Turner and Townsend (International consultants)

The ABS is an example of a National statistics agency; producing a range of price information related to the economy. The ABS is the official government authority charged with data collection, and is the most reliable measure of statistics in Australia. The ABS construction series collects information that relates to Producer Prices, comprising labour, material prices and price deflators for adjusting construction activity data across a range of building types.

The Australian Construction Industry Forum (ACIF) is an example of an industry association and lobby group. They produce a range of forecasts of building activity for various building types. The information relates to the value of work done (activity) and is not price data. However, the activity forecasts have strong links to price, and the data is produced for each capital city in Australia, making it a useful guide to the prediction of price demand (ACIF, 2021).

Rawlinsons' price book is an example of a subscription-based information service. The first edition was published in 1983 from cost data collected by firms associated with the Rawlinson's Group. As a QS consulting group, this was actual historic price data that was assembled from past projects, which was then used to provide their clients with cost plans for future projects (Rawlinson, 1991). The book is published annually and is intended to provide detailed cost information to those who purchase the book. The editors state in the introduction that every item of the thousands of prices in the detailed Unit Price section has been "individually analysed in sufficient detail to allow the effect of the previous year's cost adjustment, both in scope and emphasis to be accurately allocated to those particular activities as opposed to the convenient "across the board" adopted by some analysts". The Handbook is intended to provide information necessary to implement cost control, cost management, and cost-benefit studies effectively at all stages of planning and construction (Rawlinson, 1991).

The final category is marketing-based providers. This comprises several private firms that provide construction cost services to their clients. In this context, the majority are consulting quantity surveying (QS) firms. For instance, Rider Levett Bucknall produces the annual Riders Digest, which is a compendium of high-level building costs and indices, and Turner and Townsend provides a cost index comparing a range of international cites. The information produced is provided free of charge and is produced to market consulting services to their clients.

Past experience with the cost data has shown the collection of raw data s the single biggest challenge in maintaining the databases. Rawlinsons has noted that it spent 2,500 hours in research and formal planning for the first edition construction cost handbook. The AIQS cost information comprises 1,500 items of cost data for each of six Australian cities (1,500 x 6 = 9,000), which requires a considerable effort to update. While AIQS member firms have considerable goodwill towards AIQS, they do not derive any financial benefit from updating the data collection. The onerous collection of data, requiring a 12-week turnaround for publication, creates a substantial demand for volunteer time and resources.

The research team and reference group carefully considered the ongoing publication of existing cost data in its current format and scope understanding that, if change was deemed necessary, the design of a new collection process would need to be decided upon, including the type and style of outputs. The next section of this paper describes how the research data was collected in order to examine the value of the cost data to users and explore the types of information that are most useful in making business decisions.

3 Research Methods

This research used a two-stage exploratory approach to collecting the data; the first stage used semi-structured interviews of end users to understand their needs, and the second stage was an online structured survey of users of the AIQS data. Semi-structured interviews are a verbal interchange where one person, the interviewer, attempts to elicit information from another person by asking questions. Although the interviewer prepares a list of predetermined questions, semi-structured interviews unfold in a conversational manner offering participants the chance to explore issues they feel are important. (Longhurst, 2010). Semi-structured was considered most appropriate considering that there were a limited number of viewpoints in this context. To explore the issues, a set of questions were developed based on the overall objectives of the research project.

To select the participants, an experienced building construction expert was contacted and asked to nominate other experienced professionals who may be willing to participate in the interviews. A broad panel of users were identified, who had (1) knowledge or expertise in using construction cost data, and (2) extensive experience in the construction industry. After contacting several suitable individuals, four persons were identified and each had diverse viewpoints on the AIQS cost data.

Table 2. Interviewee Characteristics

Interviewee Code	Perspective
A	Professional QS is a director of an international consulting firm
B	Building estimator/Cost planner who worked for a major construction company
J	Former state public servant who ran the government's cost planning department
N	Building consultant, arbitrator, adjudicator, and expert witness, who consulted to clients involved in building disputes.

All the expert professionals had between 15–50 years of work experience and were recruited on a voluntary basis in compliance with the research ethics policies of Deakin University. Interviewees were all qualified QS’s and AIQS members; each candidate was selected based on their different perspectives (See Table 2). They each had an understanding of the usefulness of information, and also were aware of similar price data that was published by other sources. The semi-structured interviews each lasted between 40 and 60 minutes, and each interview was recorded and transcribed

Results from the first stage informed the questions that were included in the structured questionnaire. Online survey questionnaires were used for their advantages in obtaining responses from a geographically dispersed sample. The online survey was distributed in October 2021. Participants were approached through email invitation and social media recruitment. This survey is categorised as cross-sectional as it occurred in one session.

Questionnaires were tested and reviewed before being distributed to respondents through pilot surveys to ensure the questions would be clearly understood and there would be no ambiguities. For this research, the questionnaire consisted of close-ended questions with multiple choice answers, and Likert Scale questions measured the level of respondent's opinion towards the statement. There were 212 responses received at the end of the data collection period. There were 20 incompletely-answered questionnaires by the respondents. Therefore, a total of 192 valid questionnaires were collected. There are approximately 2000 subscribers to the AIQS magazine, hence the response rate was about 10% of all possible users.

Three demographic dimensions were asked in the survey (refer to Table 3), which were gender, Age, and Employment Type. Table 3 shows the descriptive analysis of respondents' demographic background. The majority of respondents were Male (77%) compared to female (19%). In terms of the type of employment, 67% worked for QS consulting firms, followed by 15% for Main Contractors; the remainder were self-employed QS, or worked for Building Owners, Government Agencies, and subcontractors.

Table 3. Respondent Demographics

	Demographics	Frequency	Percentage
Gender	Male	148	77%
	Female	36	19%
	Unspecified	1	1%
	Prefer not to say	6	3%
Age	20-30	31	16%
	31-40	47	25%
	41-50	38	20%
	51-60	38	20%
	61+	33	17%
	Prefer not to say	3	2%
Employment Type	Professional QS consultancy	128	67%
	Main Contractor	29	15%
	Subcontractor	1	1%
	Government Agency	9	5%
	Building Owner	1	1%
	Self-employed consultant	12	6%
	Other	11	5%

The next section examines the results of the survey and explains how that will impact the usefulness of the data produced by the AIQS.

4 Findings and Discussion

This section discuss the findings that emerged from the survey. As previously mentioned, prior to undertaking a survey, a series of semi-structured interviews were conducted which highlighted several themes. In general, they were divided into broad categories, namely; i)

What do users see as the value of the information? ii) Is the information considered trustworthy and reliable? iii) How do you use the Unit Price, Square Metre Rate, and Building Cost Index? and iv) what should be changed or added to improve the data?

4.1 What is the Cost Information Used for?

The survey asked respondents to consider whether the AIQS cost data was useful and to state how the information was used. It became clear from the responses, and the free text comments proved, that the AIQS cost data was not used as a primary source. Most of the respondents were QS's who had access to their own internal databases of costs. This information was considered to be the most reliable source of data. The results (Table 4) showed that the AIQS information was mostly used to benchmark costings for cost planning (39%), for assessing subcontract tender prices (17%), and variations (16%).

Table 4. Purposes of AIQS cost data

Question	Response	Frequency	Percentage
What purposes do you use cost per unit data?	Assessing tender prices	40	14%
	Price check on subcontract prices	47	17%
	Guide for cost planning	109	39%
	Check of pricing of variations	44	16%
	Calculation of cash flows	10	4%
	Other	28	10%
	Total	278	100%

4.2 Is the Data Considered to be Reliable?

There was no specific question that asked respondents to rate the reliability of the AIQS cost data. However, there were many opportunities for respondents to provide free text comments. This was taken up enthusiastically by those surveyed, which provided good insights into their perceptions. While some respondents embraced the AIQS data and believed it was useful, there were also many critics (Table 4). The comments indicated that the data was considered valid in legal cases. Respondents suggested the stakeholders did not question the reliability of the data itself but were likely to consider the context in which the information was applied.

Table 4. Comments from survey respondents

Positive Comments	Negative Comments
The AIQS data is very useful because it is consistently updated each quarter; no other source provides that level of currency.	Rawlinsons has more types of information and generally, I have found it to be more accurate and reliable
The AIQS is not my first reference guide for construction costs but is in my top 3, I use it for benchmarking data to confirm cost plans & estimates. I see the AIQS as the most up-to-date pricing manual	I occasionally used it for benchmarking, but our own database represents the real prices for the types of projects and locations we work on
Useful for pricing and validating (legal) Expert Reports	In my opinion, the rates are not reflective of market rates, they are too high
It is only a reference point for comparison/trend etc. and instead locality and project specifics are more important, especially when working across a variety of different markets	Very sparse in detail and contains no indication of how the cost is collected or updated, a simple cost index update is not enough.

Many respondents suggested that the data was reliable, but indicated it would not be a substitute for cost data that they derived in-house from their own projects. The information in the magazine was believed to be credible but was defined in such a way that users did not know what project(s) it was based on. As a result, there was some suggestion that, because the data sources were not explicitly identified, the prices tended to be generous. As a result, the AIQS information was at best considered a guide to the cost of construction and not an accurate indicator of any particular project. Nevertheless, there was a general consensus that the AIQS was highly professional and had a good reputation for producing cost data. However, many comments suggested that respondents did not use AIQS as their primary source of cast data, and further, if there was a gap, Rawlinsons data was their next choice.

4.3 How Useful are the Building Cost Index, Unit Price, and Square Metre Price?

The third round of questions asked each respondent to comment on the AIQS Building Cost Index (BCI), Unit Prices, and Square Metre Prices. The cost data is updated by a coordinator, based on the opinions of an expert group who meet each quarter to discuss price movements.

4.3.1 Building Cost Index

The Building Cost Index (BCI) is a price indicator which represents the inflationary costs of building over time. The AIQS has the base year of 1974 and contains indices for six Australian cities. The publication also contains an Australian Weighted Average index which is supposed to represent the cost increase of the whole nation, and can be used for international comparisons. The BCI is also forecasted for one year, which is supposed to indicate the level and direction of future price movements. Respondents (Table 5) indicated that the BCI was an important piece of information published in the AIQS magazine. One comment stated that the Building Cost Index was a “trusted reference, often used in Expert Reports to escalate or backdate expert reports” The results (Table 5) show that most respondents (57%) agreed that the BCI was useful; however, a surprisingly large group (15%+28%= 43%) were either in disagreement or were circumspect about its value.

Table 5. Value of the cost data to users

Question	Agree/Disagree	Frequency	Percentage
I find the Building Cost Index useful in my job	Disagree/Strongly Disagree	27	15%
	Neither Agree or Disagree	51	28%
	Agree or Strongly Agree	104	57%
I find the Unit Price data useful in my job	Disagree/Strongly Disagree	31	21%
	Neither Agree or Disagree	36	24%
	Agree or Strongly Agree	82	55%
I find the Cost/M2/GFA for each building type useful in my job	Disagree/Strongly Disagree	20	13%
	Neither Agree or Disagree	25	17%
	Agree or Strongly Agree	104	70%

4.3.2 Unit Prices

The Built Environment Economist (BEE) magazine publishes a large number of individual cost items for small details of work. These are known as Bills of Quantity rates, or Unit prices. The prices represent low-level tasks, such as the cost of painting a plasterboard wall ($/m2), or the price of pouring concrete into a footing ($/m2). There are 1,400 lines of data for each of the six cities, comprising 8,400 separate prices, which are updated quarterly.

The results (Table 5) show that this information was considered useful by respondents, but not overwhelmingly so. Only 55% indicated that they use the information, and the remainder did not consider it useful. Many comments addressed the issue by saying that they either don't use the data or lack confidence in it. It would be reasonable to assume that this data was the most difficult to update, due to the vast volume of data published.

4.3.3 How useful is the cost per Square Metre Area/GFA?

The Square Metre Area data published refers to the full price of the buildings by type. The prices are expressed as the price for each square metre of Gross Floor Area (GFA). The AIQS publishes information on 130 different building types, ranging from residential buildings to high-rise office buildings. The results (Table 5) show that this information was considered useful by most respondents (70%). This information is at a high level, comprising the cost of the entire building ($/M2/GFA) It is prepared using a standardized international cost planning method (ICMS, 2017) and can be directly compared with similar buildings in other cities and countries.

It is not surprising that this data was typically used as a cost-checking mechanism against other cost models. One respondent stated, "I am a regular user of the Current Construction Costs section of the Built Environment Economist and a very strong supporter of it, however: the per unit figures for flats/apartments are so wrong it demeans the whole document." This strongly suggests that the data is being viewed critically by the respondents. Other comments suggested that the data was a useful benchmark in circumstances where their internal database did not contain information on an uncommon building type.

The last theme asked respondents to consider if there was any information not currently produced that would be useful. A number of comments were made about difficulty of obtaining the cost building work of a specialist nature. In particular, they mentioned vertical transportation, mechanical, and fire services. They suggested that industry specialists should be engaged to advise on the nature of costs and the direction of future price movements.

The survey also asked about forecasting the BCI. The AIQS currently forecasts the index for one year in advance. Respondents indicated that, because of the time taken to design and plan most buildings, two or more year forecasts would be more useful.

The next section draws together some conclusions, and makes suggestions for future consideration.

5 Conclusion and Further Research

Respondents did believe AIQS is highly professional and has a good reputation for producing price data, and the survey showed that the AIQS cost data was useful to some stakeholders. The unit price information was not widely used, with one respondent suggesting that he had never seen it used. On the other hand, respondents reported the Square Metre Rates (by building type) were valuable and mostly used as benchmarking information against their own internal databases. The Building Cost Index was of interest to many quantity surveying professionals and to the industry more generally. One respondent commenting that, even if the index did not move, it was useful to know the market was flat. As a result, it was clear that the Building Cost Index was widely utilized for benchmarking and against other suppliers of similar information eg. Rawlinsons.

The way forward is not clear. The current publication of cost data in the Built Environment Economist publication has been a feature of AIQS for over 60 years. In that time, other competitors have entered the market, and potentially provide a better service. The dominant industry provider is Rawlinsons, which contains a much larger range of data, which some believe is more accurate. Rawlinsons price book is an example of a subscription-based information service. It is unlikely that the AIQS can compete with them on the large-scale production of cost data. However, the role of the AIQS as an professional association is very different. Other organisations (e.g. ACIF) use their influence to lobby various parties about the importance of the construction sector. The AIQS's role is to promote its members and comment on issues confronting the profession. So, it is reasonable to suggest that it should provide commentary on building costs to stakeholders or media, who are outside of the QS profession.

This research suggests that information that assists industry decision-makers should be the focus of any future data provision. That information needs to be at a high-level, (eg. $/M2/GFA), and easily understood by users. Finally, industry would benefit from some insight into the reason there is movement of prices, and a rationale for why the change has occurred. If the above can be done, the AIQS is likely to improve an understanding and appreciation of the services offered by quantity surveyors.

6 Acknowledgement

The authors would like to recognise the generous assistance of AIQS, who provided funding for this research. In particular, we would like to highlight the support of Grant Warner, Mark Chappe FAIQS, CQS, Stephan Warne FAIQS, CQS from the AIQS Board. In addition, the authors would like to acknowledge the expert professional advice from; Adam Robinson MAIQS, CQS, Domenic Schiafone MAIQS, Hugh Mackie MAIQS, CQS, Bradley Marino MAIQS, CQS, John Stranger FAIQS, John Drillis FAIQS, CQS, and Norman Faifer FAIQS, CQS,

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Do Australians Dislike Chinese Investment in Australian Infrastructure Sector?

Yongjian Ke[1*], Liyaning Tang[2] and Changqing Zhai[3]

[1]School of Built Environment, University of Technology Sydney
Ultimo NSW 2007, AUSTRALIA
[2]School of Architecture & Built Environment, University of Newcastle
Callaghan NSW 2308, AUSTRALIA
[3]Australian Artificial Intelligence Institute, Faculty of Engineering and Information Technology, University of Technology Sydney, Ultimo NSW 2007, AUSTRALIA

yongjian.ke@uts.edu.au; maggie.tang@newcastle.edu.au; changing.s.zhai@student.uts.edu.au
* Corresponding author

Abstract:
Chinese investors feel discriminated against by Australian officials and the mainstream media, and some case studies validated the Australian anxiety and discourse on China. But it is unknown whether the general public holds the same attitude. This research hence aimed to examine the public perceptions of general Australians on Chinese investment in Australia on social media. The infrastructure sector was chosen to study, and the Twitter platform was chosen for data collection. We used Python to retrieve tweets from Twitter accounts with Australian IP addresses using pre-defined relevant keywords and a time range from 2009 to 2021. After cleaning the data, there were 5110 tweets on Chinese investment in Australia and 498 tweets about Chinese investment in the Australian infrastructure sector. A sentiment analysis was then conducted. It was found that the general public is not sharply against but slightly towards Chinese investments in the Australian infrastructure, as evident by the result that there are more positive tweets than negative ones. A noticeable decrease in sentiment was seen in 2016 due to a discussion on the lease of Darwin Port to China and in 2021 because the Federal government teared up Victoria's Belt and Road agreements with China that year. This study contributes to practice by validating the potential of using social media to monitor the public perception of a specific topic in the infrastructure sector.

Keywords:
Chinese investment, Infrastructure, Public perception, Sentiment analysis

1 Introduction

Australia-China relations have hit the lowest ebb in decades. According to Khalil (2020) on BBC News, a turning point was in 2017 after the Australian Security Intelligence Organisation warned of growing Chinese attempts to influence decision-making in Canberra. Anger and mistrust between these two countries have been accumulating since that. Correspondingly, Chinese investment in Australia peaked in 2016 and continued to decline from 2017 to the current (KPMG and University of Sydney, 2016, 2017, 2018, 2019, 2020, 2021, 2022).

The outlook for Chinese investment in Australia became mixed and uncertain, with a shift in sentiment among Chinese investors towards more pragmatic business attitudes compared to the more lofty bilateral ambitions expressed in previous years (KPMG and University of Sydney, 2022). In other words, when deciding whether to invest in Australia, Chinese investors would take into account business factors such as investment environment, return on investment, exchange rates, and tax rates more than political ones. This is, to some extent, different from investment scenarios when Chinese investors invest in other countries, especially in the Belt

Road Initiative countries - representing a newly ambitious Chinese drive into the global politics (Narins and Agnew, 2020).

Although the government officers claimed that Australia's policies on screening do not discriminate against Chinese investments, McCarthy and Song (2018) delivered an opposite message by exploring Australian anxiety and discourse on China via six Australian case studies. Mainstream media has been expressing the same anxiety toward Chinese investment. It is unknown whether the general public holds the same attitude. This research hence aimed to examine the public perceptions of general Australians on Chinese investment in Australia.

2 Literature Review

KPMG and the University of Sydney (2016, 2017, 2018, 2019, 2020, 2021, 2022) conducted a series of studies on demystifying Chinese investment in Australia, which paint a clear picture of changes in Chinese investment in Australia over recent years. Chinese investment in Australia rose substantially in 2015 with a 59.5 percent increase in AU$; 2016 saw the highest Chinese investment inflow to Australia since the 2008 peak, and Chinese investment in Australia increased by 11.7% from 2015; Chinese investment in Australia declined by 11% in 2017, dropped to AUD 8.2 billion in 2018 – down by 36.3% from 2017, fell 58.4% to AUD 3.4 billion in 2019, declined by 26.8% in 2020 to AUD 2.5 billion, and further dropped by 69.8% to AUD 0.8 billion in 2021. The outlook for Chinese Investment in Australia has been a concern.

There is no doubt that Australia-China relations play a vital role in the changes in Chinese investment in Australia. Besides this, studies have been carried out to examine other influencing factors. Zhou (2017) argued that the level of liberalisation and protection provided by the China-Australia Free Trade Agreement for Chinese investment/investors is limited, and it was China's 'Go Global' policy and the investment complementarity between the two economies that had driven the rapid growth of Chinese investment in Australia over the decade. Bath (2012) examined the overview of Australia's foreign investment regulation and highlighted that in Australia's policies on screening, Chinese investments are not discriminated against.

However, McCarthy and Song (2018) explored Australian anxiety and discourse on China via six Australian case studies, which delivered the opposite message. Their first case study on Chinalco's bid for Rio Tinto showed that when Chinese companies adopt the same takeover practices as other international firms, they are constructed as being threateningly dissimilar and not conforming to a homogenising capitalist logic, in contrast to Australian corporations. Their other case studies on private real estate investments, Cubbie Station sale, Kidman estate sale, and the leasing of the Port of Darwin to Chinese private company Landbridge all contended that China's rise had created intense anxiety over its forms of capitalism and its political regime. The authors also argued that Australia requires a new collective imagination, especially at the political level, to appreciate China's Non-Western distinctiveness and to dispel Australia's instinctive angst over China's rise.

Mainstream media has been expressing the same anxiety toward Chinese investment. Examples include Seidel (2021) on news.com.au mentioning, "It was meant to be China's moment to squash Australia but instead it's been labelled a 'spectacular failure'"; Galloway and Wright (2021) on the Sydney Morning Herald discussing Australia's plan to boost foreign investment without focusing on China; Karp (2021) on the Guardian presenting a few major Chinese deals that the federal government has blocked, including the proposed sale of Australia's largest landholder, S Kidman & Co, which comprises 1.3% of Australia's total land mass, the proposed $600m takeover of Lion Dairy, and a $300m bid for a major Victorian construction contractor; Butler (2021) on the Guardian reporting the way by the Foreign Investment Review Board to find Australia's sweet spot between blocking China and driving foreign investment.

The political environment and public opinion on mainstream media have been confirmed to be negative for Chinese investments in Australia. This led to the question of whether the general public holds the same attitude. Laurenceson et al. (2019) conducted a choice modelling analysis of original survey data to determine the drivers of local public preferences, which indicated that the Australian public is found to be more concerned by the share of foreign ownership an infrastructure investment would bring rather than the fact it is from China. A limitation of their study is that the results only reflect the determinants of public opinion in Australia at the particular time the survey was undertaken and from those respondents involved in the survey.

This study attempted to improve and propose a tool using social media for examining and monitoring public perceptions of general Australians on Chinese investment in Australia. The potential of using social media to examine public perceptions of a topic has been validated by previous research (Tang *et al.*, 2017, 2020; Mathur *et al.*, 2021; Melton *et al.*, 2021; Zulfiker *et al.*, 2022). Tang et al. (2020) discovered similarities and differences in the construction industry in China and the United States by using data analytic tools on data crawled from social media platforms. Mathur et al. (2021) reported on an exploratory study on how social media could provide an opportunity to evaluate benefits qualitatively by analysing tweets from metro rail projects in India and Australia. Melton et al. (2021) conducted a sentiment analysis on textual data collected from 13 Reddit communities focusing on the COVID-19 vaccine. Zulfiker et al. (2022) also used social media data to analyse the views of Bangladeshi citizens regarding the COVID-19 vaccines and the vaccination campaigns.

3 Research Methodology

This study aimed to examine the public perceptions of Chinese investment in Australia on social media. The infrastructure sector is chosen to study because Australian public support for foreign investment in infrastructure is limited. Infrastructure investment can bring significant economic and social benefits but, at the same time, can create domestic political challenges. It is imperative to embrace public support for overseas investors to deliver an infrastructure project in Australia successfully. The Twitter platform was chosen for data collection because it has a free search application programming interface (API) to collect relevant tweets matching a specified query. Unlike other social media platforms, almost all tweets are public and pullable. It serves well for this study.

Two research questions were set:

- Whether is Twitter an appropriate tool to monitor public perceptions of Chinese investment in Australian infrastructure? The data collection method adopted by Laurenceson et al. (2019) is a survey targeting Australian citizens. The survey data are more focused on the topic so that the results can be analysed directly. Relatively, tweet content may not be directly relevant. Careful content analysis is required to reflect the perceptions behind the content. It is necessary to investigate what perceptions we can obtain from tweets.

- What are the opinions expressed by Twitter users about Chinese investment in Australian infrastructure?

We used Python to retrieve tweets using pre-defined relevant keywords and a time range from 1 January 2009 to 31 December 2021. The unit of the period was set as one year; hence, the end date was 31 December 2021. The start date of 1 January 2009 was chosen because it was the earliest date available through the search API. The full-archive search endpoint was used to collect data from Twitter accounts with Australian IP addresses. The limitation is that Australians living overseas would be excluded because their IP addresses are not in Australia, and foreigners living in Australia would be included because their IP addresses are in Australia.

We carried out the first round of searching using a combination of keywords "(China OR Chinese OR Beijing) and (invest OR investment OR FDI OR deal OR bid OR acquisition OR acquire OR buy OR purchase OR sale)". The first bracket includes keywords denoting China, and the second includes keywords relevant to investment. The tweets from the first round of searching (hereinafter referred to as "short keywords") are related to Chinese investments in Australia in general. Another round of searching was then conducted, adding one more bracket of keywords relevant to infrastructure, i.e. "(infrastructure OR megaproject OR construction OR port OR road OR land OR asset OR mining OR healthcare OR energy OR metro OR rail)". The search results in the second round of searching (hereinafter referred to as "long keywords") are tweets discussing Chinese investment in the Australian infrastructure sector.

The original tweet text may include useless information such as numbers, punctuation, hashtag, and other special characters. Such information was removed at the data cleaning stage. After cleaning the data, sentiment analysis was conducted to examine the public attitude towards Chinese investment in Australian infrastructure over time. Natural Language Toolkit, a toolkit for natural language processing in Python that provides a group of text processing and sentiment analysis libraries, was used to determine "Negative", "Positive", or "Neutral" for each tweet based on sentiment words used in the tweet. Because the neutral sentences in the tweets are less informative for this study and thus, they were filtered out in the presentation. Examples of negative, positive and neutral tweets are shown below:

- Negative: "*China's mass aussie investment was a part of the 50 yr Belt & Road plan idiotic government's focused on naive money, it should have been seen as a trojan horse. Prioritising Sovereignty has been a monumental govermental failure a new strategy is nessesary*"
- Positive: "*Fears of China buying up the country run deep, with opportunistic politicians and commentators long showing a willingness to not let "facts" get in the way of the truth. And the facts are that: China's land interests are predominantly leasehold*"
- Neutral: "*The announcement that a Chinese construction company (Jangho Group), has offered $2 billion to buy out the dominant Australian health clinic chain Healius has me wondering how this will impact the model of General Practice in Aus?*"

4 Findings and Discussion

The search for tweets using short keywords returned 5110 results, while using long keywords returned 498 results. Figure 1 presents the results per year returned using short and long keywords. No tweets were returned from 2009 to 2013 when searching with long keywords, and only two results were received using short keywords. This is likely because Twitter does not have much data in its database before 2013. We then delimited the scope of discussion to the time range from 2014 to 2021. In both rounds of searching, the number of results peaked in 2020.

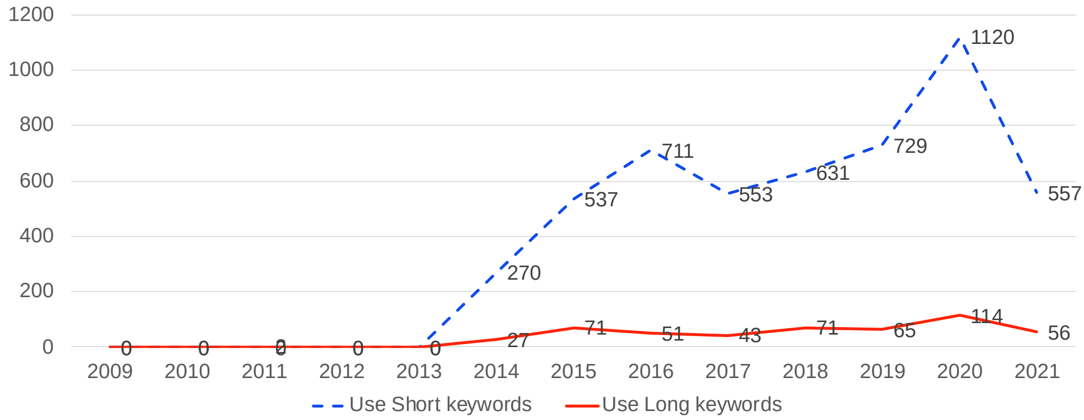


Figure 1. Tweets Counted by Year

The sentiment analysis results are shown in Figure 2, the upper figure of which presents the sentiment trend over time of public perception of Chinese investment in Australia, while the lower figure of which looks at Chinese investment in the Australian infrastructure sector. The results show that the sentiment trend based on all tweets about Chinese investment in the infrastructure sector is consistent with that about Chinese investment in general. The number of positive tweets is slightly greater than that of negative tweets.

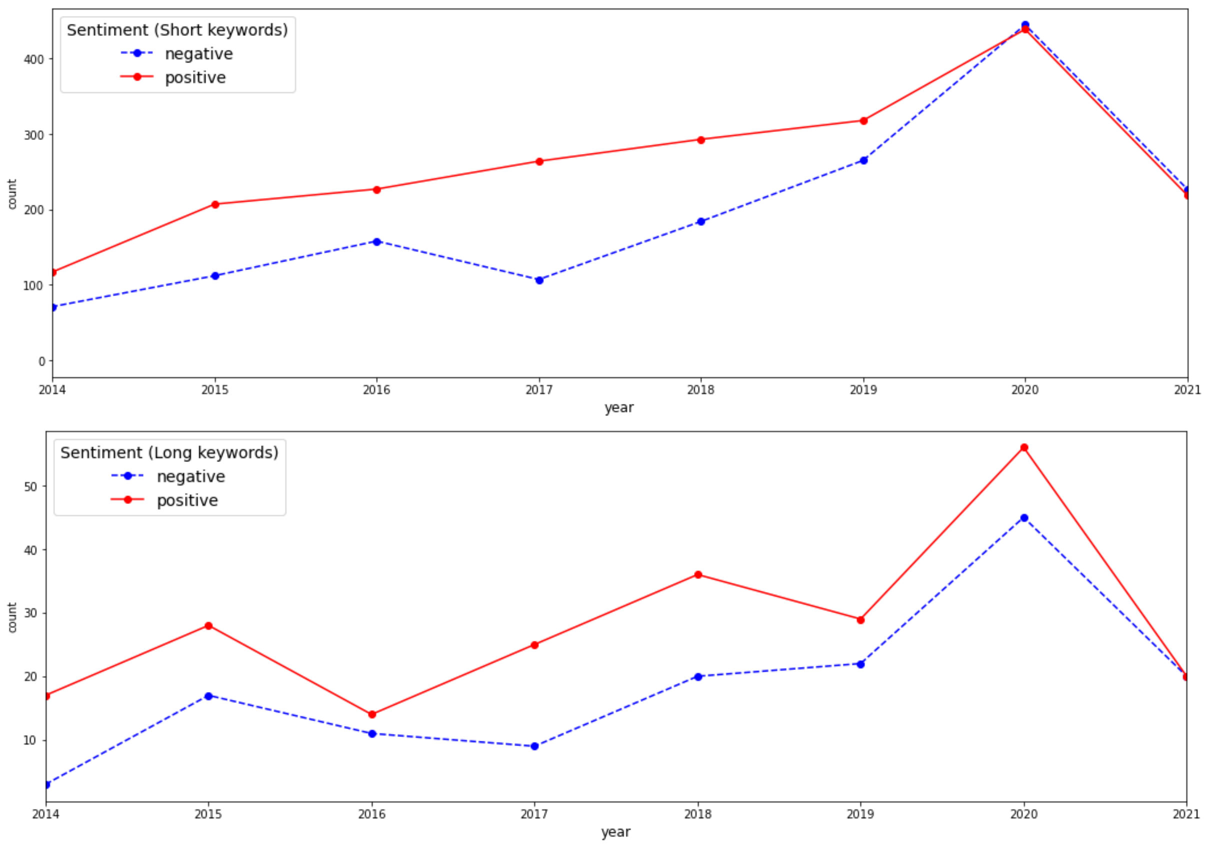


Figure 2. Yearly Sentiment Trend of All Tweets

It is noticeable that the results returned include tweets posted by verified accounts. Figure 3 shows the percentages of different account types in both rounds of searching. The types of accounts Twitter currently verifies are those from government, news organisations, individuals in news & journalists, companies, brands & organisations, entertainment, sports & gaming, activists & organisers, and content creators & influential individuals. Some of these verified accounts belong to individuals and post tweets that reflect these individuals' perspectives and opinions. But many other verified accounts are the official accounts of governments, organisations, and other entities. The tweets from such accounts represent the voice of organisations, such as mainstream media's opinion. These tweets do not the scope of this study and hence should be removed from the analysis.

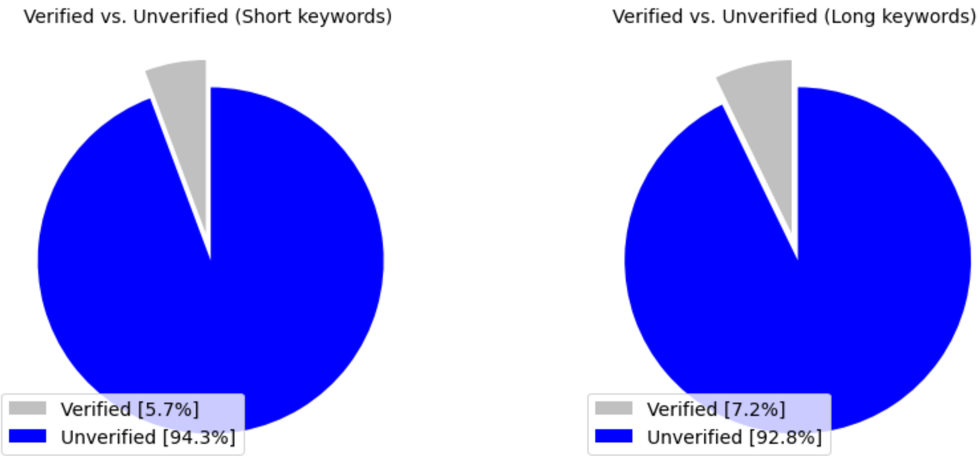
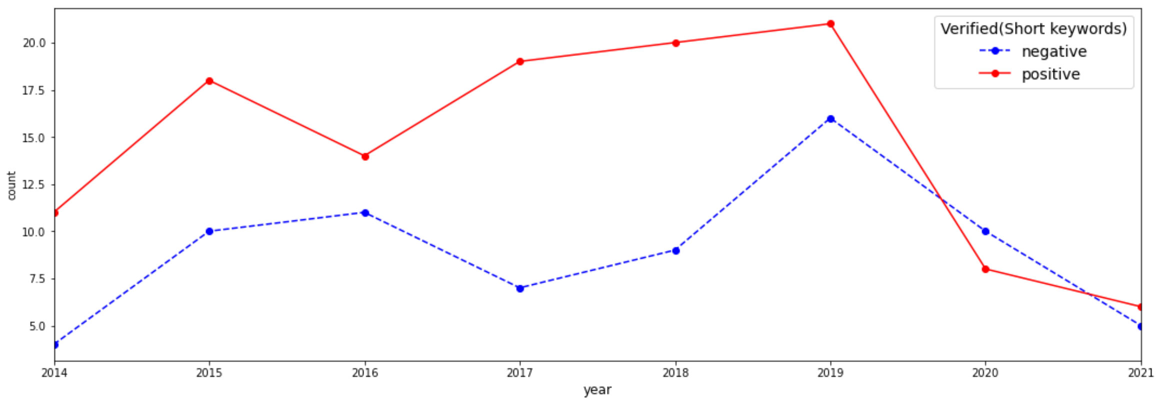


Figure 3. Percents of Different Account Types

We then divided the results into two sets, one from verified accounts and the other from unverified accounts, which are presented in Figures 4 and 5. Based on verified accounts' tweets and shown in Figure 4, the sentiment trend demonstrates a significant change over time, especially on the topic of Chinese investment in the infrastructure sector (i.e. the lower figure using long keywords). However, the small number of tweets should be considered in Figure 4 because one or two tweets can lead to a sharp change in the figure. In addition, as explained above, tweets from verified accounts may not reflect individuals' perspectives and opinions and are out of the scope of this study.



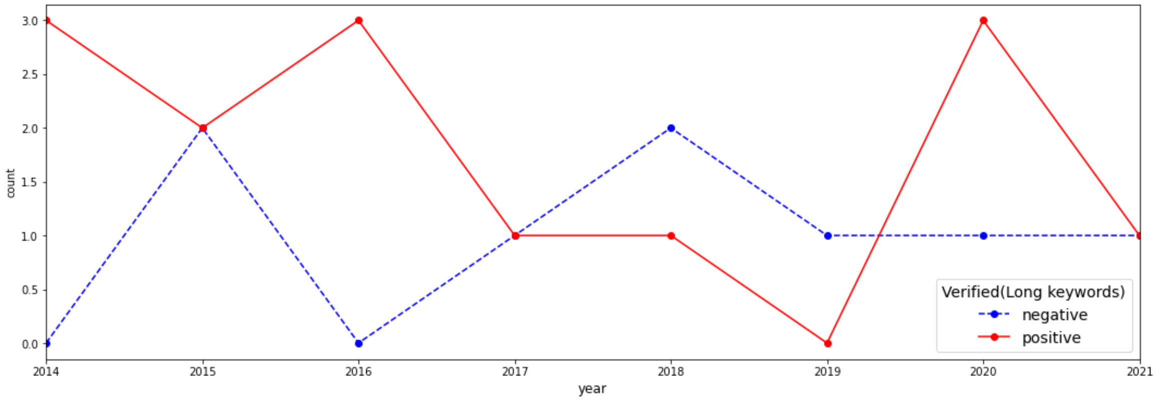


Figure 4. Verified Accounts' Sentiment

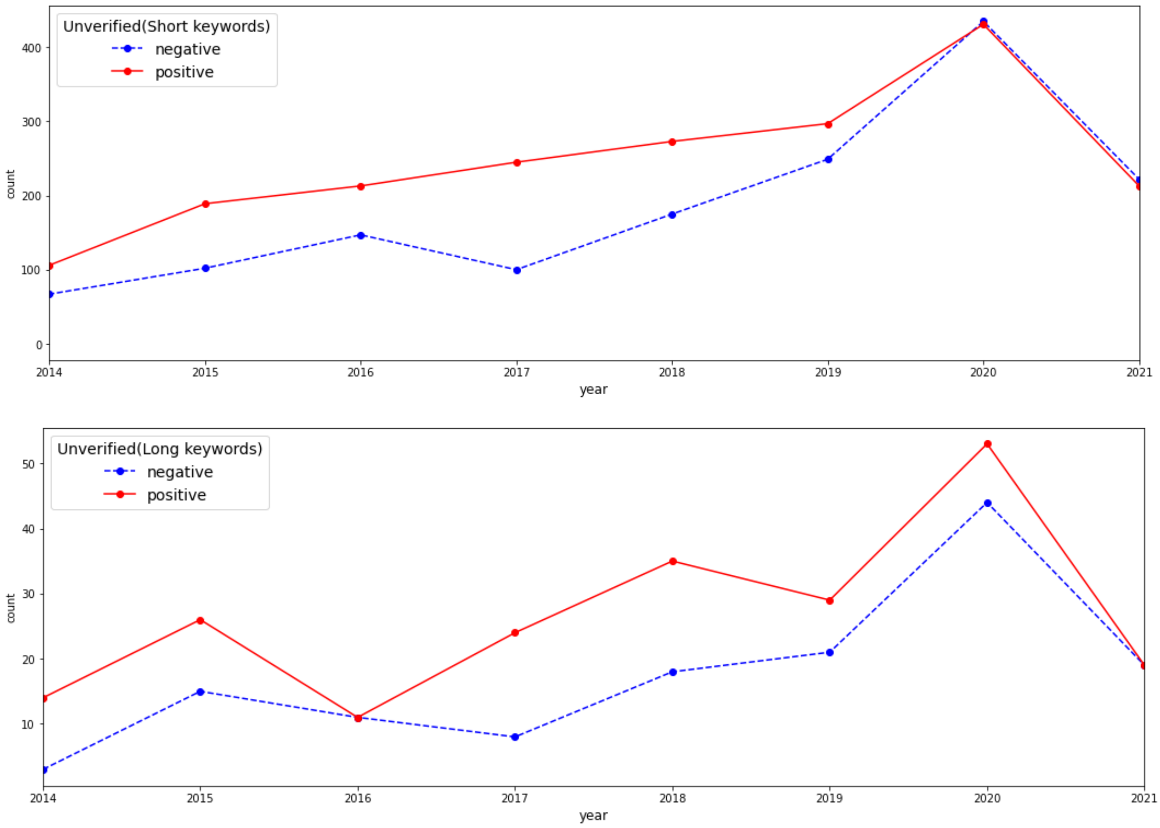


Figure 5. Unverified Accounts' Sentiment

Based on unverified accounts' tweets and shown in Figure 5, the sentiment trend is consistent with the result shown in Figure 2 but responds to the research questions more accurately. It is worth noting that not all Australians are active on Twitter. How much the results of this paper represent the actual perception of the popular is subject to the demographics of Australian Twitter users. For instance, 38.5% of Australian Twitter users are aged between 25-34 years old, 20.7% of Australian Twitter users are aged between 35-49 years old, and 42% of Australian Twitter users are college graduates (FIBER, 2022).

As per the lower figure of Figure 5, the general public is not sharply against but slightly towards Chinese investments in Australian infrastructure. The willingness to express the attitude (either positive or negative) toward the chosen topic (shown in the number of both positive and negative tweets) has been increasing since 2017. One of the possible reasons may be because of more frequent reports in the mainstream media about the declining Chinese investment. With more visible discussions and information input, individuals would be keener and more capable of expressing an explicit opinion.

Two periods could be identified, i.e. 2016 and 2021, when a noticeable decrease in sentiment was seen. A careful content analysis was conducted to scan the tweet text in those two years. The change in sentiment in 2016 is due to a heated discussion on the lease of Darwin Port to China. At that time, the Northern Territory government entered a 99-year lease agreement over land and operations of the Port of Darwin for $506 million to Landbridge Group, the Australian subsidiary of a Shandong-based energy and infrastructure group. The deal immediately attracted controversy and has been brought back by the mainstream media from time to time. According to Figure 5, the sentiment was down in 2016 mainly due to the decrease in positive tweets instead of an increase in negative tweets, which may indicate that the general public discussed the case in a neutral tone. The reason behind the drop of sentiment in 2021 is that the Federal government teared up Victoria's Belt and Road agreements with China in April 2021. The Chinese embassy had criticised Australia's decision as "unreasonable and provocative", leading to a few individual statements like "Australia will not surrender to threats of retaliation from China" that were recognised as negative tweets by the algorithm.

5 Conclusion and Further Research

We retrieved tweets from accounts with Australian IP addresses using pre-defined relevant keywords and a time range from 1 January 2009 to 31 December 2021. To respond to the research questions more accurately, tweets from verified accounts were removed from the analysis. After cleaning the data, sentiment analysis was conducted. It was found that the general public is not sharply against but slightly towards Chinese investments in Australian infrastructure. A noticeable decrease in sentiment was seen in 2016 due to a discussion on the lease of Darwin Port to China.

The limitation of the research design is that Australians living overseas would be excluded, and foreigners living in Australia would be included because of their IP addresses. In terms of results, the number of tweets about Chinese investment in the Australian infrastructure is too small. If we have more tweets, we could monitor the sentiment changes weekly or monthly, providing an excellent opportunity to identify factors influencing the sentiment changes.

The concept of using social media to monitor public perception on a specific topic has been widely applied in the marketing and politics areas but not very often in the infrastructure sector. This study contributes to practice by validating its application in the infrastructure sector. For instance, a well-known issue in the development and operation of infrastructure projects is that the voice of the general public and local community could hardly be heard by the infrastructure project manager. A potential solution could be that we replace the search keywords with the project title to have real-time public sentiment on the project. Further to this direction, we may also consider whether public sentiment based on social media data could be used to measure the level of Social License for Infrastructure.

6 Acknowledgement

This work was supported by the Project Governance Control Symposium and Australia-China Relations Institute, University of Technology Sydney.

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Building Wiser: Fostering Excellence in Procurement Risk Governance

Rita Peihua Zhang[1*], Yen Pham[1], Jan Hayes[1] and Nader Naderpajouh[2]

[1]School of Property, Construction and Project Management, RMIT University, 360 Swanston St., Melbourne, Victoria, 3000, AUSTRALIA
[2]School of Project Management, Faculty of Engineering, University of Sydney, Level 2, 21 Ross St, Forest Lodge, NSW, 2037, AUSTRALIA

rita.zhang@rmit.edu.au; yen.pham@rmit.edu.au; jan.hayes2@rmit.edu.au; nader.naderpajouh@sydney.edu.au
* Corresponding author

Abstract:
Project procurement failures in the infrastructure and engineering domains, including the energy sector, are common and costly both financially and sometimes in terms of human lives. A systematic understanding of procurement risks in the energy sector is lacking, which can hinder the ability to control or mitigate risks to improve project outcomes. A research project is being undertaken with a range of stakeholders in the Australian energy sector to understand their experience with procurement of services or goods and their views on procurement risk management. As fieldwork is underway, only interviews with 25 engineers were analysed to provide preliminary results of procurement issues that affect the ability to meet project expectations. The interview data were analysed using the inductive thematic analysis technique. Data analysis revealed procurement risk factors linked to four major categories, including supply chain coordination and management, supplier, external environment and cooperation and trust. Some risk factors identified are not specific to the energy sector but have also been reported as critical in other engineering and construction sectors, including project planning, supply chain configuration, project scope and specifications, and supplier performance and behaviours. Some risk factors are linked to the Australian energy sector's contextual characteristic of relying on international suppliers, including custody transfer and meeting Australian standards and regulatory requirements. Offshore procurement makes it critical to have appropriate interface management structures and quality control/assurance systems to ensure effective communication and compliance with the specification requirements. Procurement risks identified in the study are used in developing a procurement risk governance framework as the next step of this ongoing research.

Keywords:
Energy sector, Infrastructure project, Procurement risk, Supply chain

1 Introduction

Major infrastructure projects delivered by the construction and engineering industry are sometimes unsuccessful in meeting deadlines, cost targets or specifications (Rudolf & Spinler, 2018). A well-known example is the Channel Tunnel between France and the UK, which experienced a cost overrun of 80% in construction and 140% overrun in finance (Flyvbjerg, 2011). Major infrastructure projects are inherently risky due to characteristics such as complex technical nature with long planning horizons and many interfaces, changing project scope and requirements during the project execution process, and involvement of multiple parties with conflicting interests (Flyvbjerg, 2011). Additionally, major infrastructure projects have a complex supply chain with a large network of involved companies and suppliers. It is estimated that goods and services procured from companies in a construction project supply chain account for as much as 80% of the project cost (Construction Excellence, 2015), highlighting the importance of effective supply chain management and procurement practices. The process in which products and services are procured affects the ability to meet project expectations of cost, schedule, quality and functionality, and is critical to the 'golden thread' connecting compliant design to a successful project outcome. The term golden thread was introduced by Dame Judith Hackitt in her inquiry report, 'Building a Safer Future', following the Grenfell Tower tragedy. A golden thread is needed in the procurement process "…so that their original design intent is preserved and changes can be managed through a formal review process" (Hackitt, 2018; p.102). Managing supply chain and procurement risks should therefore be considered a central activity in infrastructure projects (Rudolf & Spinler, 2018).

Despite the criticality of supply chain management and procurement procedures in the successful execution of infrastructure projects, there have been many examples of procurement failures leading to unplanned adverse outcomes. Cost and schedule implications of late delivery of procured items, potential safety risks as a result of items that do not meet standards, and failure to meet expectations for levels of service provided are among the common issues. The energy sector has not been immune from incidents resulting from supply chain and procurement issues. Failure to procure appropriate products, equipment or services in the energy sector is associated with not only the consequences of cost and schedule blowouts, but also the possibility of major accidents such as fire and explosion that result in casualties, economic losses, and significant environmental impact (Chen et al., 2021).

The importance of these observed issues necessitates a systematic understanding of project procurement risks in the energy sector, a lack of which is likely to hinder the ability to control/mitigate risks to improve project outcomes. This research gap has led to a research project being undertaken to identify and analyse procurement risks and associated mitigation strategies with the purpose of establishing a project procurement risk governance framework in the Australian energy sector. For this purpose, a range of stakeholders is being interviewed to collect data. As the project is ongoing, the paper reports results from a subset of interviews conducted with engineers who specify goods and services to be procured. The paper seeks to answer the question 'what are the major project procurement risks in the Australian energy sector?'.

2 Literature Review

2.1 Procurement and Procurement Risk

Procurement is a series of planning, organising and coordinating processes to obtain goods and services from an external source by an organisation (Turban et al., 2017). Researchers have attempted to differentiate between procurement risk and supply chain risk. Hong et al. (2018) suggested that procurement risk is more concerned with risk in relation to supply disruptions and the contract between the purchasing firm and suppliers. Sodhi et al. (2011) considered supply chain risk much broader, arising from design and development to outsourcing and from finance to logistics. This is reflected in the definition of supply chain management, which involves the management of materials, information and financial flows throughout a network of organisations aiming to produce or deliver goods or services for the purchasers, as well as includes the coordination and collaboration of processes and activities across a variety of functions (Tang, 2006). Procurement risk is not separable from supply chain risk because any failure in the processes and activities within a supply chain is likely to cause procurement failure. For example, problematic specifications developed in the design stage will lead to procurement of inappropriate items. In this paper, we have assumed that procurement management and supply chain management are synonymous, so we have drawn on both literatures in discussing procurement risk. We consider that procurement fails when failures in procurement planning (scoping or contracting), specification, purchasing, manufacturing, or delivery of goods or services result in a project failing to meet stakeholder objectives (both short and long term). This implies that procurement failures can occur at various stages along the supply chain.

2.2 Types of Procurement and Supply Chain Risk

Several studies have attempted to categorise procurement risks as an initial step for risk mitigation (Sodhi et al., 2012). Bogatai and Bogataj (2007) considered risks arising within the supply chain and categorised supply chain risks as supply risks, process risks, demand risks, and control risks. Christopher and Peck (2004) added that procurement risks also include those external to the supply chain. Three groups of risks are categorised, including risks internal to the companies within the supply chain network (i.e., process and control risks), risks external to the companies but internal to the supply chain network (i.e., demand and supply risks), and risks external to the supply chain (i.e., environmental risks). In addition, Tang (2006) categorised risks inherent in the supply chain as operational risks and risks external to the supply chain as disruptive risks. These categorisations are useful in providing high-level guidance to understand procurement risks, but do not provide industry-specific implications.

Through a systematic literature review, Rudolf and Spinler (2018) developed a taxonomy of procurement risks specific to large-scale engineering and construction projects. Their risk taxonomy covers risks both internal and external to the supply chain, risks related to the supply chain network and actors within the network, as well as behavioural risks which are less frequently discussed in other risk categorisations. The risk taxonomy includes four main risk categories:

- Supply chain coordination and management: These risks include failures of the processes of specifying what is required by end-users, selecting and managing suppliers, and coordinating and managing the supply chain to meet the customer demand.
- Supplier: These risks can adversely impact activities and functions undertaken by suppliers in providing the goods or services as specified.
- External environment: These risks are changes in external factors beyond a firm’s control that can adversely impact the supply chain. These include legal, political, social and economic risks in human systems and threats and hazards in natural systems happening outside the internal supply chain environment.
- Cooperation and trust: These risks are related to behaviour resulting from individual and organizational factors including mistakes, attitudes, corporate cultures and behaviours, which can interrupt the supply networks and cause not only short-term losses but also long-term underperformance.

Rudolf and Spinler’s (2018) procurement risk taxonomy has high relevance to energy sector infrastructure projects which share many common characteristics with large-scale engineering and construction projects. However, the taxonomy was conceptually developed from the literature review. It remains unclear whether the taxonomy is applicable to empirical data. This study will use the taxonomy as a framework to organise coding results and identify the extent to which the taxonomy aligns with empirical data.

3 Research Methods

A qualitative approach was adopted to explore stakeholders’ experiences with procurement of services or goods and their views on procurement risk management in the energy sector, with a focus on the gas sector and future fuels such as hydrogen. Semi-structured interviews were used to collect qualitative data, enabling researchers to reach 'areas of reality that would otherwise remain inaccessible such as people's subjective experiences and attitudes' (Peräkylä & Ruusuvuori 2004, p.669).

The target population for this study is professionals involved in procurement across the energy sector from owners/operators, to consultant companies, suppliers, specialist contractors and regulators. Recruitment of interview participants started with members of the project's steering committee from various stakeholder groups in the energy sector with adequate experiences to provide insights into procurement risks. They were then requested to assist in recruiting other experts on the topic from their networks. Interviews were conducted via Microsoft Teams, recorded with participants' consent, and transcribed. All personal information was de-identified to meet ethics requirements. The research project is ongoing with 51 interviews conducted so far. Interviews will continue until data saturation occurs. This paper reports on subsection of the collected data, i.e., interview with 25 engineers who are responsible for specifying goods and services to be procured. Among the 25 engineers, 18 worked as Owner/operator engineering specialists and 7 worked for engineering consultants.

Inductive thematic analysis of the data was conducted following steps by Nowell et al. (2017), i.e., familiarising the data, generating initial codes, searching for themes, reviewing themes, and defining and labelling themes. The themes were partly informed by the existing literature. Rudolf & Spinler's (2018) risk taxonomy was used as the framework to organise the themes into higher level categories..

4 Results

4.1 Supply Chain Coordination and Management

4.1.1 Planning

Interviewees described problems associated with unrealistic timeframes or inadequate planning at the start of the projects, which has led to a rush in project execution, from design to procurement and construction stages. As one interviewee shared, 'designers are told to just get on with the design, constructors are told to get on with construction… and they didn't wait for the vendor data… because we're late' (I04). Consequently, 'we may have to rework, we may have some changes, etc. To mitigate that risk, we can order some extra materials' but 'you as a client need to be prepared to make those decisions and suffer the schedule risk' (I20). One interviewee believed that 'the attitude comes from not having a realistic view of what the project and the schedule should be for a project – that's where a lot of projects go off the rails right from the start." (I20). Consequences of inadequate planning include equipment being not fit for purpose, which then leads to rework, delayed completion, and increased costs. As an interviewee explained, 'poor project planning leading to rushing into buying materials and not enough time to spend on the specifications' (I13), which resulted in poor specifications and inappropriate items procured.

4.1.2 Supply Chain Configuration

The selection of inappropriate contractors can result in poor outcomes with significant economic consequences. Examples of failures include choosing suppliers only based on price rather than the quality of their goods or services or their track records. An interviewee described a project where the client decided to choose a supplier who was not technically qualified for the job at hand but provided a low-bid offer, as a result, ‘two years later they spent millions of dollars to totally replace’ the entire product (I04). Another interviewee referred to a project where procurement was effectively driven by the decision of choosing a contractor based on their marginal cost difference rather than their technical capability, consequently, ‘the equipment hadn’t been used for years. It all broke down. They didn’t have the right skilled foreman, etc. The machinery wasn’t up to it. The job got spread out badly... There were huge damages. There were [environmental] breaches and the thing finished four months late and it was just the absolute false economy…’ (I07).

Appropriate interface management is also essential for supply chain configuration as 'the amount of coordination that went into managing all interfaces’ (I02) contributes to the success of project. As one interviewee explained, ‘as project managers and project engineers, it's very much dealing with interfaces between design, between packaged equipment, construction contractors, obviously getting things commissioned at the end of the day, owners’ objectives, etc.’ (I11). Conversely, in many cases, ‘people either just weren’t aware of the interface or didn’t maybe quite think about the criticality of that particular interface’ (I02). One interviewee described a project where ‘there was no coordination with the shipments from overseas’ and ‘it all just got really messy’ and suggested to ‘ensure that the right contractors got the right deliveries at the right time’ and ‘carefully check everything to make sure … what we wanted … is in good condition’ (I04). Information validation is critical at supply chain interfaces as one interviewee commented '…don’t believe what people tell you … till you’ve checked it yourself or someone that you trust has checked it.’ (I11).

4.1.3 Scope and Baseline Specification

Poorly defined specifications can result in products and equipment being purchased are not fit for purpose. An interviewee explained a situation where ‘the client didn’t appreciate the differences between spiral wound pipe and seamless pipe or operating and construction of main gas pipelines’ (I04) that ended up with inappropriate pipe being specified and supplied. Clear information about scope and specifications is critical, as one interviewee explained, ‘the other side of procurement shortcomings is that the scope of what actually was required in terms of duration or performance, etc. wasn’t explained. So the person who’s then won the job… or meant to be delivering a good or a service suddenly is finding themselves through scope creep and there's not just then the conflict issue but are they still the best organisation or entity to deliver the service or is the product still the most fit for purpose’ (I07).

When talking about specifications, some interviewees emphasised the importance of using standard items where possible. Unnecessarily bespoke specifications are a challenge for overseas fabricators, causing additional costs and delays. As one interviewee explained, ‘The technical specification was very bespoke, so therefore difficult to implement by a fabricator who was used to common industry standards’ and ‘from the start there was lots of work on clarifying requirements…' (I05). In the end, the whole process had major impacts on project schedule and resource planning, even though the products could meet the requirements.

4.1.4 Quality Assurance and Control

Interviewees described cases where quality control (QC) and/or quality assurance (QA) systems failed, causing procurement failures. A typical example mentioned is a project in which the plug valves were manufactured in Europe but the coating was completed in Asia, ‘there was a breakdown in the QA, where it wasn’t appropriately coated or there was no QA of that coating and it was sent back to [Europe]. And before they got ready to ship them back to Australia, they realised all this coating was fundamentally cracked, so they had to send it back to [Asia]…’

(I05). The required rework incurred significant cost and delay. In this case, QA processes were not applied throughout the whole supply chain, from manufacturers down to sub-suppliers. The product was sent off to [Asia] and 'there was no QA from the company's perspective or assurance because as far as they were concerned, their listed or approved manufacturer list was that particular company in [Europe]' (I05).

4.1.5 Logistics

Consideration of custody transfer was identified as lacking in contracting strategy, leading to unclear liability and responsibility. One interviewee shared an example where there was a complication around forged equipment, which contractually put his company in a challenging position to manage that. As he described, 'the contracting model shouldn't have had [us] in that custodial position' where 'there was this period between these pieces being on ship and being on the dock' (I06). Interviewees were concerned about chain of custody and liability with some examples of procurement failures, particularly related to damages during transport because 'there wasn't much clarity around the custody transfer, handover and transportation', 'it's a bit hard to specify things along the way' and 'put any KPIs in place to manage it' (I02). The interviewee further explained about degradation of the pipe in transport, 'it becomes a lot more grey about who is ultimately responsible for it just due to the change in custody ownership', whether it should be the responsibility of the supplier, the transporter, the vendor who 'didn't give any detail but a certain protection needed to be taken', or the contractor 'who joined the two bits together' and 'should have noticed the degradation where they could cut the damage bits off' (I02).

4.2 Supplier

4.2.1 Supplier Performance and Operation

Interviewees shared how suppliers from overseas were selected due to the lower costs of their products. Lower costs don't necessarily come with good quality. In fact, extra expenses might incur during project execution due to poor quality or sometimes non-compliant products. One interviewee referred to a pipeline project 'where there were so many defects that it costs them $5 million before they got the pipe out of the yard… and that was purely because it was bought out of an [Asian] mill, again, poor quality' (I03). Another interviewee explained a decision to buy a fiberglass pipe from overseas instead of Australia because of cost differences: 'the construction price was actually double because there's twice the number of joints, and the risk of leakage was double because every single joint has a propensity to leak' (I19).

Interviewees also indicated performance problems of manufacturers, with the QA/QC system being either missing or not adequate to detect problems before delivery. An interviewee described a project where gas processing equipment from European suppliers did not operate during commissioning, which costed all parties significantly more time on the engineering to rectify issues. In this case, 'it was very clear that the package had not undergone the factory acceptance testing' by the vendor (I12).

4.2.2 Supplier Behaviour

Interviewees described cases where certificates supplied from the vendor through the agent were fabricated or forged, materials purchased from overseas through a known Australian agent were falsified. One interviewee shared his experience with elbows purchased from overseas that had fraudulent certificates, 'we had a look at them, and they were just dangerous, they hadn't even been hydrotested, they couldn't have been hydrotested because they would have blown up, and everything was out of specification' (I19). Even with reputable agents, there are still risks of the products 'not been milled to your specifications' and sometimes 'you just don't have the opportunity to put the QA in place at the mill to watch it being milled and tested' (I01). As a result, the procurement process had to be repeated and the project schedule and costs were significantly impacted.

4.3 External Environmental Factors

4.3.1 Natural Events

There is a range of risks related to external environment factors that are beyond the control of both purchasers and suppliers. The most common issue is shipping disruptions due to natural events such as the Covid-19 pandemic. As one interviewee described, 'it's just about impossible to get things on ships and when you do get them on ships, it's impossible to tell when they're going to arrive. And even our suppliers can't tell us when it's going to arrive' because of 'the changing notions of quarantine in different countries' (I01). Covid-19 is causing 'raw material delay and price increase' (I10), making global supply chains a mess and uncertain (I11, 12, 13).

4.3.2 Standards and Codes

Sourcing goods internationally and ensuring their compliance with Australian standards is another issue. As one interviewee explained, 'when it comes to oil and gas pipelines, Australia is not a big market for that. And especially if you are ordering small quantity of pipes and equipment… you may not encourage them to comply with all your Australian standards that you identify, because they have a much bigger order' from other countries (I13). An issue closely related to meeting Australian standards has been discussed above, i.e., bespoke specifications. There is 'a need to standardise the standards or the specifications internally', or 'reduce the need for bespoking' to reduce costs without compromising safety (I05).

4.4 Cooperation and Trust

Trust and relationships with suppliers have a significant impact on project procurement. With regard to interests between different parties, 'good risk-sharing is going to only occur when you've got open trusting relationships, and there's a recognition of a common goal between the participating parties' and 'if you've got competing interests, then you don't have trust' (I11). Even with a good relationship, it can be risky to skip necessary checking procedures. For example, one interviewee described a case where pipes were not tested in the mill and the certificates were forged, 'there's really no way of working out exactly who had done that. I think we trusted our supplier, so we suspected it happened at the mill end' (I01).

Interviewees also raised internal relationship issues within the owner/operating companies, primarily resulting from conflicting interests among different departments. An interviewee suggested that there should be a clear division of responsibilities and good communication between the three key groups, 'the technical people or the requisitioner, clearly specifying what they need, the buyer or the contracts or procurement people, and the quality, safety, environment people' (I06). Interviewees further suggested that procurement should be an enabling service to 'support the technical outcome and the equipment to work' instead of a governing factor (I01). Procurement should be surrounded by 'the other disciplines that are necessary to make the end product the most efficient and effective outcome' (I03) because 'you centralise stuff - it's a single point of failure, and you can't do that unless you have full competency in your procurement team' (I03). However, there has been a tendency to centralize procurement to have ‘the focus on transactional role’ and ‘look after the purchase orders and budgets, cost savings and how to get the best KPIs’ (I29).

5 Discussion

While Rudolf and Spinler's (2018) risk taxonomy is generally applicable in this study, interviewees placed a stronger emphasis on risk factors that refer to broader categories of "supply chain coordination and management" and "supplier". Some risks identified in these categories were consistent with key risk factors reported in other sectors. For instance, poor planning of resources and schedule has also been identified as the major challenge to the effective operation of supply chains for prefabricated building projects (Luo et al., 2019), while supply chain configuration, scope and baseline specification, and supplier performance and operations were among the top ten critical supply chain risks ranked in a survey in large-scale engineering and construction projects (Rudolf & Spinler, 2018).

Regarding supply chain configuration, interviewees in our study highlighted interface management issues that can affect procurement success. Interface management has not been extensively discussed in supply chain and procurement literature, but its important role has been acknowledged in the management of mega-construction projects involving many geographically distributed stakeholders (Ahn, et al. 2017). Interface management improves coordination between disciplines, enhances information sharing and communication, increases alignment between stakeholders and reduces potential project conflicts (Shokri, et al. 2016). This is highly relevant to the energy sector where interfaces among design, manufacturing, transportation, and installation need to be appropriately coordinated. In particular, checking mechanisms should be established to make sure information or physical goods are exchanged successfully at the interfaces to maintain the 'golden thread', i.e., ensuring what is specified at the beginning is what is delivered at every stage (Hackitt, 2018).

Surprisingly, cash flow issue which has been identified as a supply chain configuration related risk in previous studies (Tang, 2006; Rudolf & Spinler, 2018) was not considered by interviewees as a factor that might hinder procurement success in the energy sector. This can perhaps be explained by the make-to-order nature of projects in the energy sector, whereby manufactures often structure milestones linked to payments in the contract to manage their cash flow, therefore, experience less cash flow risk compared to manufactures in industries of make-to-stock nature.

The Australian energy sector relies heavily on international suppliers. Issues in relation to transporting goods from overseas to Australia were identified as a concern. Inappropriate handling of products during transportation may cause damage with great cost implications. This is further complicated by inadequate consideration of custody transfer in contracting strategies, causing ambiguous liability and responsibility among project stakeholders. It appears that custody transfer has received less attention in other types of infrastructure projects, where raw materials (e.g., steel, concrete) are often procured for in-situ construction. However, it has been a concern in construction projects where prefabrication has been used (Luo et al., 2019).

Offshore procuring often raises the challenge of international suppliers' failure in understanding specification requirements and complying with Australian standards and regulatory requirements. The challenge can be compounded by bespoke specifications and underperforming suppliers. Suppliers' capabilities determine their ability in meeting performance expectations, which reinforces the importance of appropriate supplier selection.

Critically, the supplier selection process should not be cost-driven but also consider criteria of technical competency and capability. When procuring products from overseas suppliers, standardisation of requirements should be preferred because bespoke specifications involve higher risks of misinterpretation and non-compliance as well as additional efforts in clarifying requirements. The geographically remote nature of suppliers also makes QA/QC systems critical in ensuring that products procured from overseas meet requirements. Interviewees in this study emphasised on-site inspections in the QA/QC process and suggested that QA/QC systems should be extended to sub-suppliers.

Interviewees in this study placed less emphasis on cooperation and trust, while such behavioural factors were identified as top critical risk factors in supply chains of large construction and engineering projects (Rudolf & Spinler, 2018). Behavioural risks such as trust and cultural issues were viewed as strategic supply chain risks that affect business strategy implementation in the construction industry (Alonio et al. 2018). The results reported in this paper were based on the insights of engineers, who have more concerns about technical and operational issues due to their disciplinary background and professional roles in projects. More discussion about relationships and trust issues may emerge when analysing interviews with project managers who are responsible for the overall project strategic success. However, engineers in this study did raise concerns about the relationship between design and procurement disciplines, arguing that procurement decisions should not be entirely commercially driven but based significantly on technical considerations.

6 Conclusion

This paper reports project procurement risks identified from interviews conducted with engineers in the Australian energy sector. Interviewees had a stronger emphasis on risk factors from supply chain coordination and management and suppliers. Consistent with results reported in other sectors, issues related to project planning, supply chain configuration, project scope and specification, supplier performance and behaviour are considered critical procurement risks in the energy sector. Other risks identified are linked to the Australian energy sector's contextual characteristic of relying on international suppliers. Particularly, issues in relation to interface management, custody transfer, meeting Australian standards and regulatory requirements, quality control/assurance are emphasised by interviewees to ensure that offshore procurement complies with specification requirements. The research results provide implications to energy sectors in other countries that also rely on overseas procurement. Procurement risks identified in the study will be used in developing a procurement risk governance framework for the Australian engage sector as the next step of this research.

7 Acknowledgement

This work is funded by the Future Fuels CRC, supported through the Australian Government’s Cooperative Research Centres Program. The cash and in-kind support from the industry participants is gratefully acknowledged.

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Determining the Optimum Risk/Reward for a Mega Infrastructure Project: A Case Study of a 2.5-Kilometre Rail Bridge Project

Matt Stevens[1*] and Ali Eghbaljoo[2]

[1]School of Engineering Design & Built Environment, Western Sydney University,
Locked Bag 1797 Penrith NSW 2751, AUSTRALIA
[2]ORBIZ Consulting Pty Ltd, 93 Pickles Street
Port Melbourne, VIC 3207, AUSTRALIA

matt.stevens@westernsydney.edu.au; ali.eghbaljoo@orbiz.io
* Corresponding author

Abstract:
Shutdown construction installation operations are logistically and technically challenging when coupled with significantly limited space and restricted material delivery parameters. This case study will examine the pre-mobilisation planning for a publicly sensitive 2.5 rail bridge in Melbourne, Australia. It was on the critical path of an AUD 542 million infrastructure project. A leading Lean Consulting Firm organised and facilitated Value Stream Mapping (VSM) working sessions to assist the involved organisations in working through various issues such as material logistics, crew staffing and installation processes to determine the optimum cost/risk balance for stakeholders. The result was a well-balanced and reasoned installation approach which eventuated in better-than-expected outcomes.

Keywords:
Lean construction, Takt time, Theory of constraints, Value stream mapping

1 Introduction

A Lean consulting firm was asked to help solve a significant problem on a train-motor vehicle level-crossing removal section of an AUD 542 million project. The challenge was determining the schedule/cost risk profiles for possible construction scenarios on a 2.5-kilometre rail bridge in Melbourne, Australia. The original schedule estimate was 130 days, but the owner considered it unacceptable. So, through further discussion, a 93-day maximum occupation of the rail line was agreed upon; however, it was also agreed that the schedule needed significant contingency for this new scenario. Specifically, the number of days float (19%) that part of the 93-day occupation demand by the owner was not sufficient in the experience of the contractor. To ensure timely completion, it was critical to have enough schedule float (25%) given the the rail bridge's construction uncertainties. In addition, the implications of poor planning and execution coordination that could lead to time overruns would negatively impact public confidence in the Level Crossing Removal Project.

The Lean consulting firm, ORBIZ Performance Specialists organised and executed four Value Stream Mapping (VSM) working sessions to assist the organisations by exploring the various issues, including material logistics and installation processes. Approximately 10 stakeholder representatives attended, and each session was 4 hours in length. In addition, two reporting and debriefing sessions were held after project completion. Making production goals highly probable was the challenge of this project's leadership. However, several factors appear to lessen that probability, and some well-accepted and proven actions can increase it. Due to paper count limits of this conference paper, some areas are discussed more briefly than desired.

2 Literature Review

This literature review briefly treats a limited number of areas, either input, process or output in the case study. Each was considered a significant component that affected the successful completion of this infrastructure project.

2.1 Takt Time

Takt is a well-accepted approach for construction project planning, valued for its fundamentals, including the material and task flow (Binniger 2018). Takt's production goal is to optimally organise flow (Lehtovaara et al. 2021), partially facilitated by eliminating waste and fulfilling information needs. In addition, Lehtovaara et al. (2021) asserted that less work waiting for others helps optimise productivity. This is achieved by accelerating process flow and keeping a minimum amount of work in progress. Current research has shown that planning using takt time in implementing construction work can have significant benefits such as saving time, reducing cost and improving quality

Takt-time analysis (TTA) can be combined with a job site management system to save time, reduce costs and improve quality (Frandson and Tommelein 2014). Frandson et al. (2013) designed a process for TTA, including gathering productivity and quantity data, defining work scopes and areas, distilling task sequence (flow), determining the duration of individual tasks, balancing material demand and task timing, and creating a production plan. However, the implementation of TTA is not necessarily a simple transformation of these steps but rather an iterative collaboration process.

2.2 Flow

In Lean construction, the idea of flow which includes the proper rate of inputting people, equipment, materials, and information to produce the designed result while minimising waste, is crucial to understanding. Excellent flow continuously achieves prerequisites and the value transformations of inputs (Koskela 2000). Unrealistically, optimal flow is a process in which value is added constantly in preparation and installation with no waste (Sacks 2016). Managing flow in a production system requires an understanding of the process and product mix (Hopp and Spearman 1996). Contractors use the CPM schedule or Gantt Chart as a proxy for managing flow; however, Koskela (1992) asserts that these are poor substitutes.

Shingo and Dillon (1989) assert that there are two kinds of flow: Process and Operations. The process flow is increased by keeping only value-added steps and removing those such as moving, waiting, inspection, scaffolding, and cutting. Operation flow is improved by balancing work crews, refining practices, choosing the better tools and equipment and minimising setup times.

2.3 Value Stream Mapping

Value Stream Mapping (VSM) is a Lean approach that generates a process flow diagram of activities and other project information. It is a well-accepted method of displaying the process steps and workflow and then providing a system to analyse these practices in creating an effective improvement plan (Chen and Cox 2012). It clarifies any ambiguity in the minds of managers and workers that may emerge from factors controllable or not. VSM diminishes uncertainties during everyday production and construction operations and categorises them into materials, human resources, equipment, cash flow, information or nature-based events. Each can be classified as controllable and uncontrollable (Ballard and Tommelein 2016). Lerche et al. (2020) showed how working with Takt planning, and the plan-do-check-act (PDCA) approach could minimise or eliminate uncertainties by focusing on variations and emphasising the learning of lessons. Most project scheduling is primarily concerned with resource assignment and levelling and neglects constraints affecting the uncertainty of the total project duration. Due to this, the first scheduling concern for a contractor is managing the variation of project duration without reducing it (Debasi et al. 2021)

2.4 Theory of Constraints

The advent of time-oriented TOC emerged as a powerful tool and methodology for structuring problems and creating specific solutions. Goldratt and Cox (1986) presented the theory of constraints (TOC), which developed a new scheduling method called critical chain project management (CCPM). It is primarily focused on activity durations. According to the concept, for effective project implementation, the project buffer (PB) needs to be incorporated at the end of the last activity to meet the Takt Time with a safety buffer. Therefore, it was critical to recognise the importance of feeding buffers (FB) at non-critical paths, which may affect the critical path if delayed.

CPM and other scheduling forms such as (Linear and GANTT) are based on transforming an input's value and the throughput's speed. However, each typically ignores the achievement of critical prerequisites before the activity starts (flow) (Koskela 2000). Schedule contingency protects the end date achievement. When handling uncertainty with scheduling, the float among activities acts as a risk management method and resource-levelling opportunity (Gong 1997).

Regardless of the value of these methods and their positive effect on capacity and WIP, there is limited knowledge of them within operations management under construction project conditions (Lerache 2022). A critical concern for a construction organisation is project completion as contracted under various constraints such as the internal budget, material logistics and operating hours. Hence, the primary scheduling objective is to reduce project activities' uncertainty and duration to make scheduling reliable (Debasis et al. 2021).

3 Framing the Problem

ORBIZ collected data from the client before the workshop to fully understand the issues. For example, the contractor and owner forwarded information about their previous experience and the proposed rail bridge construction, such as identifiable crew tasks, costs of different approaches, the number of crews, delivery constraints, storage space, and production cycle times. This was the starting point of the iterative exercise in reducing the time needed to install. The viaduct and superstructure were on the critical path and were central to increasing contingency while maintaining the 93-day occupation maximum. Other factors increase the complexity, such as limited space for movement, material storage, resource flow and winter climate conditions.

In the first session, the planning team was reminded that the following Lean Concepts were critical to apply:

- *Value Stream Mapping* was used to display tasks each hour of the 93-day occupation graphically. Those activities that continued for the most extended number of hours were first examined.

- *The Theory of Constraints* prompted construction leaders to identify and overcome areas that slowed productivity and thus increased schedule adherence. Each of the 9 installation steps – see Figure 3 – were treated machines in a production line. The slowest one – where successor activities grow to more than 1 in the queue – were the first to be examined.

- *Takt Time* prompted alignment of the customer schedule requirements with construction process throughput plus the desired buffer of 25%. So, the previous recorded cycle times were the starting place and the reduction needed was calculated on the slowest installation step. The goal was to exceed Takt Time and thus build schedule contingency.

The construction installation subassemblies were identified for error-free analysis. See Figure 1.

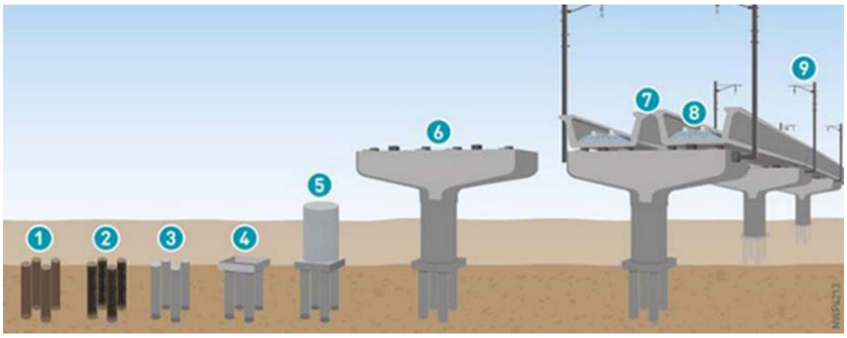

Figure 1. Sequential steps of installing rail bridge.

The ORBIZ team created a first- to last-day study to identify overrun risks and time-cost cost savings opportunities. They considered the complete set of Lean Construction tools, but only a few were selected for their specific utility in addressing the challenges. See Table 1.

Table 1. Current State Analysis

Operation – See Figure Number	Present Experience – Cycle Time in Hours	Comments
1 - Drill 4 piles	40	
2 - Pour 4 piles	12	
3 - Excavate	14	
3 - Break back	10	
4 - Pile caps	58	Longest Cycle Time makes the Primary Constraint
4 - Strip & backfill	16	
5 - Construct piers	46	Secondary Constraint – if pile caps (above) are reduced to a shorter cycle time, this will become the primary Constraint
6 - Crosshead and bearing assembly	44	Third Constraint - if pile caps and construct piers (above) are reduced to a shorter cycle time than 44 hours, this will become the primary Constraint
7 - 4 L-beams Lift	8	
8 – Rail Track	NA	Not considered for examination
9 - Electrification Standards	NA	Not considered for examination

Generally, the many uncontrollables in the construction industry were no different in this project than others. Unfortunately, there were a few more such as COVID regulations, public sensitivity, and a densely populated site. The case's facilitation firm performed consultation workshops for the contractors involved to determine a well-reasoned approach for constructing a 2.5-kilometre rail bridge in 93 days. The main contractor requested planning, scheduling and execution solution to increase the time contingency (number of days of float) and generate process flow while maintaining its safety program among the teams. The activity differences between delivery constraints and installation pace were critical for material inventory on-site. The material needed was deemed an "oversized load" and required special permits and a limited delivery time from 11 p.m. to 5 a.m. Pre-stocking on site was critical due to the projected lack of delivery capacity compared to each crew's relatively faster erection capability. These bottlenecks must be removed through specific mitigation measures to complete the level-crossing removal project within the stipulated time and cost goals.

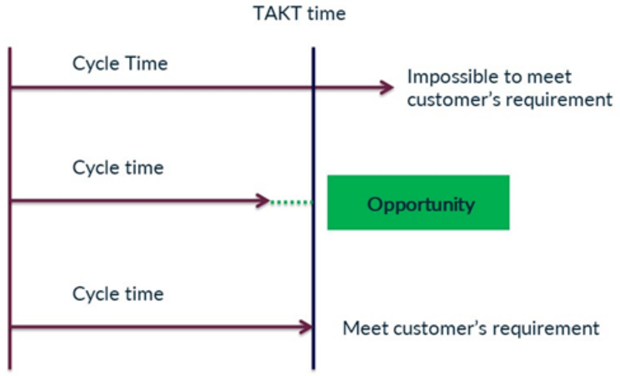

Figure 2. Takt Time dynamics of three situations

The contractor used the Takt Time concept to determine how they might meet the customer schedule requirements with a cushion of extra time for unforeseeable events. Reconfiguring the installation process to provide 25% schedule contingency at planned completion was viable. The cost of each scenario was one determining factor in selection.

However, flow constraints govern productivity. The theory realistically affects the production potential of any operation. So, analysis is critical to uncover the slowest throughput. This will regulate the pace of output in each process and multifactor productivity (MFP). See Figure 2.

Figure 3. The most restrictive Constraint reduces the flow of those steps upstream and downstream.

A Value Stream Map (VSM) visualises value-added and non-value-added work steps, material and information flow. A VSM visually shows the capability, constraints and wastes within a process or system and facilitates decision-making based on data, not opinion or experience. It also displays essential process control factors such as a) inventory, b) lead time/queue time, c) process/cycle time, d) change over time. The project structure possessed many sub-structures that segmented operations. See Figure 3. However, they were categorised as work activities for analysis and planning purposes: 1. Drill & pour piles, 2. Excavate, break back & pour binding, 3. Form, reinforce & pour – pile cap, 4. Form, reinforce & pour – piers, 5. Install crosshead bearing plinths 6. Erect L-beams 7. L-beam stitch. (Activities 8 and 9 were outside the contractor's work package). Several essential rules had to be adhered to in the planning and execution of the work

Except for the first and last, each process had a successor and predecessor process. The successors are the customer of the predecessors. The predecessors are the suppliers of completed work to the successors. Each supplier will furnish a complete task to the satisfaction of the downstream "customer".

1. Crew availability had to be determined. The team decided from all available information that six crews should work concurrently, each occupying approximately 500 meters of the rail line to complete work on the substructure and superstructure.
2. The work-in-process (WIP) was minimised at all times. This meant the entire crew was focused on completing the present task as practicable, so there was little time overlap between the current activity and the successor. This produced shortened cycle time of the constraints, so there is minimal work waiting at any of the eight successors.

From here, all throughput cycle times were determined, and the slowest was targeted for acceleration. Also, filtering for the most uncertain situation, i.e., variable output, cycle times or heightened installation risk, focused the analysis and decision-making deeper. Data collected and analysed is shown in Table 1. To reach a state of optimisation, the following activities were identified as critical to achieving a higher schedule contingency and acceptable construction cost. Next, the team reviewed cycle times to identify constraints. See Table 2.

Table 2. Example Questions, Answers with Clarifying Comments

Question	Answer	Comment
What is the basis for the previous 130-day schedule?	Assuming a 25% schedule contingency, previous experience shows a continuous work time of 98 days without disruption,	To reach 93 days with a 25% contingency, a 70-day or 28% reduction in the schedule was required.
In the experience of the constructors, what is the most significant physical Constraint for the rail bridge?	The substructure is the most common element that the constructors will install and is on the critical path.	The substructure is the most complex set of interdependent tasks of the 9-steps required.
What is the current Cycle Time?	Currently, the cycle time for constructing one substructure is 58 hours per work front. Critically, there are six work fronts – one per crew	The pile cap construction process's throughput speed was increased; thus, the time was reduced from 58 to 48 hours. The total in-place cost of precast versus pour-in-place showed the latter's value against the former when contrasted against schedule savings,
How often can one substructure be built?	Every 9.67 Hrs. (58/6) one sub-structure is built. Therefore every 9.67 Hrs. 4 L-beams can be lifted (there are 4 L-beams between two sub-structures)	Material delivery logistics needed to be simulated to identify problems and potential solutions
What is the maximum number of L-Beams can be lifted a day?	The maximum number of L-Beams to lift a day was: 9.92 = ((24 Hrs. a day/9.67 to build one sub-structure) x (4 L-Beams))	On-site inventory of L-beams should be increased from 69 to 92 before starting work.
How long should it take to lift 268 L-Beams?	It takes 27 days to raise 268 L-Beams (268/9.92 per day	The installation rate of L-Beams completes this phase in less than 30 days.
Precast versus Poured-in-Place Piers	The calculation showed that 80 hours or approximately 3.5 days would be saved.	This is due to the cycle time of the piles and the multiple piers that can be formed, reinforced, and poured in a single shift making the savings only on the first installation on the schedule.

3.1 Constraints

3.1.1 Constraint 1

What will be the takt time if 12 L-beams a day are installed on average? Which installation steps are constraints?

- Per the design – there are 4 L-beams per pier to be installed. There are 6 work crews
- 12 L-Beams a day = 3 sub-structure a day x 4 L-beams per pier
- Therefore every 8 Hrs. a sub-structure should be constructed (24 hours a day / 3)
- Assuming 6 work crews, every crew must construct a sub-structure every 48 Hrs. (6 work front x 8 Hrs) Therefore, the takt time for a substructure is 48 Hrs.

3.1.2 Constraint 2

Curfew for L Beam deliveries - a maximum of 8 can be delivered a night (special crew and equipment were required due to size of product).

- The expense to store on-site (narrow corridor and stacking cost due to special racks needed)
- Lift 9.6 L-beams a day on average,
- L-Beams JIT delivery, curfew & lift may cause a delay in the overall program
- Weather - rain/wind may cause delays when lifting occurs between 1 a.m. – 5 a.m.
- Previous experience and data show it takes 2 hours to lift and place 1 L-beam

Develop an effective plan to lift 12 L-beams a day to reduce the overall program by 5.6 days. So, the actions determined were the following:

- Increase inventory to 92 L-beams to support lifting 12 L-beams a day
- Reduce or eliminate reliance on JIT delivery by replenishment
- Remove constraints of lifting L-beams from 11 p.m. - 5 a.m. (Have the option to lift 12 L-beams during any time of the day)

Precast piers appeared to offer time savings compared to in situ (poured-in-placed) pier installation. The assumption was that due to the 500-metre span and the multiple piers needed, many hours of cure time would be saved if precast was utilised. The calculation showed that 80 hours or approximately 3.5 days would be saved. This was due to the cycle time of the piles and the multiple piers that can be formed, reinforced and poured in a single shift making the savings only on the front of the schedule.

3.2 Flow Analysis

Operations flow is the enabler of productivity, such as balancing work crews, smoothing material logistics, minimising setup times, and selecting the type of tools and equipment. Process Flow is the technical construction approach and the determination of the value of each step. This elimination of steps that add no value or the consolidation of two steps to decrease the overall time would fit the flow instruction. Reducing cost and schedule in construction contracting can be interpreted as increasing value even though sometimes it does not benefit the construction service buyer. In this case study, both types of flow were analysed and improved such as the switching from poured in place to precast.

Careful information gathering and collaborative planning start an effective construction installation process. The first step of information collection has to be coupled with anticipatory questions. This aids the accumulation of facts, data and costs. The level of facilitator understanding partially determines the workshop's effectiveness in problem-solving.

This analysis and follow-on actions produced the following results.

- Days of Schedule Contingency increased from 19% to 25%. Scenario 2 was recommended by the Lean consulting firm.
- Further schedule savings from other areas expanded the time contingency to 30%
- When executed, the planned 93-day occupation and rail bridge work was finished two weeks earlier.

Table 3. Current State and Three Proposed Future States

		Scenario 1 Current State		Comments	Scenario 2 Future State		Scenario 3 Future State		Scenario 4 Future State	
	Operation	Cycle Time - Hours	Days	Action	Cycle Time - Hours	Days	Cycle Time - Hours	Days	Cycle Time - Hours	Days
Work Activities	*Drill 4 piles*	*40*	*2.5*	*Reduce*	*40*	*2.5*	*40*	*2.5*	*36*	*2.25*
	Pour 4 piles	12	0.75		12	0.75	12	.75	12	.75
	Excavate	14	0.875		14	0.875	14	.875	14	.875
	Break back	10	0.625		10	0.625	10	.625	10	.625
	Pile caps	*58*	*3.625*	*Reduce*	*48*	*3.0*	*41*	*2.6*	*36*	*2.25*
	Strip & backfill	16	1.0		16	1.0	16	1.0	16	1.0
	Construct piers	*46*	*2.875*	*Reduce*	*46*	*2.875*	*46*	*2.875*	*36*	*2.25*
	Crosshead & bearing assembly	44	2.75		24	1.5	24	1.5	24	1.5
L-beam logistics	# of L-beams to install	268			268		268		268	
	L-beams lift a night	*9.6*	*27.9*	*Increase*	*12*	*22.3*	*14*	*19.1*	*16*	*16.75*
	Holding stock	*69*		*Increase*	*144*		*144*		*144*	
	Daily delivery of L-beams	8			8		8		8	
	Rail workdays needed		16 days	Negligible Opportunity		16 days		16 days		16 days
	Program contingency	19.0%	17.7 days		25.0%	23.25 days	28.4%	26.4 days	30.9%	28.7 days
	Total Days to complete rail bridge with contingency		93 days			93 days		93 days		93 days
	Cost	Target			Target + 0.10%		Target + 0.25%		Target + 0.5%	

4 Findings and Discussion

A significant characteristic of ORBIZ's process was its iterative nature. Their continuing data collection and analysis of its impact gave the decision-makers options. In addition, the extensive discussion gave them a clear picture of trade-offs and the probability of failure. For example, calculations analysing the use of precast in the structure were shown to be a disadvantage on the piers – the first installation was shorter but limited re-supply hours made this a constraint; therefore, pouring them in place was planned.

It is essential to contrast this with the contractor's experience. Assuming a 25% schedule contingency, a continuous work time of 98 days without disruption was expected, which was the normalised completion time; however, the planning team's goal was to create a 93-day schedule with a 25% contingency. This meant an approximated 70-days of construction activity is the work was performed "business as usual". When compared to their productivity and logistics experience on this project, this required a 28% reduction in time.

Upon initial review, the substructure was the most complex set of interdependent tasks of the 9-steps required and therefore was the starting point of examination. Notably, the substructure is the most common element to be installed install and is on the critical path. Initially, the cycle time for constructing one substructure is 58 hours per work front. Critically, there were six crews available which insured less work per. The team's previous median productivity rate for one substructure was one every 9.67 Hrs. (58/6). Therefore, the analysis assumed 4 L-beams could be lifted every 9.67 Hrs i.e., there are 4 L-beams between two sub-structures. In total, the calculation concluded it took 27 days to raise 268 L-Beams (268/9.92 per day

So, the pile cap construction process's throughput speed was increased; thus, its cycle time was reduced from 58 to 48 hours. In addition, the total in-place cost of precast versus pour-in-place showed the latter's value against the former when contrasted against schedule savings. Material delivery logistics were simulated to identify problems and potential solutions. It was discovered that the on-site inventory of L-beams should be increased from 69 to 92 before starting work. As an aside, this required a new stacking method and additional equipment. The expense and its benefit were deemed acceptable. The installation rate of L-Beams completes this phase in less than 30 days. This is due to the cycle time of the piles and the multiple piers that can be formed, reinforced, and poured in a single shift making the savings only on the first installation on the schedule.

This custom TTA produced highly confident information for stakeholders to decide. This process was similar to the "Hollywood Method" in highly custom products in which planning keeps the expensive parts as efficient as possible. In both industries, the cost of failure is not just monetary but reputational. This makes the extra time, careful effort, and choreographed execution appear worth it.

The end result of this iterative Lean process was increased confidence in the plan to construct the rail line in the takt time required. When executed, the site staff completed the work two weeks early – approximately in 80 days – and the travelling public returned to its regular routine.

5 Conclusion and Further Research

The planning process included gathering information, analysing structured formatting, and evaluating potential scenarios. Each required expertise and time to do well and was afforded in this rail occupation planning process. Previous LXRP rail bridge experience and resulting quantitative data provided some certainty but had to be iteratively analysed. The Lean Construction approach provides the needed tools to provide solutions. Creating schedule contingency or float was one of the primary goals of this team in their planning process. It was made by starting with a full understanding of previous results, including construction "physics" and resource logistics, to organise the work in a highly efficient manner.

Capturing previous experience accurately and analysing carefully provides alternative execution strategies. This is the result of TTA supported by understanding the Lean construction process. This can be seen partially as a knowledge transfer and scenario planning process that should be valuable to main contractors and their stakeholder teams.

This 2.5-kilometre rail bridge project was built successfully, i.e., completed early within budget at the specified quality, no adverse safety events and without negative impact on the public. Significant credit goes to the project ownership team that was highly aware of the trade-off between careful scenario analysis with planning and increased predictability. As a result, they budgeted time for this pre-mobilisation examination, including carefully assessing each of the three scenarios for risk/benefit.

6 Acknowledgements

The authors wish to acknowledge and thank ORBIZ Performance Specialists for sharing and actively collaborating on this paper.

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Theme:

Digitalisation of Construction

Comparison of Blockchain Solutions from the Perspective of BIM Integration

Klaudia Jaskula[1*], Eleni Papadonikolaki[1] and Dimitrios Rovas[2]

[1]Bartlett School of Sustainable Construction, University College London, London, UNITED KINGDOM
[2]Bartlett School of Environment, Energy and Resources, University College London, London, UNITED KINGDOM

k.jaskula@ucl.ac.uk
* Corresponding author

Abstract:
Blockchain technology is gaining a lot of interest from both industry and academia as it provides a high level of security, immutability, and transparency. It might be one of the key enabling technologies towards the fourth industrial revolution of the construction industry. Blockchain has a potential to solve some of the challenges surrounding BIM-based collaboration such as lack of accountability and trust, low security, and protection of data ownership. This paper aims to provide an overview of literature on blockchain and BIM integration and a comparison of blockchain solutions for this type of applications. Forty-six publications were identified and analysed through a systematic literature review process. Furthermore, a thematic analysis was conducted to identify benefits and limitations of different blockchain platforms from the perspective of BIM and blockchain integration. The outcomes of the analysis will help researchers interested in developing such applications to quickly understand the differences between blockchain platforms. Hyperledger Fabric and Ethereum blockchains were identified as two most often used blockchain environments in this domain. Hyperledger Fabric was often a preferred solution in construction industry as it provides privacy and confidentiality for sensitive data, lower transaction cost and lower environmental impact. Recent transfer of the Ethereum blockchain to Proof-of-Stake consensus mechanism may lead to higher adoption of this platform in near future; however, the consequences of the merge should be further investigated.

Keywords:
BIM, blockchain, construction industry, Ethereum, Hyperledger

1 Introduction

The Architecture, Engineering and Construction (AEC) industry is well known for its low productivity and slow adoption of process and technology innovations (Koeleman et al., 2019). In terms of digital technology adoption, the AEC industry in Europe is better than the agricultural sector but worse than all other sectors (Agarwal et al., 2016). One pillar in the digital transformation of the AEC industry can be traced to advances in Building Information Modelling (BIM) (Mathews et al., 2017). However, the adoption of BIM technology raises concerns about data security, data ownership, legal implications and responsibility distribution in shared BIM models (Sacks et al., 2018). Many authors claim that blockchain technology could address these concerns and provide a catalyst for BIM in reaching its full potential. Blockchain is a Distributed Ledger Technology (DLT) which can be defined as a database of transactions stored in a network on multiple (computer) nodes simultaneously, with no need of a central authority controlling the network (Perera et al., 2020). Combining BIM and blockchain can create significant value for all stakeholders involved in the project as it would create a trusted and democratic environment for a true collaborative process (Mathews et al., 2017).

The benefits of blockchain for construction industry raise a lot of interest from both the academia and the industry. The variety of blockchain applications in AEC industry and the benefits and limitations of using blockchain were extensively summarised in a number of recent literature reviews, such as Li and Kassem (2021) and industry reports such as the ICE report (Penzes, 2018). The report identifies three potential areas of blockchain applications in the construction industry: Payment and Project Management, Procurement and Supply Chain Management, and BIM and Smart Asset Management (Penzes, 2018). Blockchain applications can be based on private, public or consortium blockchain architecture (Li and Kassem, 2021). Some authors claim (Perera et al., 2020) that private blockchain networks are more suitable solutions for the construction industry. However, in the same time, a large number of authors still develop their tools on public blockchains (Li and Kassem, 2021). The aim of this study is to investigate which blockchain platforms are used for BIM-based applications and why the authors have chosen them, as this aspect was not explored in any of the previous reviews. The research questions that will be answered in this paper is: What are the benefits and limitations of public and private blockchain solutions specifically in BIM-based applications? The answer will enable researchers and practitioners to understand the benefits and limitations of using different blockchain platforms and help them deciding which solutions they could use in their research and development of applications.

2 Research Methodology

To answer the research question, we conducted a systematic literature review which is “a form of secondary study that uses a well-defined methodology to identify, analyse and interpret all available evidence related to a specific research question in a way that is unbiased and (to a degree) repeatable” (Kitchenham and Charters 2007, p. 6). For data identification Scopus database was used as it has a good coverage of business, economics and engineering subjects and allow advanced search strings using Boolean operators. Grey literature was omitted in this review, as most of the industry reports focus on general benefits of blockchain without describing technological solutions in detail. Figure 1 presents the steps of the review process which led to selection of forty-six journal articles for bibliometric analysis.

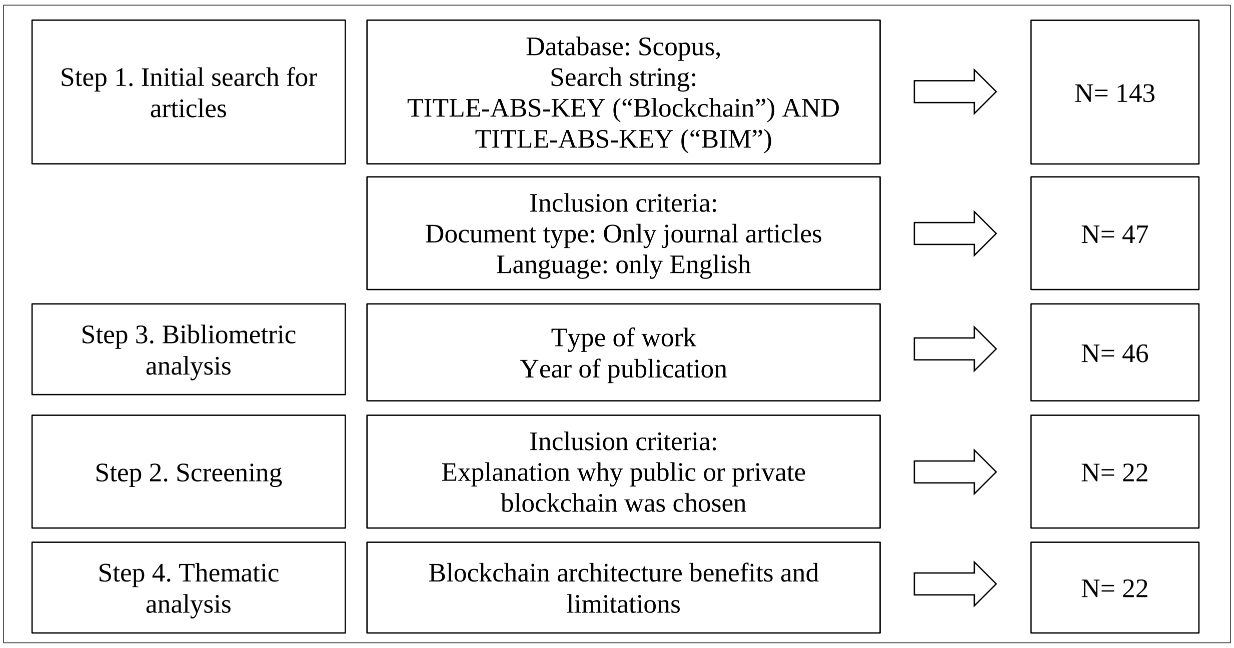

Figure 1. Research methodology flowchart.

Selected documents were screened and only papers explaining the differences between blockchain platforms were further included in the thematic analysis. We used the NVivo 12 software to line-code the text explaining the reasons for choosing a particular blockchain platform. In the last step, we synthesised the codes in a comparison table.

3 Literature Review

3.1 Bibliometric Analysis

In the first step of the review, a short bibliometric analysis of forty-six selected papers was conducted. Figure 2 presents the occurrence of the publications about BIM and blockchain over the years. This topic has emerged in the literature in 2018 with the first review paper from Amaludin and Bin Taharin (2018). In the next year, already four review papers and four papers proposing a framework for BIM and blockchain integration have been published. First proof of concepts and prototypes emerged in 2020. In total, the highest number of publications are review papers followed closely by papers presenting frameworks. Number of prototypes and proof-of-concepts is still relatively small but is slowly increasing in recent years.

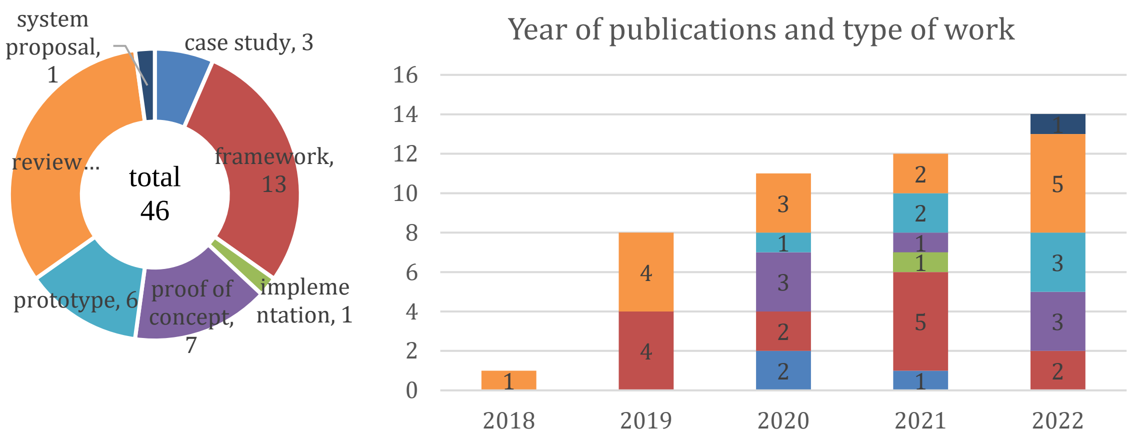

Figure 2. Number of publications per year and type of research.

3.2 BIM and Blockchain Applications

In the last step of bibliometric analysis we classified the identified applications according to their type (Figure 3). Most of the authors focus on the BIM information management including developing blockchain-based document management systems (Das et al., 2021a) and Common Data Environments (CDEs) (Hijazi et al., 2022; Tao et al., 2021). As a CDE facilitates continuous collaboration between all project participants and ideally works as a single source of truth for all project information, it must uphold data security, quality, and integrity standards, which can be secured by blockchain-based technologies (Nawari and Ravindran, 2019a). One of the biggest strengths of blockchain is the high level of security, making it a suitable solution as an underlying technology for BIM exchange servers (Das et al., 2021a). Integrating blockchain in BIM collaboration process offers a number of advantages: an immutable record of changes in a digital model, assigning responsibilities to all stakeholders according to their roles, and a transparent record of data entries and ownership in the BIM model (Li et al., 2019). Through blockchain features such as decentralization, the immutability of decisions and files, and intellectual property protection, some of the shortcomings of centralised CDE platforms could be tackled (Dounas et al., 2020).

A large number of authors focus specifically on tracking changes in BIM models and different methods to implement it. Thanks to timestamping of transactions and a tamper-proof guarantee, the record of changes is transparent and easy to follow. A cryptographically secure digital signature protects data provenance and metadata such as timestamps or author information (Turk and Klinc, 2017). Blockchain mechanisms can be used for decentralised design optimization conducted by both human or artificial intelligence agents in parallel (Dounas et al., 2020). The prototype from Dounas et al. (2020) enhances design problems, allowing both a collaborative and competitive approach, as it records all developed design variants transparently. The results of a case study demonstrated by Li et al. (2021) indicate that blockchain combined with AI can provide evidence support for stakeholders especially during a claim.

High number of publications investigates the use of blockchain and BIM to enhance a more secure and transparent payment system and eliminate the problem of late payments (Chong and Diamantopoulos, 2020). Blockchain-based smart contracts enable to automatically release payments triggered by various events during the lifecycle of a built asset (Sonmez et al., 2022).

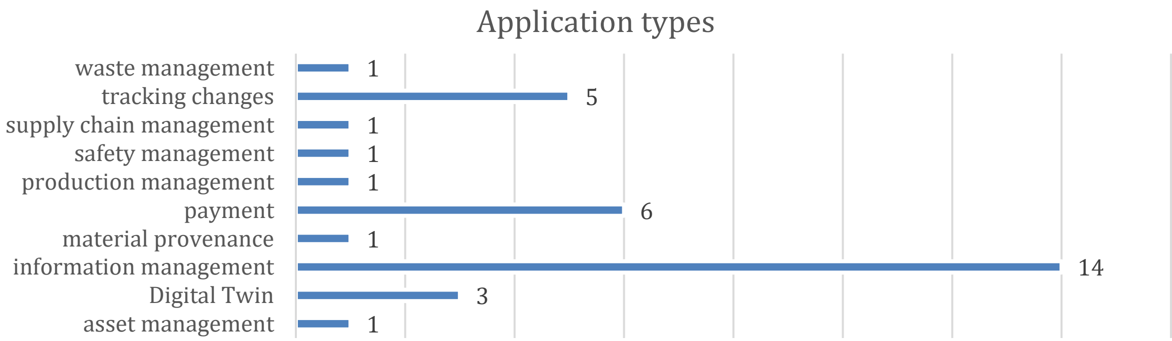

Figure 3. Types of blockchain applications.

3.3 Limitations of BIM and Blockchain Integration

One of the biggest challenges of integrating BIM with blockchain technology is information redundancy, as BIM files are known for their massive data volume (Hamledari and Fischer, 2021; Kiu et al., 2022). There is a significant conflict between the need to transact large BIM files and the limitation of blockchain to store data (Das et al., 2021b; Teisserenc and Sepasgozar, 2021). Xue and Lu (2020) developed an innovative method to minimize information redundancy using a semantic differential transaction approach. In their proof of concept, instead of recording the entire model on the blockchain once a change is made, they record only the differences between different model versions (Xue and Lu, 2020). In contrast, a tool developed by Zheng et al. (2019a) stores only the BIM files' hashing signatures on a blockchain and this way, historical records of BIM modifications are maintained (Zheng et al., 2019a). Zheng et al. (2019b) developed another application that allows a context-aware access control to BIM data based not only on the roles of the stakeholders in the project but also on the specific use-case situation. Third solution to the scalability problem is a hybrid blockchain solution where large BIM files are stored on a distributed storage such as Inter-planetary File System (IPFS) that could be coupled with blockchain (Das et al., 2021b).

The Inter-planetary File System (IPFS) was created to address the challenge of saving large files in distributed applications (Dounas et al., 2021). IPFS is "a peer-to-peer distributed file system that seeks to connect all computing devices with the same file system" (Benet, 2014).

IPFS utilizes some successful ideas of four other enabling technologies. It uses a routing system based on Distributed-Hash Tables (DHTs), a block exchange protocol inspired by BitTorrent, a version control system from Git and a naming system based on the self-certified filesystem (Benet, 2014). Each file stored on the IPFS is associated with a unique cryptographic hash generated by the SHA256 algorithm called the content identifier (CID) (Dounas et al., 2021). The CID works as the "address" of the file, making it findable and addressable to other network members and giving them access for downloading (Tao et al., 2021). Only concerned stakeholders receive the CID link to ensure the right access and permission control, which offers a solution to data privacy and security (Li and Kassem, 2021). Replacing central data storage with distributed IPFS could improve information flows in the construction industry as it offers faster and safer exchanges and enhances data protection (Darabseh and Martins, 2021).

4 Findings and Discussion

4.1 Blockchain Architecture Comparison

In the last step of this review, we analysed blockchain solutions used for the developed tools and frameworks. Figure 4 compares the number of applications developed on different blockchain platforms. We classified ten use cases as unknown as some of the authors did not specify the platform they used in their proof-of-concept and prototypes. The two best-known blockchain platforms, Ethereum (public) and Hyperledger Fabric (private), were predominantly used for BIM-based applications, with publication authors showing a preference for the Hyperledger platform.

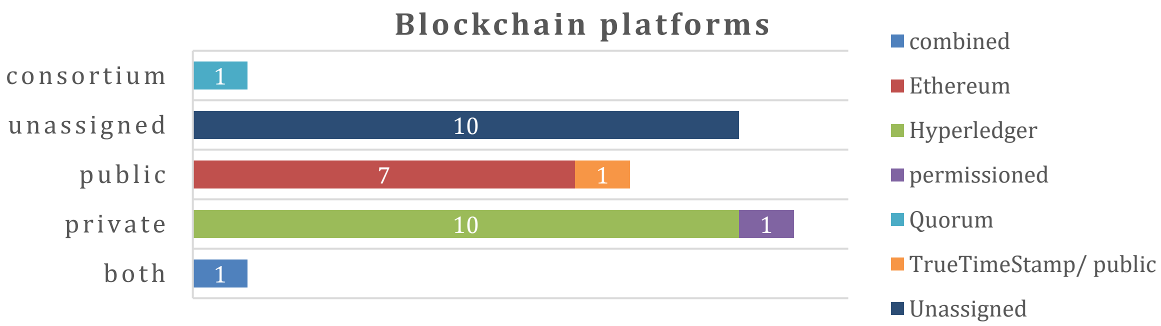

Figure 4. Number of identified use cases using each blockchain platform.

A similar usage level of public and private blockchain platforms suggests that both types are seen as suitable and are used interchangeably in the construction industry. Both secure immutability, transparency, and accountability, enable automatization through smart contracts and remove the need of a central authority or a third party overlooking the process.

Some authors claim a clear advantage of using a private blockchain network like Hyperledger in the construction industry, as they are characterised by high data privacy and confidentially which is required to store sensitive construction data (Hijazi et al., 2022; Li et al., 2022). Tao et al. (2021) argues that Hyperledger protects data privacy by allowing only authorised project members to participate in the network. Furthermore, they reported that Hyperledger is the most suitable solution to develop a CDE due to its modularity and extensible open-source character. Other advantages of private blockchain solutions are higher scalability and more throughput (Hunhevicz et al., 2022; Li et al., 2022), faster and more affordable transactions (Zheng et al., 2019a) and easier implementation of changes (Li et al., 2019). If public auditability is required, it is also possible to connect parts of data from private blockchain to a public blockchain (Teisserenc and Sepasgozar, 2021).

Public blockchains such as Ethereum are also quite common solutions chosen by developers of BIM-based applications. In general public blockchains are known for providing the highest level of security due to having the highest hash rate (Erri Pradeep et al., 2021). Moreover, the use of cryptocurrencies enables rewarding the participants for using the network rightly which effectively creates more trust (Hunhevicz et al., 2022; Teisserenc and Sepasgozar, 2021). Public blockchains are the most decentralised systems, without any controlling party, which also leads to more openness and transparency (Hunhevicz et al., 2022; Zheng et al., 2019a). Furthermore, they are more robust and can provide a long-term storage as they are independent from any centralised party and its failures (Hunhevicz et al., 2022). As access to public blockchain is anonymous, the privacy and the identity of the participants is protected (Zheng et al., 2019a). Ethereum is the most established public blockchain with the most of support for developers, which is one of the reasons why developers are choosing it over other public systems (Hunhevicz et al., 2022; Sonmez et al., 2022). One of the most significant strengths of Ethereum is the use of Solidity as a main programming language for smart contracts as it is a universal, interoperable and very powerful language (Ciotta et al., 2021; Sonmez et al., 2022). Additionally Ethereum smart contracts operate on a Turing complete Ethereum Virtual Machine - EVM (Erri Pradeep et al., 2021; Hunhevicz et al., 2022).

However, public blockchain platforms including Ethereum, have some significant limitations. First of all, the extreme transparency and openness of public blockchain leads to lack of privacy and confidentiality of transactions which is a significant barrier for most of the construction companies (Li et al., 2019; Teisserenc and Sepasgozar, 2021). A complete immutability of transactions means that it is impossible to remove data from the blockchain, which might be another barrier, as the “right to be forgotten” rule might apply to some of the data generated during projects’ lifecycle (Teisserenc and Sepasgozar, 2021). Another problem hindering the acceptance of public blockchain by construction professionals is the volatility of cryptocurrencies, resulting in unstable costs of transactions (Erri Pradeep et al., 2021; Hunhevicz et al., 2022). Additionally, due to the extremely high prices of some of the most common cryptocurrencies, the costs of conducting transactions on the blockchain can reach unreasonable levels (Hunhevicz et al., 2022; Sigalov et al., 2021). In case of blockchains using Proof-of-Work (PoW) consensus mechanisms a very important limitation is their low scalability, resulting in low number of transactions per second (Hunhevicz et al., 2022; Zheng et al., 2019a). PoW is also known for being extremely computationally expensive, leading to very high levels of energy consumption (Nawari and Ravindran, 2019b; Sigalov et al., 2021). Hunhevicz et al. (2022) reported that high prices of transactions on Ethereum require an efficient use of storage space used for smart contracts emulation, limiting the flexibility of the development process.

Due to the very recent migration of Ethereum to Proof-of-Stake consensus mechanism, some of the disadvantages of public blockchain platforms resulting from the use of PoW do not apply to Ethereum anymore (Ethereum, 2022). PoS has generally much lower environmental impact, as it does not require solving difficult computational problems and additionally is a more scalable solution than PoW (Teisserenc and Sepasgozar, 2021). However, the “merge” of the Ethereum to PoS did not influence high prices of transactions, as gas fees are still required to deploy a smart contract (Ethereum, 2022). As the merge is a very recent change in Ethereum’s architecture, the consequences of it for application development are still unknown.

A consortium blockchain such as Quorum or Hyperledger Besu, provides the access to transactions to a limited group of stakeholders, leading to more security, better scalability and lower costs of transactions than public blockchains (Sigalov et al., 2021; Zheng et al., 2019a). A Quorum blockchain is a business oriented system that is based on the Ethereum and has some of Ethereum's benefits (Sigalov et al., 2021). In the same time, it enables private interactions on-chain providing limited access to specific data only to authorised users (Sigalov et al., 2021).

Table 1. Comparison of public and private blockchain features relevant for BIM-based applications based on the identified literature.

<table>
<tr><th colspan="2">Public blockchain</th></tr>
<tr><th>Reported benefits</th><th>Reported limitations</th></tr>
<tr><td>1. Highest security levels due to highest hashrate (Erri Pradeep et al., 2021; Hamledari and Fischer, 2021; Sigalov et al., 2021)
2. Cryptocurrencies provide incentive and more trust (Hunhevicz et al., 2022; Teisserenc and Sepasgozar, 2021)
3. More robust and long term storage (Hunhevicz et al., 2022)
4. Most decentralised system, more openness and transparency (Hunhevicz et al., 2022; Zheng et al., 2019a)
5. Anonymity and protecting privacy of the identity (Zheng et al., 2019a)
6. Independent from software provider or controlling party (Zheng et al., 2019a)
7. Easy accessibility (Zheng et al., 2019a)</td><td>1. Lack of flexibility (Elghaish et al., 2020)
2. Lack of possibility to delete data (Teisserenc and Sepasgozar, 2021)
3. Lack of privacy and confidentiality of transactions (Li et al., 2019; Nawari and Ravindran, 2019b; Teisserenc and Sepasgozar, 2021)
4. Unstable cost of transactions due to cryptocurrencies' volatility (Erri Pradeep et al., 2021; Hunhevicz et al., 2022)
5. High cost of transactions (Hunhevicz et al., 2022; Nawari and Ravindran, 2019b; Sigalov et al., 2021)
6. Low scalability and throughput, slow validation of transactions (Hunhevicz et al., 2022; Nawari and Ravindran, 2019b; Zheng et al., 2019a)*
7. High energy consumption (Nawari and Ravindran, 2019b; Sigalov et al., 2021; Zheng et al., 2019a)*
*only for PoW</td></tr>
<tr><th colspan="2">Ethereum</th></tr>
<tr><th>Reported benefits</th><th>Reported limitations</th></tr>
<tr><td>1. Universal, interoperable and powerful programming language Solidity (Ciotta et al., 2021; Hamledari and Fischer, 2021; Sonmez et al., 2022)
2. Turing complete Ethereum Virtual Machine (EVM) for smart contracts execution (Dounas et al., 2020; Erri Pradeep et al., 2021; Hunhevicz et al., 2022)
3. Most established blockchain (Erri Pradeep et al., 2021; Hunhevicz et al., 2022; Sonmez et al., 2022)
4. Gas fees enabling termination of smart contracts (Dounas et al., 2020)
5. Change to a Proof of Stake (PoS) consensus mechanism in September 2022 which has lower environmental impact (Teisserenc and Sepasgozar, 2021)
6. PoS providing more scalability (Teisserenc and Sepasgozar, 2021)</td><td>1. Need for efficient use of storage space due to high cost (Hunhevicz et al., 2022)</td></tr>
<tr><th colspan="2">Consortium blockchain</th></tr>
<tr><th colspan="2">Quorum</th></tr>
<tr><th>Reported benefits</th><th>Reported limitations</th></tr>
<tr><td>1. Business compatible blockchain using Ethereum advantages (Sigalov et al., 2021)
2. Compatible with other blockchains (Sigalov et al., 2021)
3. Enhanced privacy thanks to access control system (Sigalov et al., 2021)
4. Using IBFT mechanism provides better scalability (Sigalov et al., 2021; Zheng, et al., 2019a) and confidence to reliability of transactions (Sigalov et al., 2021)</td><td>1. High safety and performance requirements (Zheng et al., 2019a)</td></tr>
<tr><th colspan="2">Private blockchain</th></tr>
<tr><th>Reported benefits</th><th>Reported limitations</th></tr>
<tr><td>1. Role-based access control and authorisation (Hunhevicz et al., 2022; Li et al., 2019; Tao et al., 2021; Teisserenc and Sepasgozar, 2021; Wu et al., 2022; Zheng et al., 2019a)</td><td>1. Risk of network collapse along with their administrator</td></tr>
</table>

2. Providing confidentiality and security of sensitive data (Chong and Diamantopoulos, 2020; Hijazi et al., 2022; Li et al., 2019, 2022; Nawari and Ravindran, 2019b; Zheng et al., 2019a) 3. Scalable solution, more throughput (Hunhevicz et al., 2022; Li et al., 2022) 4. Fast transactions (Li et al., 2022; Zheng et al., 2019a) 5. More affordable (Hunhevicz et al., 2022; Zheng et al., 2019a) 6. Easier to agree on changes (Li et al., 2019) 7. Possible to connect parts of data to public blockchain to make it auditable for public (Teisserenc and Sepasgozar, 2021)	(Hunhevicz et al., 2022) 2. Higher risk of data manipulation and receiving attacks (Zheng et al., 2019a)
Hyperledger	
Reported benefits	Reported limitations
1. Modular, flexible and reusable architecture (Elghaish et al., 2020; Hijazi et al., 2022; Li et al., 2022; Nawari and Ravindran, 2019b) 2. Open-source blockchain using general purpose language (Nawari and Ravindran, 2019b; Suliyanti and Sari, 2020; Tao et al., 2021) 3. Cross-chain design allowing to split private communication and transactions to a protected channel (Li et al., 2022; Nawari and Ravindran, 2019b) 4. Transaction integrity between the channels (Li et al., 2022) 5. Practical Byzantine Fault Tolerance (PBFT) consensus needing a decision from all parties (Chong and Diamantopoulos, 2020) 6. Crash fault tolerance (CFT) consensus for network completeness and high speed 7. Compatible with commercial software such as IBM® Blockchain Cloud, the Oracle Blockchain (Elghaish et al., 2020) 8. Query functions (Li et al., 2022) 9. Minimal computing power needed (Tao et al., 2022) 10. Well established and secure permissioned blockchain (Wu et al., 2022)	

4.2 Emerging Technological Solutions

The belief that public blockchain cannot provide data privacy and does not offer setting permissions levels is not entirely correct. Public blockchain was not developed to handle private transactions but it is possible to achieve a better privacy level by using protocols like zero-knowledge proofs or simple techniques like end-to-end encryption (Teisserenc and Sepasgozar, 2021). In some public blockchains such as in the BSV, the identity of actors is private and the data can be encrypted using hashing techniques (Louw, 2022). The IOTA is another emerging blockchain alternative designed specifically for IoT data and providing energy efficiency, low cost, privacy, and high security standards (Bernal Bernabe et al. 2019). As mentioned solutions are very recent and still developing, there is a need to investigate their implementation in construction industry domain through further research and tests.

5 Conclusion and Future Research

The aim of this study was to identify applications integrating both BIM and blockchain technology and to evaluate blockchain solutions utilised in those applications. First, a systematic literature review was conducted to identify all publications mentioning BIM and blockchain. Forty-six documents were selected and analysed in a bibliometric and thematic analysis. Finally, a comparison of different blockchain platforms from the perspective of BIM and blockchain integration was presented. The results show that private blockchains such as Hyperledger Fabric are more often a preferred solution in construction industry. One of the main reasons for that is the need for privacy and confidentiality of sensitive information exchanged in construction projects. Lower environmental impact and costs of the transactions are other factors playing a significant role in choosing private blockchains over the public solutions. The only disadvantage of private blockchain networks identified in this study was lower level of security and higher risk of network failure or manipulation of data on the blockchain, due to higher centralisation of the control over the network. For that reason, a substantial number of researchers have chosen Ethereum to develop their BIM-based applications.

This study is analysing the technological solutions for BIM and blockchain integration in a greater depth than the previous reviews. It provides a comprehensive overview of benefits and limitations of different blockchain platforms used in this domain. Blockchain technology is very recent and new methods and techniques are still rapidly being developed to overcome its current limitations. The difficulty of storing large files on the blockchain could be solved by integrating blockchain with distributed storage such as the IPFS. On the other hand, new protocols and various encryption methods might be used to improve the privacy and confidentiality of data in public blockchains. However, little research was done on implementation of these techniques for blockchain applications in the construction industry and it should be investigated in the future studies.

6 Acknowledgement

The support of the Cloud-based Building Information Modelling (CBIM) European Training Network funded by the European Union’s Horizon 2020 Programme under the Marie Skłodowska-Curie grant agreement No 860555 is gratefully acknowledged in making this research possible.

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Closing the Existing Circularity Gap in the Building Construction Industry Using Artificial Intelligence: A Systematic Review of Literatures

Benjamin I. Oluleye[1*], Daniel W.M. Chan[1] and Prince Antwi-Afari[2]

[1] Department of Building and Real Estate, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China
[2] Department of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong, China

benjamin.oluleye@connect.polyu.hk; daniel.w.m.chan@polyu.edu.hk; pantwiaf@connect.hku.hk
*****Corresponding author

Abstract:
The Circularity Gap Report 2022 has proven how linear the world is nowadays. The globe can only recycle 8.6% of materials used, which leaves a wider circularity gap of over 90%. To address this unfavourable outcome, the Circularity Gap Report 2022 advocated for a technology-driven circular economy (CE) using artificial intelligence (AI) in the building construction industry (BCI) which is regarded as the most resources intensive sector, to close the existing circularity gap. Researchers in the construction domain are currently making gradual progress in enabling systemic circularity using AI techniques toward closing the circularity gap. However, relevant research findings are still scattered, and no known essential studies have made credible efforts to systemize the results for reference and implementation in practice. This paper aims to conduct a thorough systematic review and evaluation of related studies on AI and CE to understand and evaluate how AI could be applicable in bridging the extant circularity gap. The various application areas of AI along the building life cycle were uncovered including pre-demolition auditing, design for deconstruction, optimization of circular business model, on-site recycling, and reverse logistics. The roadblocks of the AI applications were identified together with forward-looking directions for the wider promotion of AI applications. This study has provided a clear path and roadmap for AI applications in closing the existing circularity gap and enhancing more CE implementation in BCI worldwide.

Keywords:
Artificial intelligence, circular economy, circularity gap, construction industry

1 Introduction

The circular economy (CE) concept is growing rapidly among scholars and practitioners globally. Aimed to enhance sustainable production and consumption diffusion based on waste and resource circularity, the CE paradigm is perceived as the alternative to the traditional linear economy of take-make and waste (Oluleye et al., 2022a). Despite this, global circularity is trending down and not up (Wuni & Shen, 2022). This is evident in the Circularity Gap report 2020 where the global economy was 8.6% circular, although two years earlier, 9.1% global circularity was recorded (Circle Economy, 2022). This connotes that things are getting worse as the globe is still shackled by the outmoded 'take-make-waste' methods (Oluleye et al., 2022b). This problem is attributed to all sectors across the globe. However, the building construction industry(BCI) contributes more to the widening circularity gap because it consumes the highest of resources globally (Antwi-Afari et al., 2021). Also, activities of the BCI produce the highest waste relative to other sectors globally(Bilal et al., 2020). Therefore, to reduce the waste and resource consumption in BCI, and continue to enjoy the contribution of BCI to the global GDP, attention must be devoted to closing its circularity gap. Technology-driven circularity has been advocated as an enabler that could promote better circular advantage and bridge the circularity gap in the BCI (Yu et al., 2022).

One of the veritable technologies that could be a game changer in closing the circularity gap is artificial intelligence (AI) (EMF, 2019). AI is the science and technology of developing an intelligent system that can reason, learn, plan, and solve problems (Schlüter et al., 2021). AI technology has countless benefits which exist in extant studies. For instance, it can adopt complex algorithms to learn from big data and use the knowledge gained to assist industrial practice (Pan & Zhang, 2021). Thus, AI could enhance productivity and accurate predictions at a high speed. Due to the strength of AI, it has gained attention in the BCI, especially in enabling systemic circularity development (Akanbi et al., 2020). This has resulted in a recent rise in research work and publications at the intersection of AI and CE in the BCI. Despite this, the AI-driven circularity situation is still worrisome as it is still very difficult to capture the state of the art of AI in CE in the BCI. In fact, veritable domains where AI could enable a systemic circularity in the BCI are still vague to researchers and practisers.

To tackle this research problem, undertaking a comprehensive review and analysis of AI potentials in BCI toward closing the circularity gap is important. This study stands out because existing reviews have only considered AI in the Architecture, Engineering, and Construction (AEC) industry, green building, and solid waste management (c.f., Abdallah et al., 2020; Darko et al., 2020). Despite the usefulness of extant reviews and the promising prospect of AI in the BCI, none have examined how AI could enable CE in BCI towards bridging the existing circularity gap. This sluggish development is attributable to the incumbent nature of CE in the BCI and the low knowledge of promoting CE among major stakeholders using digital technology. This research adopts a systematic review lens of academic studies concerning the applications of AI in closing the circularity gap in BCI, status quo, prospects, and possible challenges. This review will enable practitioners and academics in developing innovative AI-enabled solutions and technologies for application in bridging the circularity gap and enhancing sustainable production and consumption in the BCI.

2 Bibliographic Materials Collection

A critical review technique is used to assess the existing academic research published comprehensively. Initial search was carried out in google scholar to identify relevant reviews if any to better structure to research question, but none exist. Based on the combinations of different search terms, the actual search was conducted in Scopus databases (being the largest database for academic papers) in June 2022. Theme specific keywords used include:

"circular economy" OR "circularity" OR "circular business" OR "circular business model" OR "circular advantage" OR "recycling" OR "reuse" OR "CE" OR "waste") AND TITLE-ABS-KEY ("digitalisation" OR "deep learning" OR "Big Data" OR "Artificial Intelligence" OR "machine learning" OR "robotics" OR "artificial neural network" OR "digital technology " OR "sensor" OR “computer vision” OR "image processing") AND TITLE-ABS-KEY ("building project" OR "project life cycle" OR "construction and demolition")).

The keywords used were based on combination of keywords from various related extant studies. Moreover, a wild card (*) was added to certain keywords to ensure that their plural was also captured during the search. Also, the query string was limited to English language. The search conducted resulted in 262 articles. The results were screened manually to exclude immaterial papers by examining the title, abstract, and significance of all the articles. After the eligibility check, 60 journals were found relevant. Further, deep scrutiny was conducted on the relevant articles by reading the contents which resulted in 21 journal articles, which formed the sample size for the study.

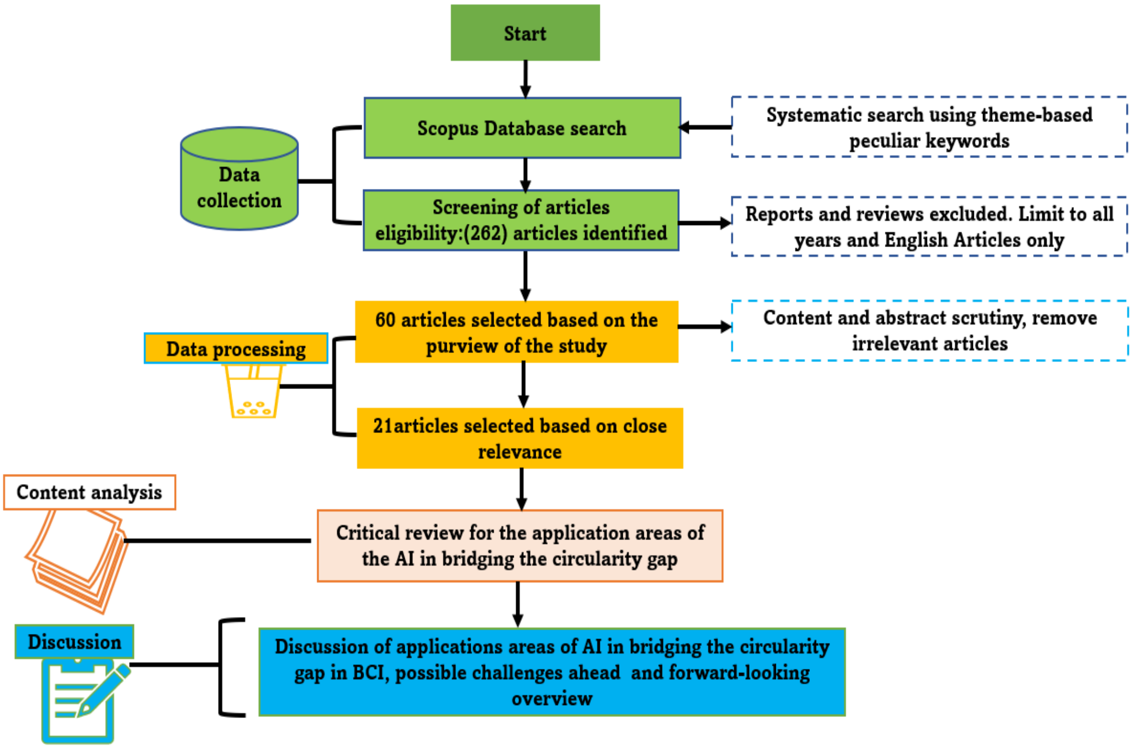

Figure 1. Research methodology flowchart for the study

3 Application Domains of AI in Closing the Circularity Gap in Building Construction Industry

In this section, the areas AI could be adopted towards closing the circularity gap in BCI are reported based on review of extant studies. The summary of the application domains is presented in Figure 2.

3.1 Design for disassembly, deconstruction, and resilience

Circular economy requires an innovative design to keep products and materials at their highest value always (EMF, 2019). This is necessary because the design stage is the most critical in complying with the CE. Decisions regarding materials type, connection type, and specification are often made at this stage. Innovative design can enable the disassembly, deconstruction, and resilience of materials at end of life (O'Grady et al., 2021). Various design characteristics must be taken care of to enable value-creating, cascading, and looping of materials at end of life (Akinade et al., 2018). The choice of materials and the required specifications needed are usually subject to manipulations by designers thus creating a wider circularity gap at end of life. Therefore, through iterative machine-learning-assisted design procedures that enable quick prototyping and testing, AI may enhance and expedite the creation of circular building products, components, and materials suitable for a CE (EMF, 2019). Various circularity complexity at the design stage of the building can be effectively managed with AI. To promote design for disassembly, deconstruction, and resilience, designers must examine a large amount of data regarding the properties of materials, which could be easily identified by AI. Aziz et al. (2021)

posited that neural networks could enable construction materials optimization towards a systemic circularity. Further, Genetic algorithms are quite popular in solving complexity in a circular design to enable veritable disassembly, deconstruction, and resilience of materials at end of life.

3.2 The technical and economical circularity of materials

One of the recent efforts to promote the circularity of building materials entails determining their circularity potentials to enable stakeholders to make credible judgments regarding bridging the circularity gap at end of life. This process seems complicated and complex. Thus, a machine learning model can effectively predict the circularity potentials of structural building components at end of life. Rakhshan et al. (2021a) proposed a novel probabilistic machine learning model using a support vector machine, random forest, K-Nearest neighbor, and Gaussian Process to predict the circularity potentials of structural elements at the end of life of a building. The model revealed that matching the design of a new building with the recovered element strength is the most significant predictor of the circularity of potential building structural components. Further, economic and market situations are the aspect of CE that is quite important when delivering secondary products. Thus, it is very effective in closing the circularity gap. As such, Rakhshan et al. (2021b) adopted K-Nearest Neighbours, Random Forests, Artificial Neural Networks, and Support Vector Machines to develop a probabilistic predictive model that can evaluate the economic circularity of building elements. The models predicted financial risks, the procurement process, and the labor cost as the most influential economic factors affecting the economic circularity of materials. An adequate understanding of these factors would promote the economic dimensions of CE and improve the market and supply of secondary materials which would invariably close the circularity gap.

3.3 Onsite robotic recycling

Closing the circularity gap during the building construction stage can be enabled using a robotic waste sorter. Thus, onsite recycling of waste can reduce construction waste disposal at a landfill. Wang et al. (2019) developed a prototype nail and screw autonomous robot using computer vision (CV) technology and a complete coverage path planning algorithm. The CV technology was used by the robot in identifying the nails and screw waste by searching the entire workspace during construction. Neural network technology assisted the movement of the robot in an unknown environment while faster R-CNN methods were used to find the scattered nails and screw waste in real-time for easy onsite recycling. Wang et al. (2020) also developed a vision-based robotic system for recycling pipes and cables waste on-site using mask R–CNN based on a faster R–CNN algorithm for construction waste detection, picking, and placing. A database of CDW was developed and used to train a CV model for recognizing residual pipes and cables. Simultaneous Localization and Mapping (SLAM) technology enabled the robot to cope with complex site situations.

3.4 Pre-demolition auditing

Closing the circularity at the end of life of a building requires effective and accurate estimation of the quantity of materials and waste during deconstruction and demolition (Song et al., 2017). This will facilitate appropriate planning for the reuse or recycling of materials at the end of life. Pre-demolition has been seen as a technique that gives veritable information needed by construction stakeholders to optimize existing buildings as part of the deconstruction and demolition process. Nonetheless, the current approach for pre-demolition auditing at end of life is manual, not sustainable, and time-consuming due to a large amount of information and data about the features of buildings and various materials outputs. This has created more problems for the existing circularity gap. Akanbi et al. (2020) however developed a novel deep learning model for predicting the amount (in tons) of salvage and waste materials that are obtainable from buildings at the end of life before demolition. Using a deep neural network, they adopted 2,280 building demolition records as datasets from the UK demolition industry. The model achieved an overall accuracy of 97%. The developed model revealed the actual amount of recyclable, reusable, and waste materials obtainable from buildings when demolished. The developed model is expected to guide BCI materials' systemic circularity agenda and end-of-life in closing the circularity gap. Further, Martinez et al. (2022) developed a deep learning model for automated waste auditing in BCI. The developed system can identify waste materials, and quantity and determine appropriate CE strategies for ensuring value conservation and bridging the circularity gap at end of life.

3.5 Optimization of circular business model

The circular business model remains one of the backbones of systemic circularity in the BCI. The competitive strength of circular business models for the BCI can be optimized using AI thus bridging the circularity gap (Panu, 2021). AI can improve the circulation of construction products through the prediction of prices and smart inventory management (EMF, 2019). For instance, AI can enable the development of an intelligent pricing system for secondary products. This will become feasible through intelligent analysis of the market situation impacting the prices of secondary products to determine the actual price. Further, AI is suitable for closing the circularity gap by facilitating a circular business model. This encompasses effective waste sorting, waste estimation, and segmentation.

The sorting of waste is crucial in attaining materials value recovery and the development of markets for secondary construction materials. For example, Lu et al. (2022) developed a CV-based model for recognizing and segmenting construction waste to enable value recovery. The study used annotated big datasets of 5,366 construction waste images for model development. The formalizing of a deep learning-based semantic segmentation approach for construction waste recognition in complex environments. Further, Na et al. (2022) and Chen et al. (2022a) developed an artificial intelligence-based algorithm that can effectively quantify and recognize construction waste. Also, Lu et al. (2021) developed a machine learning model for estimating construction waste generation. Four types of popular and powerful ML models, namely multiple linear regression (MLR), decision tree (DT), Grey models (GM), and artificial neural network (ANN) were selected and compared by their strengths and weaknesses. The four models all achieved highly accurate predictions of waste generation. Amongst them, GM and ANN have higher prediction accuracy but are more like “black boxes”, not readily accessible to readers. One should also avoid overfitting issues when using the models. Thus, waste estimation, sorting, and segmentation are crucial for minimizing waste at the end of a product’s lifecycle and providing the materials for new circular products. The actualization of this using AI would promote a seamless circular business model and further support bridging the circularity gap.

3.6 Reverse logistics in BCI

To bridge the circularity gap in the BCI, careful attention must be given to the reverse logistic network of materials (Schlüter et al., 2021). Reverse logistics in a CE encompasses all operations related to the upstream movement of products and materials. Reverse logistics entails network design, collection, warehousing, and processing to recapture value (Wilson et al., 2021). The complexity involved in reverse logistics requires the adoption of AI to enable the process. To make reverse logistics work requires providing solutions to the demand and supply of construction materials and the varied conditions of the returned components (Schlüter et al., 2021). Thus, to choose the next circularity of returned construction materials such as reuse, recycling, and components recovery, various factors and data could be considered regarding the conditions of the product tother with the market force (Wilson et al., 2022). Therefore, to enable a veritable CE and bridge the circularity gap, a powerful AI-based analytical model to make sense of the whole process is veritable. This process will make circularity gap bridging decision making more feasible and practicable.

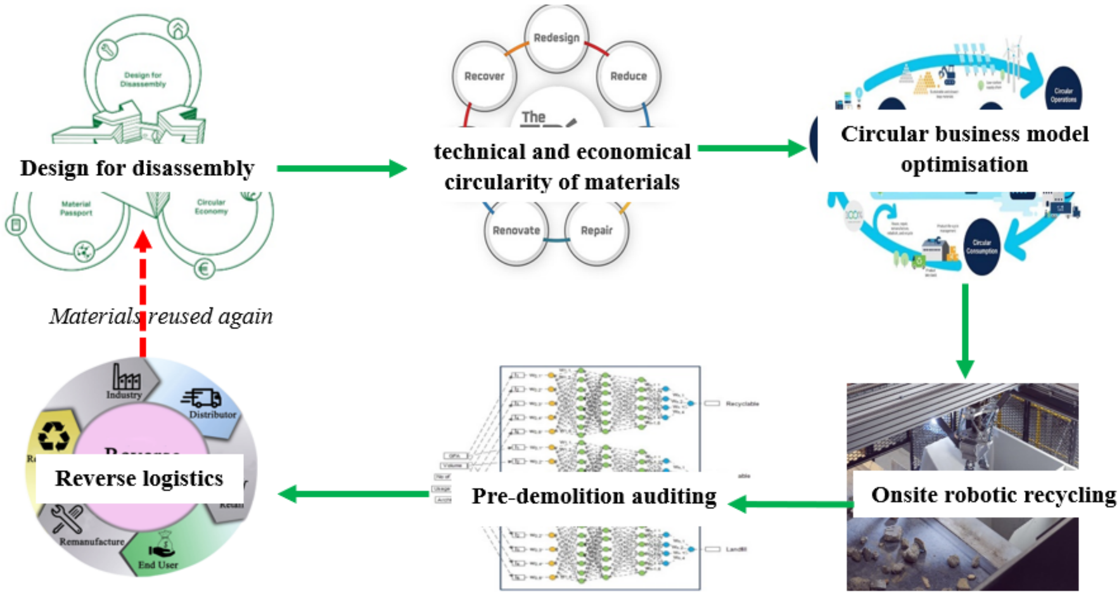

Figure 2. Framework of application domains of AI in closing the circularity gap in BCI

4 Potential Challenges and a Forward-looking Overview

4.1 Challenges ahead

The application of AI in bridging the circularity gap in the BCI is still developing. However, this review noted various lessons from extant studies, which might hamper the improvement and transformation of academic efforts into practical deployment.

a) *Lack of detailed and sharable datasets that could be adopted by researchers in training models*: Existing studies revealed that the adoption of AI in enabling CE in the BCI is limited due to a lack of real-world datasets that are oriented to the industrial practice of systemic circularity (Akanbi et al., 2020). This has resulted in difficulties in rigorous AI-based research in closing the circularity gap. If this situation persists, it will distract effort from the core line of continuous improvement of AI-based circularity in the BCI.

b) *Less attention to digital circularity in the BCI*: Limited amount of research effort has been dedicated to the application of AI in enabling circularity in the BCI (Lu & Chen, 2022). The vast amount of waste generated, and intensive resource consumption attributed to the BCI as compared to the limited number of studies poses a greater problem ahead (Oluleye et al., 2022a). Thus, an urgent need for more research dedicated to CE in the BCI enabled by AI is inevitable (EMF, 2019). If attention is not given to this need, recycling, recovery, reuse, and remanufacturing will be frustrated and further create diverse problems such as pollution in landfill, depletion of natural resources, and wilting circularity gap (Akanbi et al., 2020).

c) *The detached link between CE research and practice in the BCI*: Although there exists limited research on AI and CE in the BCI, existing research is not properly linked and adopted at the industrial level. This has frustrated the improvement of the existing circularity gap in BCI. Many of the existing research are conducted without considering the needs of the industry (Antwi-Afari et al. 2022). Thus, it is vital to link the entire AI-based research in a CE with industrial practices.

4.2 Forward-looking overview

Based on the above challenges, various directions are advocated for future AI-based research for promoting systemic circularity in the BCI. These efforts are necessary because more AI-based initiatives are needed to enable zero waste and total circularity in the BCI. Importantly, the potentials of AI in promoting CE in the BCI are still untapped. Understanding where the opportunities lie and putting in place enabling environment to realize them are imperative. Due to the embryonic nature of AI in CE, the following are therefore vital in realizing the potential of AI in enabling systemic circularity in the BCI

a) More commitment to AI for systemic circularity in the BCI: Global application of AI is expected to generate USD 13 trillion in 2030, as such, more research commitments are needed to investigate better opportunities in AI in promoting CE in the BCI (EMF, 2019; Wilson et al., 2021). Triggered by the contributions of BCI to the GDP of about 25%, it is also necessary to create better awareness and understanding of how AI can support CE through robust research. For example, effort should be put in place in the development of *autonomous circularity of waste using deep reinforcement learning*. This research direction would be able to automatically detect waste materials that could be suitable for various circularity dimensions at the end of life. Moreover, awareness of case studies and potential use cases as presented in this paper should be made known to stakeholders to further explore more opportunities on what AI can achieve in BCI systemic circularity. In addition to that, government and non-governmental organizations can increase financial investment in AI for CE in the BCI. As commitment is shifted towards more AI-CE-based research in the BCI, most of the research should specifically investigate practical problems faced by BCI in the adoption and application of CE. This will enable the real application of academic research in solving CE-related problems using AI technologies in the BCI.

b) Exploring industrial innovative approach to promote data availability, accessibility, and sharing: Adequate access to veritable data for training machine learning and AI algorithms will be credible to the upliftment of AI adoption and application towards enabling better circularity of resources in the BCI (Akanbi et al., 2020). New dynamics for data sharing must be investigated to enabled develop AI for CE (EMF, 2019). Many stakeholders in the BCI often monopolize the data set that could enable materials recovery potentials at end of life, thus effective collaboration amongst experts and stakeholders in the BCI on data collection, generation, and sharing will go a long way in facilitating high-quality data accessibility. Also, the development of centralized databases where information about materials and images of various construction waste and materials can be solicited and recovered is imperative for AI development towards CE in the BCI (Lu & Chen, 2022).

5 Conclusions

The paradigm shifts to CE is augmenting lately and various reports are being developed by international organisations. Recently, the circularity gap report 2022 was published. In the report, the global resources in all sectors including BCI are being managed in a linear form thus creating a wider circularity gap. As such, a data driven approach to bridge this gap has been advocated for in the BCI. Artificial intelligence is one of the disruptive technologies that could enhance the closure of the existing circularity gap. However, a state-of-the-art study in this domain is scanty and existing AI applications studies on bridging the circularity gap in BCI are scattered. Resting on this gap in knowledge, this study conducted a review to extant studies related to AI and CE in BCI to understand the how AI could help in bridging the existing circularity gap in BCI.

The critical review identified the application domains of AI for bridging the circularity gap in the BCI. They include the design for disassembly and deconstruction, pre-demolition auditing, technical and economical circularity of materials, onsite waste recycling, circular business models, and reverse logistics. Moreover, various challenges confronting the future promotion of AI in bridging the circularity gap were identified. They include i) lack of detailed and sharable datasets that could be adopted by researchers in training models ii) Less attention to digital circularity in the BCI and iii) detached link between CE research and practice in the BCI. In the future, research efforts should endeavour to create and share relevant construction waste and materials data sets that could be used in training models and making predictions.

Further, research efforts should concentrate more on industrial needs to bridge the enhance systemic circularity. The development of an autonomous system for the circular business model, a deep reinforcement learning model for automating circularity in the BCI, and the applications of AI in the building design, and retrofit are three promising directions that should attract more attention in the future.

6 Acknowledgements

This paper constitutes a part of a PhD research project currently undertaken at the Hong Kong Polytechnic University. The authors would like to thank the Hong Kong Polytechnic University Department of Building and Real Estate for supporting this study. We are grateful to the editors and reviewers for their insightful and useful comments, which significantly enhanced the quality of this paper.

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The Use of Virtual Reality in Reducing the Reliance on Human Visual Construction Defects Inspection

Will Nicholls[1], and Peter S.P. Wong[2]*

[1]Minicon Construction (Aust) Pty Ltd. Ground Floor, 675 Victoria Street, Abbotsford VIC 3067 AUSTRALIA
[2] School of Property, Construction and Project Management, RMIT University, 360 Swanston Street, 3000, Melbourne, AUSTRALIA

wnicholls@minicon.com.au; peterspwong@rmit.edu.au
* Corresponding author

Abstract:
Construction defect inspection has been criticised as a lengthy and costly process. This is partly caused by the heavy reliance on in-person site visits. Scarce human resources during the economic downturn, as well as the COVID lockdown measures, exposed the weakness of the current construction defects inspection procedures and the need for alternatives to reduce the reliance on physical site visits. This paper presents a study that aims to investigate the use of virtual reality (VR) techniques in reducing the reliance on human visual construction defects inspections. A systematic literature review, followed by a thematic analysis, was conducted. The results indicate that 'VR marker-based inspection', 'Automatic tracking and defect recording system', and the 'VR featured building information modelling management system' are the three major techniques that can be applied to reduce reliance on human resources in defects checking. The findings of this study provide direction in developing a protocol for immersive defects inspection for construction projects.

Keywords:
Construction defects inspection, virtual reality

1 Introduction

Defects checking and reporting are crucial for monitoring building standards (Victorian Building Authority 2015). Most standard forms of construction contracts in Australia state clearly that reporting and repairing defects are the contractor's responsibility (refer to Table 1). Nonetheless, defects checking is a complicated process. Governments from different jurisdictions have issued guidelines to formalise inspection standards to foster practical defects checking. For example, the Victorian Building Authority (VBA) published "The Guide to Standards and Tolerances" to articulate inspection standards. The guide provides both contractors and developers with a 'convenient reference for acceptable standards of workmanship in domestic building construction' (Victorian Building Authority, 2015, p.2). Likewise, similar guidelines can be found in New South Wales (New South Wales Fair Trading, 2017) and Queensland (Queensland Building and Construction Commission, 2019).

These guidelines describe in-person construction site visits as the crucial process of defects inspection. Nonetheless, such operations required tremendous input in time and cost on travels, site picture capturing, manual defects tracking, and the documentation work after the visits (Lundkvist *et al.*, 2014). Such problems become more acute during COVID lockdown when social distancing measures are put in place (Denny Smith *et al.*, 2021).

Table 1. Summary of contractor's liability in defects repairing in the Australian standard forms of contracts

Australian standard forms of contract	Descriptions about the contractor's liability for defects
AS 4000-1997 Clause 35	"As soon as possible after the date of practical completion, the contractor shall rectify all defects existing at the date of practical completion" (Standards Australia 1997, p.29).
ABIC MW 2018 – Clause M17 .1	"If there are remaining defect or incomplete work, or the contractor becomes aware through instruction from the architect or from the contractor's own observations of any defect or incomplete work during the defect liability period, it must promptly return to the site and correct the defect or finalise the incomplete work." (Australian Building Industry Contract 2018, p.53).
AS 2124-1992 Clause 37	"The direction shall identify the omission or defect and state a date by which the contractor shall complete the work of rectification and may state a date by which the work of rectification shall commence." "The direction may provide that in respect of the work of the rectification, there shall be a separate defects liability period of a stated duration not exceeding the period stated in the annexure" (Standards Australia 1992, p.32).
AS 4906-2002 Clause 21	"If the rectification is not commenced or completed by the stated date, the principle may have the rectification carried out by others…The costs incurred shall be money due and payable" (Australian Standards 1997, p.15).
ABIC MW 2018 – Clause M17.2	"The architect cannot give the first instruction to correct an outstanding defect or to finalise any incomplete work after the end of the defect liability period, unless it is for the rectification of a latent defect and the final certificate has not been issued" (Australian Building Industry Contract 2018, p.53).

In this aspect, emerging virtual reality (VR) technology has shown great potential as an intuitive and visualisation medium, allowing building inspection to be conducted in an immersive environment.

This paper presents a study that aims to investigate what virtual reality techniques are relevant to reducing the reliance on human resources for defects inspection. However, a systematic review study conducted by Wen and Gheisari (2020) had already confirmed that the research findings on the use of VR technology in construction are vast and scattered. Furthermore, their findings merely provided an overview of the VR research studies in the architecture, engineering and construction (AEC) industry. This study aims to adopt a systematic review approach, looking into the status quo of VR research specifically for construction defect inspections. The findings of this review study would enhance the appreciation of the need to further studies about how VR technology can be integrated into the existing defect inspection practice. While investments in immersive technology were noted, this study can provide a vision to help direct resources to invest in VR that can best meet the needs of improving the defect inspection practices.

2 Literature Review

2.1 Definition of construction defects

Scholars highlighted that there is more than one definition for construction defects (Chong and Low, 2006). Mills *et al.* (2009) define a defect as a shortfall in building performance that becomes exposed once the building is operational. This definition is then expanded by Aljassmi *et al.* (2016), stressing defects are arisen due to work failing in function, performance and statutory, where standards of quality in the contract are not met as a result of the contractor failing to identify, address and fix the defective work before occupancy. Similarly, Australian

Building Industry Contract (2018) describes that defective work is not following the standard quality of works stated in the contract and is considered a breach.

It is important to note that there are two types of construction defects. The first type is latent defects, which are design-related and unable to be discovered from reasonable inspection by the contractor during the defects liability period (Chong and Low, 2006). Latent defects are often associated with the structures and engineering of the building that will not be exposed until a certain period after project completion (Mills *et al.*, 2009). Whereas the second type of defect, namely patent defects, is more obvious to spot. They are expected to be reasonably addressed and rectified by the contractor within 12 months from the date of practical completion (Queensland Building and Construction Commission, 2019). As such, this topic focuses on patent defects because only this type of defect can be reasonably discovered via inspections during the defects liability period. In this study, construction defects are defined as those work/spots in the building that do not comply with the specification requirements and can be discovered through reasonable site inspections.

2.2 Definition of virtual reality (VR)

Steuer (1992) defines virtual reality as an alternate world where computer-generated images constantly respond to the users' movements providing a realistic simulation. (Vance and Berg, 2017) further describes virtual reality by integrating humans' sense of feeling, hearing and seeing through hardware and software required for the technology displays allowing people to immerse themselves in this alternate reality. Daniela and Lytras (2019) explore the theory that virtual reality disconnects its users from the real world. Shi (2017) goes on to share that virtual reality is an environment that allows people to interact and experience a virtual world together in real time.

Kirner and Kirner (2005) identified that virtual reality requires integrating real-time systems. Myeung-Sook (2001) elaborates this further, suggesting that the users' movements need an instant response from virtual simulation where display sensors require constant updates to the participants' position and time. Mandal (2013) then supports this view by suggesting that virtual reality is a computer model that exhibits interactive features manipulated by the participant's movements.

Table 2. Definitions of virtual reality

Definition	Citation
"the sum of the hardware and software systems that seek to perfect an all-inclusive, sensory illusion of being present in another environment"	Biocca and Delaney (1995, p.63)
"Virtual reality is an alternate world filled with computer-generated images that respond to human movements."	Steuer (1992, p.75)
"VR is a three-dimensional (3-D) computer simulation that immerses the user so fully that the computer-generated world appears to be as real as reality."	Pantelidis (1997, p.3)
"Virtual environment as the representation of a computer model or database which can be interactively experienced and manipulated by the virtual environment participants"	Barfield and Furness (1995, p.4)

After reviewing the above relevant studies, virtual reality in this study is defined as a computerised simulation, where hardware and software provide real-time sensory response and feedback to the participant's actions, creating a virtual world.

3 Research Methodology

A systematic review of the literature (including refereed journals, conference proceedings, and industry reports) is the methodology chosen for this study. The methods involve a thematic analysis to provide a holistic overview of the VR technology suitable for reducing the reliance on human resources in construction defects inspection. This study adopts the 4-step approach (as presented in Figure 1) to complete the systematic review.

3.1 Step 1: Keywords search

This step relies on an electronic keyword search that eliminates bias and influence that may encroach on the author's decision. Setting the start year of the search from 2000 is an arbitrary approach. However, it is a strategy to gather articles focused on the current defect inspection methods relying on human resources. Articles were searched through multiple databases, including Science Direct, Scopus, Emerald, ProQuest Central, SpringerLink and Wiley. An article containing one of the specific terms from each of the clouds, as presented in Table 3 in the abstract or title, was considered to meet the article selection requirement. For example, ‘virtual reality’ from Cloud 1 AND ‘construction defect’ from Cloud 2 were used as a pair of keywords for searching relevant articles. As such, 54 combinations of keyword pairs were adopted. A total of 126 articles were identified.

Table 3. Two clouds of keywords for searching relevant articles

	Cloud 1	Cloud 2
Keywords	‘virtual reality, ‘VR’, ‘immersive technology’, ‘BIM and virtual reality’, ‘animated virtual’. ‘virtual animation;	‘construction defect’, ‘defect check’, ‘defect report’, ‘defect inspection’, ‘construction inspection’, ‘human inspection’, ‘manual inspection’, ‘human checking’, ‘manual checking.’

3.2 Step 2: Review and filter relevant articles

The process of filtering out the relevant articles begins in step 2, which was done via reading the abstracts of each article to gain a perspective of its relevance. Articles published in the form of the editorial, editors' notes, table of contents, and volume contents were excluded. Articles that did not specifically discuss the issue of human resources or human reliance on defects checking and reporting practice were removed from the relevant data set. A common reason for disqualification was articles that merely presented conceptual models without justification that VR was being implemented. Fifty-eight papers qualified for this test.

3.3 Step 3: Adding relevant industry and government reports

The above two steps may not sufficiently include the potentially essential reviews from the industry. Therefore, a search was conducted from the official web pages of the professional bodies and the government department websites. Three industry reports were identified as relevant for this study.

3.4 Step 4: Thematic analysis

Thematic analysis is a form of descriptive qualitative analysis. This refers to an approach to systematically categorise the content of the articles and identify the central themes that can articulate the inter-relationships of those content (Grontier and Wong, 2021; Klewitz and Hansen, 2014). Scholars advocate using thematic analysis to answer why people adopt or not adopt, prefer or not prefer a particular service or practice (Grontier and Wong, 2021, Guo *et al.*, 2017). In this study, thematic analysis is conducted to categorise articles and themes for virtual reality techniques relevant to reducing the reliance on human resources for defect inspection.

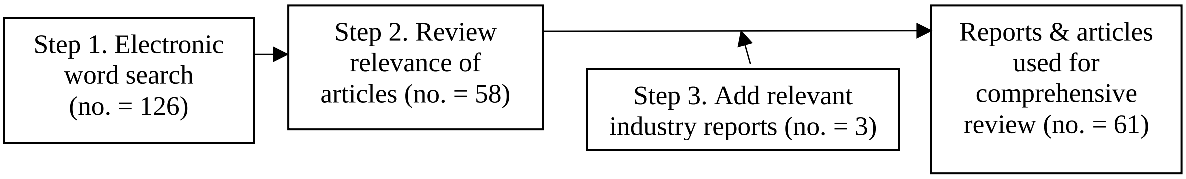

Figure 1. Four-step approach for systematic review

4 Findings and Discussion

Sixty-one publications were read to capture content describing which parts of defects checking and reporting practice relies heavily on human resources. Three themes are found in these articles: [1] VR marker-based inspection, [2] Automatic tracking and defect recording system and [3] VR feature BIM defect management system. Table 2 below outlines the frequency of 'VR marker-based inspection', 'In-person marker-based inspections', 'Automatic defect recording and tracking system', and 'VR feature BIM defect management system' referenced from the 61 publications.

Table 4. Relevant articles for themes of studies

Theme	No. of articles referenced	% of articles
VR marker-based inspection	19	31%
Automatic defect recording and tracking system	14	23 %
VR feature BIM defect management system	28	46 %
Total	61	100%

4.1 Theme 1 - VR marker-based inspection

Nineteen articles are identified as relevant to 'VR marker-based inspection'. Many studies have attempted to investigate how VR can enhance marker-based inspection (Wen and Gheisari, 2020; Karaaslan *et al.*, 2022; Gontier *et al.*, 2021; Insa-Iglesias *et al.*, 2021). The findings of these studies were mainly driven by the literature review focused on the application of VR in the construction sector. Marker-based inspection refers to the manual tracking of defects on-site by staff. In these studies, 'VR marker-based inspection' generally refers to a technique of tagging or anchoring virtual objects in a 360 panorama image or video.

A systematic review conducted by Wen and Gheisari (2020) indicates that in the construction field, VR technology is mainly applied in building inspection, where participants could practise inspecting buildings from a 3D model that accurately depicts the construction site. In this virtual environment, participants could communicate in real-time while completing the walkthrough, meaning facility managers and site workers could have direct lines of communication. This led to a better understanding of one another on the particular works and made the process more efficient.

A book chapter written by Karaaslan *et al.*, (2022) illustrates how VR technology can enable real-time inspection of bridges. They developed a system component diagram to articulate the role of VR in facilitating human (inspector) input and enabling defect analysis.

Gontier *et al.*, (2021) reported a SWOT analysis and saw the use of VR with the inspections as a strength yet not without threat. Sub-themes of threats were identified from previous papers and found that the limitations of the current technology using these immersive tools were not advanced enough; therefore is not suitable for adoption in the construction industry. The study also found that the industry did not have the resources and time it took to implement this theory into practice. This is also correlated to the attitudes of building companies that only see this as a risk of losing money and time.

Only a handful of studies developed strategies or solutions to enhance VR marker-based inspection. For example, Insa-Iglesias *et al.* (2021) developed a VR maker-based framework for structural defects inspection. They integrate VR images to the analytics interface of the structural defects inspection platform, and this 'allows the examination of defects repeatably in a realistic manner without requiring to travel to the target structure' (Insa-Iglesias *et al.*, 2021, p. 103755)

4.2 Theme 2 - Automatic defect recording and tracking system

Fourteen articles explored how defect recording and tracking systems can be automated (Shi *et al.*, 2020; Asgari and Rahimian, 2017; Al-Sabbag *et al.*, 2022). A relevant study by Shi *et al.*, (2020) demonstrates how VR technology can be applied in building inspection through a laboratory-based experiment. It was known that visualisation is an effective way for personnel in the AEC industry to gain spatial memory. An experiment was set up with 2D, 3D, and virtual reality tools to inspect a building and find discrepancies in the building to see if the more visual tool in VR would provide more spatial knowledge. The results of this experience justify that the VR technology enriches the visual context of defect recording and reporting. This improved the spatial memory of the inspectors and thus enhanced their efficiency of defect identification and the precision to which defects were reported.

Asgari and Rahimian (2017) emphasised how VR technology may improve defect tracking. They provided several examples to envision the application of VR, including lean-motion controller, Myo, and Nimble VR. Lean-motion controllers can pick up on 3D objects with up to millimetre accuracy through hand and finger sensors. Nimble VR is also a hand tracking sensor. However, this is through a camera incorporated into a headset and is based on an infrared camera that can measure the distance from the laser bouncing back from given objects. Both these technologies prove that there are new technologies out there that can be used for defect tracking and reporting.

The only empirical study that can be found is written by Al-Sabbag *et al.* (2022), who developed a novel approach for using VR technology in defect quantification. This XRIV device allows the user wearing it to measure the dimensions of a structure through the in-built sensors, where spatial mapping can be experienced from this device. This device becomes more effective through real-time damage detection, which can gather and assess quantitative information regarding the damages detected.

4.3 Theme 3 - VR feature BIM defect management system

The researchers identified the benefits of using VR technologies to comprehend the BIM-based defect management system (Meng *et al.*, 2020; Du *et al.*, 2018).

These studies conveyed more solid ideas about displaying construction designs in immersive environments. However, the VR techniques were merely seen as an add-on function for visualising the design. Such observation is backed by a review study by Meng *et al.* (2020).

They cited studies by Du *et al.* (2018), describing VR as a complementary tool of BIM to improve users' cognitive ability to read three-dimensional animated figures. However, we must consider that these studies are mainly in lab-orientated stages and have not been exposed to real-life scenarios. These studies are not focused on construction defecting; therefore, more studies would need to be conducted to prove these fit the defect inspection process.

5 Conclusion and Further Research

The thematic analysis results articulate how VR techniques can be applied in VR marker-based inspections, automatic defect recording & tracking and BIM defect management systems. In particular, VR marker-based inspections showed great potential in their existing ability to display 3D models with real-time communication allowing instructions and notes to be attached to defective objects. This led to a current development that used VR images to examine defects without stakeholders having to be present on site. New advancements in VR technologies have allowed enhancements to the VR tools used in defect inspection. The more effective visualisation of defects in the VR pictures saves inspection time and cost and improves the records' quality. The findings of this study merely reveal which parts of defects checking and reporting practice rely heavily on human resources. Further analysis of the strengths, research gaps, and future research directions of the previous studies can enrich our understanding of the potential use of VR technology in defect inspection practices. Further research is also suggested to be focused on implementing those techniques in real defect inspection practice. This will help develop a protocol for immersive defects inspection for the construction projects.

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Exploring the Nexus between Digital Engineering and Systems Engineering and the Role of Information Management Standards

Yu Chen[1*] and Julie R. Jupp[1]

[1]School of Professional Practice and Leadership, University of Technology Sydney, 81 Broadway Ultimo NSW2007, AUSTRALIA

yu.chen-4@student.ust.edu.au; julie.jupp@uts.edu.au

* Corresponding author

Abstract:

Information management standards provide much needed guidance to the implementation of processes supporting more integrated, digital, and model-based approaches to project delivery and through-life asset information management. These standards impact all stakeholders spanning the planning, acquisition and operational phases of buildings and infrastructure. In Australia, since the release of ISO 19650, a variety of state agency standards for digital engineering have been released in support of new model-based processes. A paucity of studies on the uptake of information management standards translates to a lack of understanding of their prevalence, impact, and perceived value on engineering design activities, and in particular systems engineering tasks surrounding requirements management. This paper provides the first step to providing insights into these standards via an online survey of digital engineering and systems engineering stakeholders. Findings reflect a number of differences in the experiences, interpretations, and applications of these standards between roles and sectors. Findings also reflect a greater perceived impact from government standards over international ones. The study highlights ongoing confusion in the roles and responsibilities of digital engineers and systems engineers, and the lack of interface management between information requirements and physical system requirements throughout design review activities.

Keywords:

Digital engineering, Industry survey, Information management, Standards, Systems engineering.

1 Introduction

The implementation of more integrated, digital, and model-based technologies to support strategic approaches to project delivery and whole-of-life asset information management has seen a growing number of international, national government and state-agency standards. Since the release of the ISO 19650 standards (Parts 1&2) in 2018, state government agencies have published supporting standards in digital engineering (DE) and building information modelling (BIM). These standards are aimed at providing greater consistency and maturity in information requirements management process across the diverse stakeholders engaged in the planning, acquisition and operations of buildings and infrastructure.

Transport for New South Wales (2019a, 2019b) first commenced the DE Framework Program – a fully funded program – running since 2017, with the aim of bringing together experts from around Australia to develop practical, cost effective DE solutions based on global best practices. The program resulted in the evolution and release of consecutive versions of Transport's DE Standards: Release 1 (in Sept 18), Release 2 (in Apr 19) and Release 3 (in Nov. 2019). The standards define the minimum requirements for implementing DE in project delivery phase and provide guidance in information management more generally. Similarly, Office of Projects Victoria (2020) released the Victorian Digital Asset Strategy (VDAS) in 2020, providing detailed guidance on planning, implementing, managing and maintaining an effective digital asset strategy throughout the lifecycle of an asset. As a pioneer in implementing BIM approach, in 2018 Queensland Government (2018) announced the policy to mandate BIM on all government construction projects costing over $50 million and expanding to all built assets by 2023. Other state like South Australian (2019) also published DE standard, intending to provide an overview of the minimum requirements for DE practices on road projects. From a nationwide perspective, National DE Policy Principles have been developed by governments in Australia in recognition of the potential benefits that DE and BIM can bring to the design, delivery, operation and management of land transport infrastructure assets.

The Australian experience is not unique. For the past two decades, growing maturity in the application of process and information requirements management standards supporting model-based approaches to asset planning and acquisition (Chen and Jupp, 2021). This has resulted in new service-oriented offerings linking, for example, BIM to Facilities Management (Matarneh et al., 2019), and more recently to the development of spatial digital twins (DTs) in support of the operations and maintenance (O&M) of building and infrastructure assets (Tchana et al., 2019; Johnson et al., 2021; Zhao et al., 2022). Whilst the ISO 19650 is widely acknowledged by organisations, there is a lack of studies on the uptake of ISO19650 and related DE and BIM standards. This then translates to a lack of understanding of the prevalence, impact, and perceived value of the standards. The paper provides a first step to providing insights about the effects of these standards. The objective of the paper is to explore two questions:

RQ 1: What is the prevalence of use of information management standards (e.g., ISO 19650 Standard (Parts 1&2) and other Digital Engineering standards?

RQ 2: What are the digital engineering and systems engineering roles and responsibilities, and levels of experience in information management standards?

2 Standards and Stakeholders of Information Requirements Management

In Australia, the release of the ISO 19650 standards in 2018 - together with other business and industry drivers - have accelerated recent efforts in government agencies to release DE and BIM standards for projects in support of more integrated digital approaches to the planning, acquisition and O&M of assets. In both building and infrastructure sectors, to support complex requirements management processes, a variety of formal systems engineering methods and processes play a critical role in the implementation of these standards – from the development and management of different requirement types to the verification and validation of physical system and digital deliverables. This results in a variety of interfaces between digital engineering and systems engineering standards and stakeholders.

2.1 Standards Supporting Information Requirements Management

The widespread acceptance of DE and BIM, and recognition of the growing digitalisation of the Australian construction industry has increased in both the building and infrastructure sectors (Hosseini *et al.*, 2020). However, the need to define and utilise standardised information requirements management methods as a key enabler of process consistency has received less wide-spread recognition (ABAB, 2018).

2.1.1 International Standards - ISO 19650 and ISO 55000

To support the management of information requirements in building and civil infrastructure projects, the ISO 19650 Parts 1 and 2 (2018a, 2018b) and ISO 55000 (2014) define general procedures and much needed consistency in the terminology, concepts, and principles underpinning the development of asset management strategy and identification of supporting requirements. Together, ISO 19650 and ISO 55000 are able to provide a regulated procedural method for the development of a strategic approach to asset information lifecycle management (Chen and Jupp, 2021).

Prior to the introduction of ISO 19650, projects implementing BIM did not have a consistent information requirements management process across the industry (Chen and Jupp, 2021). Together *ISO 19650-1: 2018* and *ISO 19650-2: 2018* describe the processes supporting digital information management, with a focus on information requirements management in the context of buildings and civil engineering works, including BIM (ISO, 2018a, 2018b). ISO 19650 provides a procedural method according to four requirement types, including i) organisation information requirements (OIR), ii) asset information requirements (AIR), iii) project information requirements (PIR); and iv) exchange (or employer) information requirements (EIR) of the project team. Information requirements management activities commence with the client's OIR, which are established in a statement on the information needed by an organisation to inform decision-making about high-level strategic objectives (Simpson et al., 2018).

The OIR therefore forms a critical first step in the procedural method[1] as it supports the capture and mapping of information and deliverables contained in the policies or acts of government transport agencies, including their asset management accountability framework (AMAF). This is also an integral component of ISO 55000:2014 implementation (Chen and Jupp, 2021). Australian transport agencies widely utilise the AMAF to detail mandatory asset management requirements and provide guidance for managing assets. The ISO 55000 series (2014) consists of three international standards that provide the terminology, requirements and guidance for implementing, maintaining and improving asset management systems. ISO 55000 is widely used by utilities, transport, mining, process and manufacturing industries worldwide, enabling the streamlining of expenditure, strengthening of credentials and future-proofing of facilities and assets (International Council on Systems Engineering, 2007; Transport for NSW, 2017).

The ISO 55000 and ISO 19650 standards and the procedural methods they define together play a central role in the development and management of AIR and asset information model (AIM), as well as the ongoing management of digital information and digital deliverables supporting asset management (Chen and Jupp, 2021).

2.1.2 Australian State Government Standards

Australia government commissioned a national BIM initiative in 2012 and recommended requiring full 3D collaborative BIM for all Australian Government building procurements by 1st July 2016 (BuildingSMART Australasia, 2012). However, due to the isolated and inconsistent work of different States, it was difficult to implement a national mandate (Jiang *et al.*, 2022). By contrast, the local states decided to move faster. In 2018, Queensland Government announced the policy to mandate BIM on all government construction projects costing over $50 million and expanding to all built assets by 2023 (Queensland Government, 2018). At the meanwhile, new DE standards have been developed and implemented by a

[1] It is critical that the OIR accurately reflects what information is required so as it is able to inform the development of the AIR and PIR (Chen and Jupp, 2021). The AIR and PIR in turn inform production of the EIR, which represents the overall information requirements that span the managerial, commercial and technical aspects of the AIR and PIR, where the owner's requirements for asset registers to support spatial referencing, classification, hierarchical management and location referencing as per the nominated schema, e.g., UniClass 2015 (Chen and Jupp, 2021). The EIR is then primarily concerned with the who, how and when of their delivery, and includes the information production processes and procedures, data standards, file formats, timetables for information exchange, and roles and responsibilities of the project team (Simpson et al., 2018). The EIR is used to inform the development of the Digital or BIM Execution Plan (DEXP/ BXP).

growing number of state infrastructure agencies, including *Digital Engineering Standard* (Transport for NSW, 2019a, 2019b), *Victoria Digital Asset Strategy* (Office of Projects Victoria, 2020), *Building Information Modelling Mandate Policy* (Queensland Government, 2018), and *Project Controls – Master Specification – PC-EDM5 Digital Engineering* (South Australian Department for Infrastructure and Transport, 2019).

Transport for New South Wales (TfNSW) has developed its own DE strategy since 2016 and formed the DE team responsible for development of DE Framework Program. Since the launch of the DE framework in September 2018, there have been a series of releasement of documents adding new capabilities and reflecting lessons learned on pilot projects. DE Standard was first published in 2018 and updated in 2019, providing minimum requirements for implementation of DE (Transport for NSW, 2019a, 2019b). It details how the Data & Information Asset Management Policy is to be implemented through the application of the DE Framework (Transport for NSW, 2019a, 2019b). This standard describes the language and approach to be adopted when implementing DE for TfNSW projects.

Victorian Digital Asset Strategy, also known as VDAS, was released by the Office of Projects Victoria in March 2020. This guidance consists of three parts which provide strategic-level (Part A), organisational-level (Part B) and project-level (Part C) advice for the effective management of digital information and data throughout the life of an asset (Office of Projects Victoria, 2020). It provides detailed guidance on planning, implementing, managing and maintaining an effective digital asset strategy throughout the lifecycle of the organisation's asset base (Office of Projects Victoria, 2020). It has been developed in collaboration with industry and is aligned with international standard ISO 19650. Based on VDAS, the Digital Asset Policy (Office of Projects Victoria, 2022) describes three levels of capabilities of 14 requirements in organisational and project level throughout the asset lifecycle.

Although TfNSW DE standards and VDAS are not mandate for transport infrastructure projects yet, it is clear that Australian state transport infrastructure agencies have recognised the whole-of-life benefits that DE will bring to complex infrastructure projects. These agencies are therefore implementing a complex of international and organisational standards to achieve a more strategic approach to asset information lifecycle management.

2.2 Information Management Roles and Responsibilities

To make the DE standards implementable in practice, the responsibilities and roles for information management throughout the lifecycle of the asset is defined. In ISO 19650-2 (2018b), a general information management process is presented from planning to close-out of a project. In state-based DE standards, key responsibilities and dedicated roles of information management are defined, providing a more detailed guidance for the project team (Office of Projects Victoria, 2020; Transport for NSW, 2019b).

2.2.1 Project Behaviour and Key Responsibilities

The information management processes of a project can be defined according to a series of five project behaviours including: 1) share, collaborate, deliver, 2) use common language, 3) auditable assurance pathway, 4) digital tools to support decision making, and 5) a platform to support innovation (Transport for NSW, 2019b). Key responsibility in the client-side tend to focus on the overall project DE strategy, and procurement and implementation. The client-side stakeholder is therefore responsible for the management and coordination of project execution and DE to meet the procurement strategy and cost containment (Transport for NSW, 2019b). As the accountable role for the successful implementation of DE on projects (International

Organization for Standardization, 2018b), the client-side's (also known as appointing party in ISO 19650) DE manager should manage the process of a delivery team virtually construction an asset in DE and oversee documenting it as per the EIR needs (Office of Projects Victoria, 2020). From an output documentation point of view, this include the development of OIR, AIR, and EIR and then reviewing the DEXP developed by the appointed party during the early planning and design phases (Office of Projects Victoria, 2020).

From the contractor's perspective, the responsibilities span a wide scope of tasks. Taking the TfNSW DE Standard (2019b) as an example, they include for example: 1) the development of the overall *project DE strategy* and its implementation by the Contract Project Team, 2) the setup and delivery of the project from a DE perspective, 3) the management of the overall production of the project's federated BIM Model and associated data sets, 4) initiation, agreement and implementation of information sub-plans, for control and governance of separate design packages (disciplines) and/or sub-contractor works, 5) the verification of compliance for information management in accordance with the Contract, legislation and relevant Safety, Environment & Regulation and Industry Standards, and lastly 6) the day-to-day implementation of document control processes and system support. The effectiveness and efficiency by which these responsibilities are met relies heavily on the experience of the contractor, supporting DE technical schemas and specifications, and delivery tools and templates that defined according to the client's OIR and AIR.

2.2.2 Dedicated Information Management Roles

Digital Engineering Roles: Typically, there would be three levels of DE roles that project stakeholders should perform at different stages of the project lifecycle, including: 1) DE manager – strategic level, 2) DE coordinator – management level, and 3) DE Modeller– production level (AbuEbeid and Nielsen, 2020). These roles are usually taken by different stakeholders. The DE modellers usually refer to the design team or subcontractors in various disciplines. The DE coordinator is the role sits in client side or main contractor side and responsible for coordinating the federated model among multiple disciplines. The DE manager is usually an organisational level role who is responsible for setting up DE process and workflow, standards, implementation and training (AbuEbeid and Nielsen, 2020). DE roles are the key executors to implement data and information asset management policies.

Systems Engineering Roles: Systems engineering (SE) in transport infrastructure plays a key part role in managing risk and safety during project delivery. In rail infrastructure it is essential to meeting the requirements of the Rail Safety National Law (RSNL), which emphasises the safety of the rail infrastructure projects. As described in SE standards of government transport agency, the SE roles should focus on 'defining stakeholder needs and functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and functional allocation to subsystems' (Transport for NSW, 2017, p. 12). Levels of responsibility and engagement of SE organisational roles can be mapped to SE management processes and activities across the system life cycle (Transport for NSW, 2017). SE roles include the: SE manager, Systems Engineer, Requirements Manager, Systems Integration Manager, Systems Architecture Manager, Systems Interface Manager, and Verification and Validation Manager. The setup of SE roles in a project is flexible depending on the complexity and scale of the project. In simple projects, SE roles could be carried out by the Design Manager, Engineering Manager, or Project Manager (Transport for NSW, 2017). In a project with digital deliverables, it is important to clarify the interface and interaction between DE and SE roles, as the coordination and consistency between AIR and physical system requirements is high.

3 Research Methodology

3.1 Research Design

An online survey was developed based on findings from literature review and semi-structured interviews conducted at previous stages of the research. The literature review focused on identifying the challenges of and existing methods supporting information requirements engineering practices in projects requiring digital delivery. As a result, a list of challenges has been identified (Chen and Jupp, 2021) which then form the main content of the online survey.

3.2 Survey Instrument

Engineering and Construction firms with high levels of organisational expertise in the civil infrastructure sectors were invited to participate in an online survey. The research survey specifically targeted organisations with high levels of expertise in and specifically those with expertise in DE, BIM, and Model-based Systems Engineering (MBSE) (Wymore, 2018) in order to identify the current state of implementation of different standards in in building and infrastructure projects. The respondents therefore listed a variety of DE/ BIM related roles (e.g., digital engineer, digital integration consultant, digital strategist, BIM managers and consultants, etc.), as well as systems engineers, and client-side DE and BIM management roles. In total, there were 32 valid responses recorded, providing a small, but high levels of expertise in the sound sample. The total number of respondents was relatively small because the use of DE in complex infrastructure projects is in its infancy. All survey responses were recorded from January to August 2022. Participants were asked to choose their roles, sectors of construction they involved in, and their level of experience in the application of different methods and standards supporting information management.

3.3 Data Analysis

Survey data are extracted from Qualtrics and analysed in multiple perspectives. First of all, an overview of the background of participants and the status of standard implementation in projects were presented. Based on that, further analysis was conducted to investigate the interrelationship between sectors and standards implementation, as well as relationship between ISO standards and state-based standards implementation.

4 Findings and Discussion

4.1 General Findings

As reflected in Figure 1, the respondents came from two main groups: DE roles (20) and SE roles (12). These two groups are the key stakeholders that are the executors of information management activities of a project, with their responsibilities intersecting during information requirements management tasks. DE roles are separated into three subcategories based on three roles in projects and year of experience in DE implementation. Digital Engineers are those who have 1 to 5 years' experience in DE implementation while DE managers more than 5 years' experience. DE developers / advisers are the strategic level roles who support the development of DE standards and guidelines in client-side or consultant organisations.

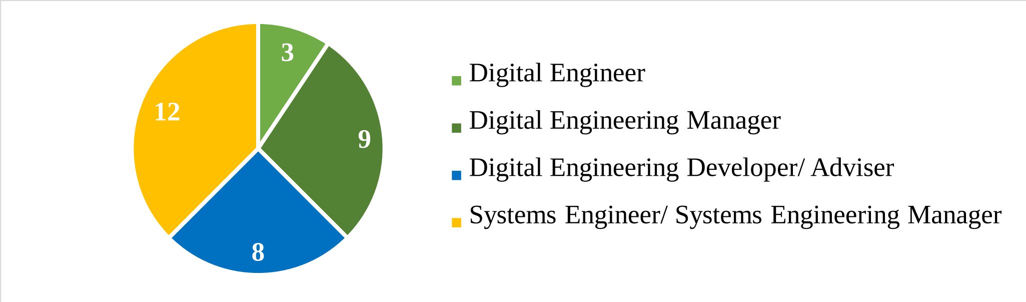

Figure 1. Breakdown of Digital Engineering and Systems Engineering Respondents' Roles

Figure 2 presents the industrial sectors that all the respondents have been involved in. More than half of respondents (R = 21) were involved in multiple sectors. The rail infrastructure sector is the main sector where most respondents accumulated their experience (R = 28), with Roads, Bridges and Highways (R = 17) and Commercial Office (R = 12) the next two sectors where respondents had most experience in the implementation of DE and SE standards.

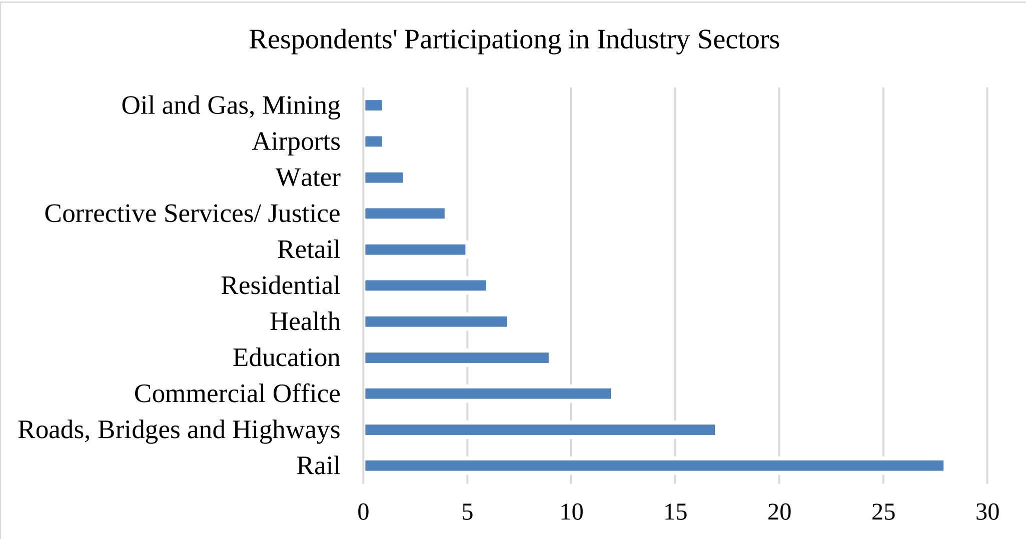

Figure 2. Respondents' Participation in Projects across Industry Sectors

4.2 Knowledge and Implementation of ISO and State-based Standards

Figure 3 presents an overview of respondents' level of experience in implementing ISO 19650 and state-based DE standards. Considering these standards have only been published for less than 5 years, four levels were defined based on their understanding of and involvement in the implementation of those standards (rather than based on the number of years of experience). These levels include: 1) No Knowledge, 2) Beginner, 3) Intermediate, and 4) Advanced.

- **No Knowledge** - participant has not heard of the standard at all.
- **Beginner** - participant has a general understanding of concepts and principles of the standard but has not been involved in implementation.
- **Intermediate** - participant has an intermediate level working knowledge of the standard as a direct result of project-based experience.
- **Advanced** - participant has advanced working knowledge of the standard as a direct result of developing or implementing the standard.

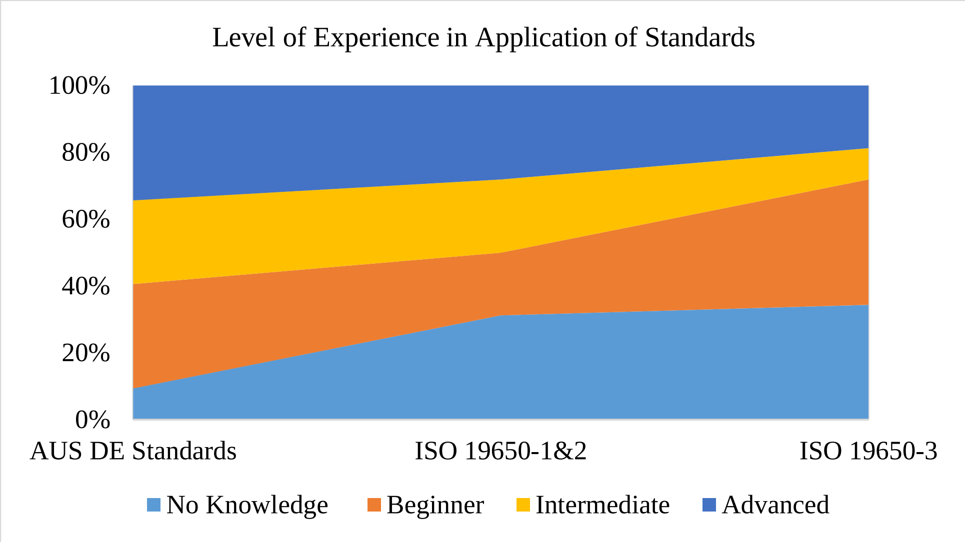

Figure 3 Overview of Implementing ISO 19650 and DE standards

An analysis of the survey findings in response of RQ1, which sought to identify the prevalence of use of ISO 19650 and related DE/ BIM standards in Australia - is presented in Figure 3. Intermediate and Advanced levels show that 60% of respondents have a working knowledge of the standards and been directly involved or responsible for the implementation of Australian (state-based) DE standards on projects, and only 50% having integrated ISO 19650-1&2 and 30% ISO 19650-3 methods in their working practices.

RQ2 attempts to build a greater understanding of the related DE and SE roles relative to their responsibilities (also ref. to Section 2.2), and their respective levels of experience in information requirements management standards. Further analysis of the survey findings in response to RQ2 is presented in Figure 4, shows that state-based standards are more commonly recognised and used on projects than the ISO 19650 standard. The respondents who have no to little knowledge of Australian DE standards were those who identified as systems engineers, who responded that they also do not have any or limited experience in DE related projects. ISO 19650 Part 3 also has a lower rate (30%) of implementation than Part 1&2 (50%), as the current emphasis of DE implementation is still in project delivery phases indicating a lower level of maturity in implementation of DE in O&M phase.

During the early implementation of DE processes, those in systems engineering roles have had limited to no understanding of international standards such as ISO 19650. Due to dependencies between ‘traditional’ requirements management practices (led by SE roles) and new, evolving information requirements management practices (led by DE roles) a significant knowledge gap arises which presents substantial risk to requirements traceability. An awareness of Australian DE Standards was reported by the majority of SE roles in transport infrastructure sectors (refer to ‘Beginner’ in Figure 4), indicating a low level of knowledge. There are potential opportunities for systems engineers to play a greater role in information requirements management processes. It also reveals opportunities for further transformation of SE roles in the use of model-based data during design review activities for requirements verification. The evolution of traditional SE competencies to MBSE competencies would assist in managing the interface between physical system, functional and performance and information requirements.

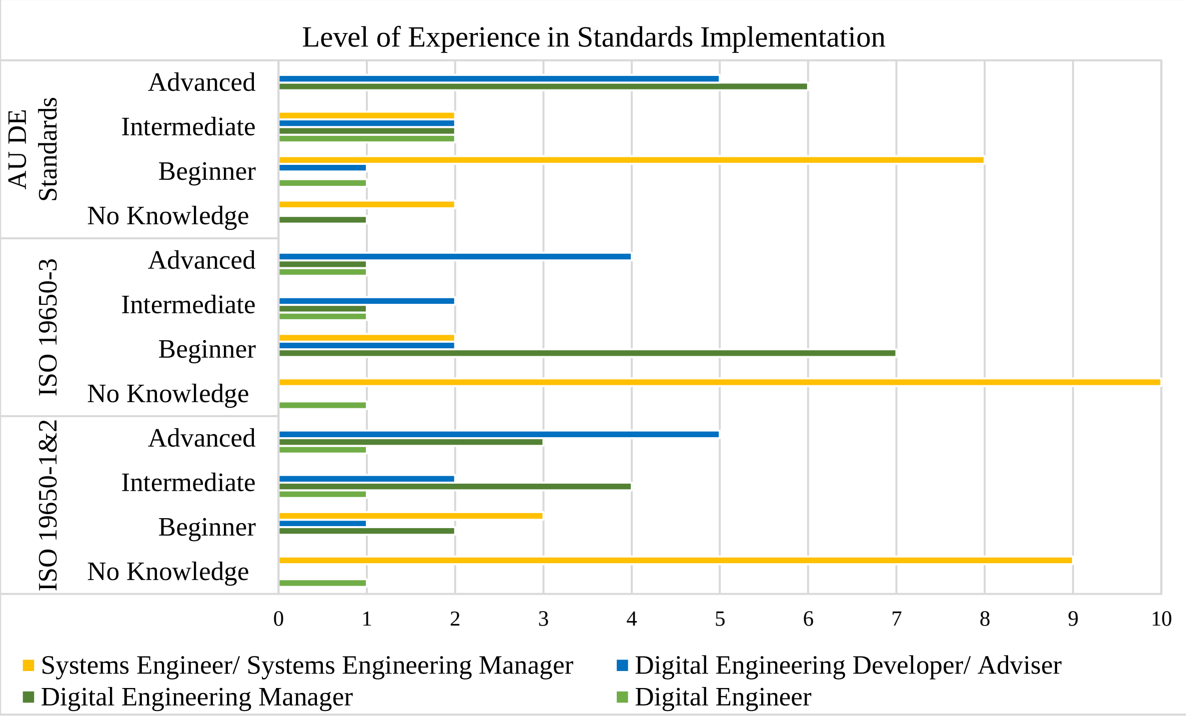

Figure 4. Respondents' Level of Experience in Implementing Different Standards

4.3 Discussion

With the adoption of new digital ways of working and information management processes come new forms of contract and a shift roles and responsibilities. Many of the individuals currently working as systems engineers or digital engineers have previously held positions as civil or mechanical engineers, architects, and construction managers. They now find themselves, through choice or circumstance, in new and rapidly evolving roles. In addition, other roles such as 'design manager' and 'design coordinator' have also evolved and become more commonplace (Emmitt and Ruikar, 2013). Beyond Australian state government transport agencies mandating DE and SE requirements and responsibilities, there is otherwise a paucity of DE and SE roles and interfaces defined in organisational standards. Thus, their exact nature is not always well-defined or understood.

Part of the confusion appears to stem from the wide interpretation and application of DE and SE standards and thereby roles and responsibilities. The impact of this confusion can be evidenced throughout design coordination and systems design review activities, where the interfaces between 3D model-based design coordination activities (undertaken by DE roles) and requirements verification activities (undertaken by SE roles) are largely ignored in the EIR and related planning documentation (e.g., DEXP and BXP). Consequently, current interfaces between SE and DE activities are managed in an ad-hoc manner throughout system functional review (scoping), preliminary design review (concept design), and critical design review (detailed design) activities.

A range of issues impact the industry's ability to address these issues. There is a lack of education and training programmes for aspiring SE and DE managers. There is also little recognition of the need for – and opportunities arising from – the creation of greater alignment between DE and SE disciplines. This has already happened in complex discrete manufacturing with increasing maturity in MBSE (Wymore, 2018). Compounding these educational issues is the lack of accreditation and benchmarking of competencies from industry bodies, particularly with regards to DE. Given that DE is an emerging discipline, and that SE is still relatively immature in transport infrastructure sectors – and often unrecognised in the building sectors – a lack of clarity is to be expected as the construction industry refines both DE and SE roles.

5 Conclusion and Limitation of Research

To support a consistent and structured information requirements management process across multiple stakeholders throughout the lifecycle of an asset, ISO 19650 standards and government state-based standards are being implemented in Australian building and infrastructure sectors. This paper investigates the application of and participation in ISO19650 and other Australian government standards supporting DE in building and infrastructure projects. Findings reflect a variety in understanding and implementation of ISO 19650 as well as other related standards across different types of organisations. Government state-based standards are more commonly used and recognised than international standards. The study also reflects a knowledge gap of ISO 19650 in SE roles who however have a basic understanding of state-based DE standards. This indicates a lack of well-defined DE and SE roles and responsibilities to support the interface management of DE information requirements with physical system requirement. The study's findings provide important insights on the challenges to applying ISO and government standards in support of digital project deliver and through-life asset information management. The limitation of this research is that because of the use of DE in complex transport infrastructure projects is in its infancy, the total number of respondents was relatively small. Future research will focus on identifying key enablers supporting interface management between SE and DE roles in transport infrastructure projects.

6 Acknowledgement

This research is supported by an Australian Government Research Training Program scholarship.

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Fuzzy Evaluation of Barriers to Digital Technologies Adoption in the Construction Industry

Xichen Chen[1*], Alice Chang-Richards[1] and Tak Wing Yiu[2]

[1]Department of Civil and Environmental Engineering, The University of Auckland, NEW ZEALAND
[2]School of Built Environment, Massey University, NEW ZEALAND

xche751@aucklanduni.ac.nz; yan.chang@auckland.ac.nz; T.Yiu@massey.ac.nz
* Corresponding author

Abstract:
Despite the benefits of adopting technologies to enhance construction project performance, the uptake of digital technologies (DT) in the New Zealand construction sector is still limited. This research adopted a mixed-method approach comprising a survey of 428 construction companies and semi-structured interviews with 38 industry practitioners to identify critical barriers to the DT adoption. The top three most critical barriers were the status quo industry standards, the lack of interest from the clients, and no financial need/drive for using DT. By using the fuzzy synthetic evaluation (FSE) technique, a DT barrier assessment model was firstly derived from the survey results. An action model was then developed to suggest coping strategies and the corresponding actors for addressing each crucial barrier. The research contributes to construction innovation literature by providing an improved understanding of critical barriers to DT adoption. The assessment model can help organisations to identify the crucial challenges to DT adoption and the action model can help key stakeholders to take targeted measures to advance digital transformation of the New Zealand construction sector.

Keywords:
Digital technology (DT), barrier, fuzzy synthetic evaluation (FSE), construction

1 Introduction

Digital revolution is one of the most critical drivers accelerating technological innovation of the construction industry to improve the performance of the sector (Craveiro *et al.*, 2019). As defined by Chowdhury *et al.* (2019), digital technologies (DT) in the construction sector are "*advanced information and communication technologies and tools used in amplifying productivity across the construction life cycle*" (p. 570). There have been extensive studies investigating the benefits of implementing DT in construction projects, such as building information modelling (BIM) (Yoo *et al.*, 2019), 3D printing (Buchanan and Gardner, 2019), artificial intelligence (AI) (Goh and Guo, 2018), and internet of things (Zhou and Ding, 2017).

Despite the perceived advantages of DT adoption, the uptake of DT is still low in the construction industry in many countries (Bademosi and Issa, 2021). For instance, in New Zealand, as indicated in the Ministry of Business, Innovation and Employment's (MBIE) Building Law Reform Programme (MBIE, 2021), the building system still follows the traditional construction methods. However, such methods are unable to meet the increasing construction demand, the adoption of new technologies and practices in the sector has been recognised as an important way to move forward (Duncan *et al.*, 2018). Existing studies about barriers to DT adoption mainly focus on specific DT, such as BIM (Marefat *et al*., 2019), drones (Albeaino and Gheisari, 2021) and virtual reality (VR) (Badamasi *et al*., 2022), instead of utilising multiple DT which is an increasing trend seen in complex construction activities (Sukanthan Rajendra *et al*., 2022). Construction organisations would have to change their key business operations, management structures, concepts and even the final products and services in order to adopt new technologies (Jafari-Sadeghi *et al.*, 2021). Given this context, knowing the types of obstacles to the adoption of multiple DT would be helpful for decision making to achieve construction sector digital transformation. Therefore, this research aims to identify the barriers to adopting DT in New Zealand. The results of this research will help the New Zealand government agencies and industry associations to set appropriate goals and implement measures to drive their technological advancement.

2 Literature Review

A comprehensive review of international literature using a content analysis method found five groups of barriers to DT adoption (Table 1). The categorisation is based on the context and meaning of each barrier: 1) financial dilemmas, 2) attitude and market issues, 3) lack of knowledge and awareness, 4) lack of support and governance, and 5) technological issues.

Table 1. Main barriers to DT adoption in the construction industry

Barriers	Sources
Financial dilemmas (e.g. high initial cost, uncertainty of economic benefits, and lack of financing schemes)	Bademosi and Issa (2021), Chowdhury *et al.* (2019), Durdyev *et al.* (2021), Hwang *et al.* (2022), Tabatabaee *et al.* (2021), and Gamil and Rahman (2019)
Attitude and market issues (e.g. resistance to change workflows and lack of interest and market demand)	Bosch-Sijtsema *et al.* (2021), Delgado *et al.* (2019), Gamil and Rahman (2019), Nassereddine *et al.* (2022), and Reyes Veras *et al.* (2021)
Lack of awareness and knowledge (e.g. lack of awareness of DT, lack of knowledge, and lack of experiences and experienced workforce)	Reyes Veras *et al.* (2021), Gamil *et al.* (2020), Oesterreich and Teuteberg (2019), and Chan *et al.* (2019)
Lack of support and governance (e.g. lack of a supportive legal environment, lack of technological codes and standards, and lack of a supportive organisation structure)	Albeaino and Gheisari (2021), Bademosi and Issa (2021), Nassereddine *et al.* (2022), Tabatabaee *et al.* (2021), and Reyes Veras *et al.* (2021)
Technological issues (e.g. immaturity of DT, data and information security, ethical and privacy, and incompatibility, and lack of training and education)	Bosch-Sijtsema *et al.* (2021), Nassereddine *et al.* (2022), Reyes Veras *et al.* (2021), and Tabatabaee *et al.* (2021)

The costs of implementing new DT could be high, such as the initial cost of purchasing software and hardware, resources, and training and hiring staff during technology implementation (Tabatabaee *et al*., 2021). High investment cost and concerns about the uncertainty of return on investment have also been identified as a critical barrier by several studies (Durdyev *et al*., 2021; Bademosi and Issa, 2021; Hwang *et al*., 2022).

Due to the deep-rooted traditional mindset of stakeholders and concerns of extra costs and resources involved, there can be resistance in the construction sector to change from using traditional methods to new technologies when designing and building (Gamil and Rahman, 2019; Nassereddine *et al*., 2022). Clients might show little interest in emerging DT due to their lack of awareness of the DT and knowledge about the associated benefits (Delgado *et al*., 2019).

A lack of experience of using DT and lack of experienced workforce has also been identified as a crucial barrier to the adoption of DT in studies, such as big data (Reyes-Veras *et al*., 2021) and IoT (Gamil *et al*., 2020). The importance of information sharing is also a vital factor to promote the implementation of new technologies (Oesterreich and Teuteberg, 2019). Because of divergence in stakeholders' perceptions of new technologies, the collaboration of functional units in a project can be inefficient (Chan *et al*., 2019).

Albeaino and Gheisari (2021) illustrated some legal and liability dispute issues due to the use of drones onsite, including property damage and personnel casualties. According to Tabatabaee *et al*. (2021), an organisation may not have a mature system for technology implementation because of their limited insights into the changes required to implement technologies. A lack of industry standards has been identified as a principal barrier to the adoption of emerging DT in the construction sector (e.g. Bademosi and Issa, 2021; Nassereddine *et al*., 2022).

Despite the success achieved in technology research, many emerging DT are still immature and require time for further technological advancement (Reyes-Veras *et al*., 2021; Nassereddine *et al*., 2022). Data security concerns and ethical and privacy concerns are also frequently mentioned in the literature (Bosch-Sijtsema *et al*., 2021; Hwang *et al*., 2022). According to Tabatabaee *et al*. (2021), incompatibility or interoperability issues between software or operating programmes can cause significant inefficiencies and data.

3 Research Methodology

A mixed-method approach was adopted in this study. A questionnaire survey was designed to collect quantitative data to identify critical barriers to DT adoption. Semi-structured interviews were conducted to obtain qualitative data for validating the criticality of barriers and collecting data about actors and coping strategies needed to deal with the barriers identified. The combination of qualitative and quantitative data collection methods is expected to enhance the strength of the research approach and reliability and validity of results. A pilot study was conducted to examine the relevance of the reviewed barriers in Table 1 to the New Zealand context. According to the feedback of the polit study, the list of barriers was refined to ensure that the survey questions were relevant, reliable, clear, and user-friendly. The surveyed barriers were presented in Table 2. In the survey, a 5-point Likert scale, where 1 indicated "not a barrier at all" and 5 indicated "a significant barrier", was employed and participants were asked to rate their perceived importance of the surveyed barriers. The interviews have been conducted to validate the survey results, examine the critical barriers, and collect insights from interviewees regarding the actors and types of coping strategies to addressing these barriers.

Table 2. Surveyed barriers to DT adoption

Codes	Barriers
B1	Lack of a supportive legal environment
B2	Status quo industry standards
B3	Lack of interest from the client
B4	Banking industry's lending restrictions
B5	Data and information security concerns
B6	Ethical and privacy concerns
B7	Lack of financial need/drive for using DT
B8	Lack of awareness of DT providers

By using SPSS version 26.0, general statistics analyses were conducted, including Cronbach's alpha for reliability assess, relative importance index (RII) (Akadiri, 2015) for barrier ranking, and t-test analysis to identify critical barriers. Fuzzy synthetic evaluation (FSE) (Ogunrinde *et al.*, 2021) was employed to quantify and determine the relative contribution levels of barriers. Finally, an assessment model was derived to help construction organisations to assess critical barriers to DT adoption. Interview data was processed based on collective themes using content analysis method and a DT adoption action model was proposed to help stakeholders to overcome the critical barriers.

4 Findings and Discussion

4.1 Demographic Information

Table 3 presented the demographic information for the total 428 survey participants. Respondents could select multiple options for most questions, except for the number of years in operation and business size. There is a good spread of organisation types. The majority of the respondents' companies had been in operation for more than 10 years. Founded within five years, start-up companies accounted for 25.2% of surveyed organisations. As for business size, a large portion of the respondents worked in small and medium enterprises (SMEs) (56.5%), followed by large companies with over 50 employees (40.9%).

Table 3. Participants' demographic information (N = 428)

Characteristic	Number of respondents	Percentage
Business or organisation type		
Engineer	120	28.0%
Building contractor/subcontractor	108	25.2%
Consultant	76	17.8%
Project manager	61	14.3%
Architect/Architectural designer	45	10.5%
Developer	40	9.3%
Manufacturer	28	6.5%
Others, please state	77	18.0%
Years in operation		
< 5 years	108	25.2%
5–20 years	151	35.3%
More than 20 years	169	39.5%
Business size		
SMEs	242	56.5%
Large organisations	175	40.9%
Prefer not to answer	11	2.6

Among the 38 interviews, the majority identified their organisation as engineering consultancies (22 out of 38) and building construction contractors (8 out of 38). Other interviewees are from three civil contracting companies, two academic institutions, and two service (mechanical, electrical, and plumbing) contracting companies.

4.2 Criticality of Barriers

Cronbach's alpha of the survey data was estimated at 0.749, which is greater than 0.6, indicating that the eight barriers were internally consistent at the 5% significance level (Hair *et al.*, 2019). Table 4 shows the RII, standard deviation (SD), and significant level (p) of each barrier. As the significance levels are less than 0.05, all surveyed barriers are considered critical. The top three most critical barriers are B2, B3 and B7.

Table 4. Critical barriers to DT adoption

Code	RII	SD	p	Rank
B2	0.633	1.184	0.004	1
B3	0.632	1.237	0.008	2
B7	0.625	1.275	0.045	3
B5	0.575	1.308	0.020	4
B6	0.557	1.133	0.000	5
B1	0.543	1.117	0.000	6
B4	0.542	1.205	0.000	7
B8	0.537	1.164	0.000	8

4.3 Fuzzy Synthetic Evaluation Results

The results of the FSE technique are presented in Table 5. Based on literature, the critical barriers can be divided into three groups: 1) environment, 2) attitude and knowledge, and 3) technological issues. The environment group includes B1, B2, and B4, the group of attitude and knowledge contains B3, B7, and B8, and the technological group covers B5 and B6. Based on the RII of each barrier, the weightings of barriers and groups can be calculated as the ratio of the RII and to the summation of RII of barriers and groups. The FSE technique establishes two levels of membership functions (MFs) with Level 2 and Level 1 denoting the barriers and barrier components, respectively. The Level 2 MFs were estimated from the collective ratings of survey practitioners. The Level 1 MF of each barrier component was established using the weightings of barriers in the component and the fuzzy evaluation matrix composed of the Level 2 MFs of barriers in the component. Based on the obtained MFs and 5-point Likert scale, the criticality indices of components were calculated and the normalised indices were presented in Table 5. Therefore, the overall DT barrier index can be estimated as 0.370 × Environmental rating + 0.386 × Attitude and knowledge rating + 0.244 × Technological rating.

Table 5. DT barrier assessment model

Code	RII	W	MF	Index
Environment	1.717	-	(0.17, 0.20, 0.34, 0.18, 0.12)	0.370
B1	0.542	0.315	(0.20, 0.22, 0.34, 0.14, 0.09)	-
B2	0.633	0.369	(0.10, 0.17, 0.35, 0.22, 0.16)	-
B4	0.543	0.316	(0.21, 0.20, 0.33, 0.15, 0.10)	-
Attitude and knowledge	1.793	-	(0.14, 0.22, 0.28, 0.23, 0.14)	0.386
B3	0.632	0.352	(0.12, 0.17, 0.28, 0.27, 0.15)	-
B7	0.625	0.348	(0.13, 0.19, 0.29, 0.21, 0.18)	-
B8	0.537	0.299	(0.17, 0.30, 0.26, 0.20, 0.07)	-
Technology	1.132	-	(0.15, 0.22, 0.36, 0.22, 0.06)	0.244
B5	0.575	0.508	(0.13, 0.22, 0.35, 0.23, 0.07)	-
B6	0.557	0.492	(0.16, 0.21, 0.37, 0.21, 0.06)	-

4.4 Discussion of Results

4.4.1 Environmental Dimension

The environmental dimension includes three barriers: status quo of industry standards (B2), lack of a supportive legal environment (B1), and banking industry's lending restrictions (B4). The B2 barrier was the top one barrier with a RII of 0.633. A lack of technical standards and reliable information for emerging DT may prevent stakeholders from considering adopting. Therefore, the government should become more engaged with the industry and act as an advocator or promoter of emerging DT by establishing technical codes, regulations, guidelines, and standards (Hwang *et al.*, 2022). Legal and contractual uncertainties (B1) can significantly influence the decisions of project practitioners regarding the adoption of DT and make them opt for the traditional and conservative ways of doing things (Redmond *et al.*, 2012). Due to the initial high cost associated with technology implementation, financial support from banks or industry associations (B4) could be crucial for the adoption and development of DT in the construction sector (Chan *et al.*, 2018), especially for SMEs (Chien *et al.*, 2014).

4.4.2 Attitude and Knowledge Dimension

The dimension of attitude and knowledge includes three barriers: lack of interest from the client (B3), no financial need/drive for using DT (B7), and lack of awareness of DT providers (B8). The B3 barrier was ranked as the second greatest barrier with a RII of 0.632. Clients play a decisive role in adopting and promoting new technologies (Mao *et al.*, 2015). To cope with this barrier, the government and industry should work together through policy intervention (Abuzeinab *et al.*, 2017) and increase public awareness of the benefits of technologies (Chan *et al.*, 2018). Project stakeholders could be less interested in supporting the implementation of DT due to the potential financial loss and uncertainty (B7) regarding the extent of return on investment (Bademosi and Issa, 2021). Ozorhon and Karahan (2017) suggested that educating industry practitioners and the public would be helpful for the wide spread awareness and knowledge of DT and their benefits in the construction market. Besides, the shortage of technology providers (B8), as the main sources of information regarding the technology, could also result in a lack of awareness of technologies among the surveyed organisations. Rahman

(2014) also argued that the development of suppliers of new technologies would also be impeded due to the market protection from traditional suppliers.

4.4.3 Technological Dimension

The technological dimension includes ethical and privacy concerns (B5) and data and information security concerns (B6). As indicated by Habibipour *et al.* (2019), information gathering, threats to data security, and inappropriate secondary use could potentially leak sensitive data during the data process of DT, resulting in the ethical and privacy concerns (B5) of practitioners (Bosch-Sijtsema *et al.*, 2021). The data and information security concerns (B6) include not only the leaks of information, but also the security of physical devices and digital assets (Gamil *et al.*, 2020). Attributes to these concerns include the immaturity of the technology and data encryption and authentication mechanisms (Chien *et al.*, 2014) and the contractual and regulatory environment (Chen *et al.*, 2019).

4.4.4 DT Barrier Assessment Model

The FSE technique has generated the grouping of the barriers and the associated criticality indices and incorporated the survey results into the DT barrier assessment model in Table 5. By using the proposed model, practitioners in construction industry can assess their organisational DT barrier index which could act as a pragmatic tool for decision making of the organisation (Ogunrinde *et al*., 2021). The computation starts from rating the eight individual barriers on the 5-point scale (1 = not a barrier at all and 5 = a significant barrier). Then, the score for each barrier group can be computed by summing up the products of the score and weighting of each barrier inside the group. A high score for any barrier suggests that the organisation recognises the barrier as the major barrier to their DT adoption. Finally, the DT barrier index can be obtained from the equation in Section 4.3. Such an index can help the organisation to identify the relevant crucial challenges to DT adoption.

4.5 DT Adoption Action Model

Based on the literature review and interview data, several recommendations are proposed for different actors to cope with the critical barriers. These actors can be grouped into three types: government agencies, industry associations & education institutions, and organisations & practitioners (See Figure 1). . The relationships among the barriers, solutions, and corresponding actors are summarised in Figure 2. The measures to overcome these critical barriers are summarised as follows:

- Financial support schemes and incentives: Government agencies and industry associations are suggested to propose reasonable incentives and investment to encourage the market to pursue emerging DT. Rewarding schemes, low-cost loans, and subsidies are also suggested to support practitioners to adopt DT and R&D institutes to improve the maturity of technologies.

- Mandatory policies, regulations, and standards: Formulating effective policies and regulations could create mandatory push for stakeholders to engage the adoption of DT. The availability of standards could regulate the usage of technologies and raise the confidence of users.

- Public awareness enhancement: Organising workshops, seminars, and conferences are suggested to educate industry practitioners and promote the information sharing in the industry. These are also platforms for technology providers to demonstrate and promote the cooperation between users and technology providers.

- Technology-specific educational and training programmes: Emerging DT-related courses and trainings in education institutions are suggested to enhance the awareness and spread the knowledge about DT among current and future industry practitioners.

- Institutional framework and local advocacy teams: Institutional framework and local promotion teams could proactively create effective and adaptive guidelines for the implementation of specific technologies and help with the establishment of regional national standards.

- Collaborative environment among construction organisations: The collaboration of firms could complement each other, promote data and information sharing, mitigate economic uncertainty, and obtain a collective efficiency regarding the implementation of technology.

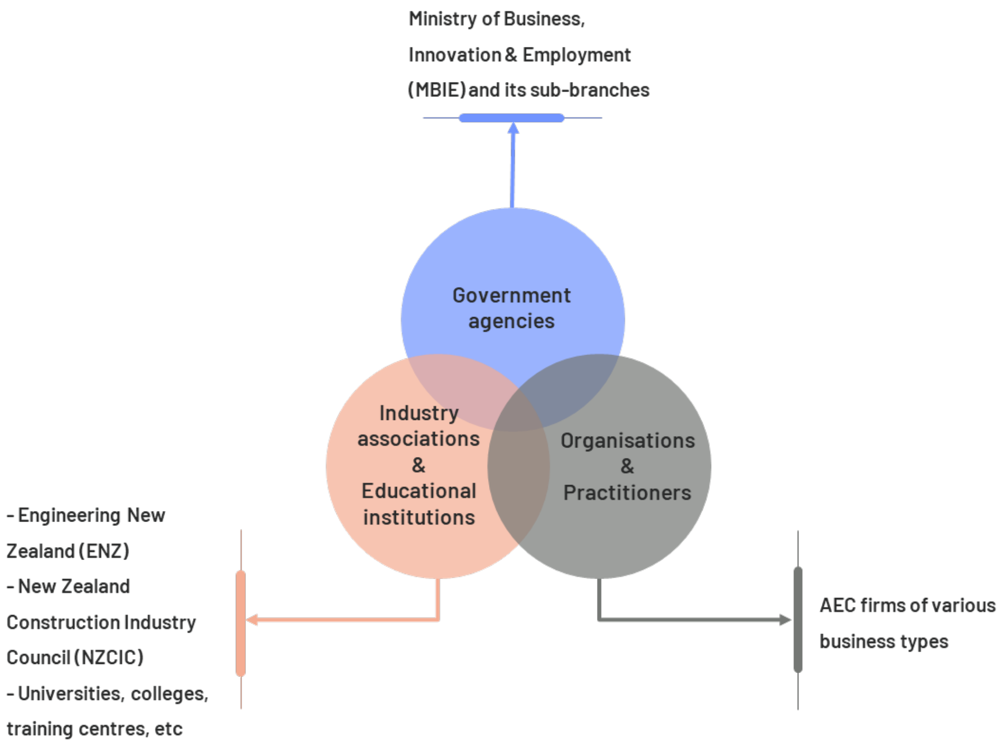

Figure 1. Main actors of proposed strategies

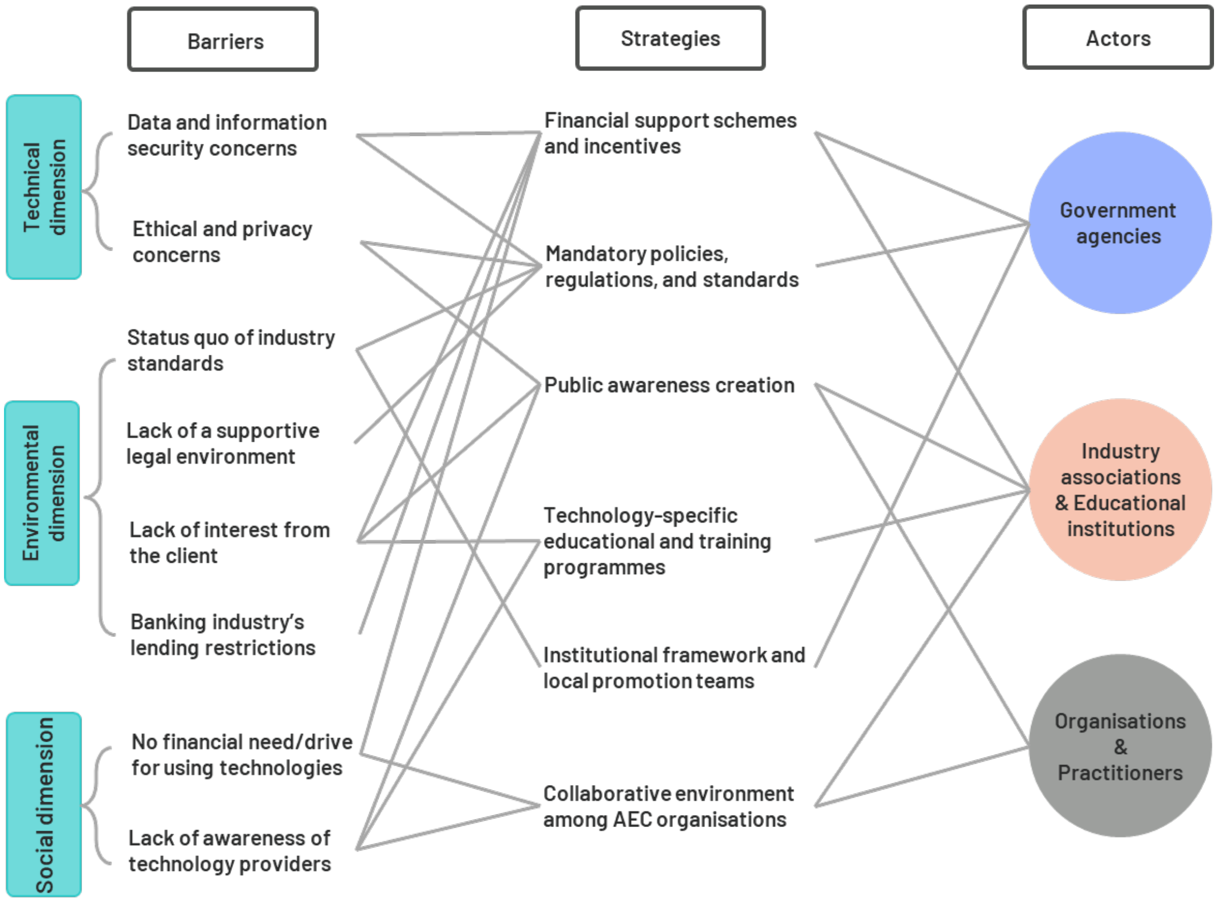

Figure 2. Digital technology adoption action model

5 Conclusion and Further Research

A range of emerging DT have been introduced over the past decade to address the challenges of low productivity and poor performance in the construction sector. Using a mixed-method approach, this study identified eight critical barriers to technology adoption in the New Zealand construction sector context. These barriers can be grouped into three dimensions: 1) environmental dimension; 2) attitude and knowledge dimension; and 3) technical dimension. The developed DT barrier assessment model and the proposed action model could be used as a tool for government agencies, industry associations & education and training institutions, and construction organisations & practitioners to diagnose and introduce associated strategies to overcome technology adoption barriers.

This study adds value to the literature about adopting technology and innovation in the construction sector. Firstly, the selection of common barriers to DT implementation excluded country/region-specific characteristics. Although the survey and interview were conducted in New Zealand, the list of common barriers could be tested in other countries and regions of a specific context. Secondly, the selection of barriers from the international literature considered common barriers to implementing DT in the construction sector, which is still rare in the literature. Finally, the study results show that the market and government-related barriers were perceived as the most prominent, which highlights the important role which government agencies can play in promoting technology implementation in the construction sector.

The outcomes of this research could serve as a guidance for promoting the collaboration among technology developers, engineering practitioners, and the government agencies to accelerate digital transformation of the construction industry. An action model has been proposed from this research, however it is suggested that a collaborative decision model could be investigated in future studies to support the DT adoption in the construction industry. Similar studies regarding the critical barriers to DT adoption can also be undertaken in other regions of the world for comparative analyses. These comparison studies will aid in the discovery of potential discrepancies and similarities between the barriers to adopting DT in the construction sector. Finally, further studies using the structural equation modelling approach are suggested to test and evaluate the structural relationships among the investigated barriers and the potential root causes of DT adoption.

6 Acknowledgement

The authors would like to thank the China Scholarship Council (CSC) and the University of Auckland Joint Doctoral Scholarship and funding from the Building Research Association of New Zealand (Project number LR12069). Without both sources' funding support, this research would not have been possible. We would also like to thank many organisations and practitioners who participated in this research.

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A Socio-Technical Model of Digital Design Coordination and Review: A Game Theoretic Approach

Julie Jupp[1*], Mohammad Hassan Azizipour[2] and M. Reza Hosseini[3]

[1]School of Civil & Environmental Engineering, University of Technology Sydney,
81 Broadway Ultimo NSW2007, AUSTRALIA
[2]School of Art & Architecture, Tarbiat Modares University, IRAN
[3]School of Architecture and Built Environment, Deakin University, Geelong, AUSTRALIA

julie.jupp@uts.edu.au; m_azizipour@modares.ac.ir; reza.hosseini@deakin.edu.au
* Corresponding author

Abstract:
A reported benefit of building information modelling is the ability to visualise and detect hard and soft clashes between design systems via the manual inspection of federated 3D models and the use of automated clash detection. Research has focused on the advantages and value of automation revealing a lack of understanding of the complexities of design coordination and how clashes are resolved within a multidisciplinary team once identified. There is a paucity of support for conflict resolution that accounts for both technical and social considerations of design, and how they can be effectively and efficiently negotiated in a distributed, heterogeneous project environment. This research seeks to address this gap by developing a theoretical foundation for digital design coordination and review. The model is used to analytically and mathematically model and manage design conflict resolution using a game theoretic approach. The research contribution therefore seeks to extend automated clash detection workflows by supporting the resolution and greater control of design conflicts. The paper closes with a discussion of cooperative game theoretic approaches and how these methods can support the automated assignment of hard and soft clashes to collaborating team members.

Keywords:
Design coordination and review, Building Information Modelling, Clash detection, Game theory, Automated design conflict resolution.

1 Introduction

Building information modelling (BIM) and, more recently, Digital Engineering (DE) now dominate the construction information technology literature (Singh, 2019), and have become mainstream in industry practice. In Australia, the transformative impact of BIM and DE, and the growing list of associated digital technologies, have seen a concomitant shift in construction research investigating a variety of digital use cases across architecture engineering, construction and operational (AECO) practices. Over the past decade, research studies have shown that the digitisation of the construction industry has evolved more efficient and effective design coordination and review cycles using automated approaches to clash detection.

The benefits, opportunities and innovations of 3D visualisation and clash detection tools are evident in the research literature (e.g., see: Ku and Taiebat 2011, Chileshe 2012). Chileshe (2012) demonstrated improved constructability, visualisation, and productivity resulting from 3D model-based clash detection (Chileshe, 2012). Recent studies have also confirmed previous findings, showing that much of the savings that can be realised from BIM are achieved due to the effective implementation of clash detection tools and processes (Yuan and Yang, 2020, Chahrour *et al.*, 2021, Daszczyński et al. 2022). Chahrour *et al.* (2021) highlight that clash detection leads to fewer construction changes, reduced cost of warranty claims, sufficient time to address errors, reduction in time spent re-developing the design, re-documenting, coordinating change orders, responding to RFIs, and redesigning in the field. Clash detection is consistently reported in the literature as having one of the highest returns on investment (ROI) from the implementation of BIM due to its support for constructability analyses and reduction of rework and change orders during delivery.

However, while there is an ongoing research agenda surrounding the advantages and value of clash detection, there is a lack of research and development surrounding the technical and non-technical conflict resolution surrounding clash detection processes. Specifically, how to support more efficient and effective design coordination and review cycles involving multidisciplinary design team stakeholders. This paper seeks to address this gap. The objective is to represent the collaborative technical and social processes of multidisciplinary design coordination and review cycles. The goal is to describe how design coordination and conflict resolution activities are influenced by social and technical interactions, and to use this as a foundation for analytically and mathematically modelling of conflict resolution strategies using a game theoretic approach. The paper presents the first step in this research, presenting a model of design coordination and review cycles that accounts for both technical and non-technical design conflicts, before then discussing the use of game theory in model-based technical design conflict resolution processes.

2 Background

The International Standard ISO 19650[1] defines Building information modelling (BIM) as a "shared digital representation of physical and functional characteristics of any built object, which forms a reliable basis for decisions" (ISO 19650 - Building Information Modelling (BIM) | BSI, 2019). Various Australian case studies have investigated BIM in support of - for example - more collaborative processes (Mostafa et al 2019), small and medium size enterprise adoption (Hong et al 2019), improved information requirements management capabilities (Chen and Jupp 2021), prefabrication (Mostafa et al. 2020), demolition and waste reduction (Han et al 2021), the integration of BIM into FM (Hosseini et al. 2018), and studies of the realised efficiencies through all phases of the project life cycle (Hosseini *et al.*, 2021). Yet several challenges still restrict the development of the construction industry's effective application of BIM and the productivity benefits from automation (Sun *et al*., 2021). The level and distribution of informatisation remains stubbornly low and patchy (Liu, 2020). Thus, whilst BIM has represented a step-change in project delivery practices, in recent years the development of automated techniques has brought innovative progress in limited sectors and organisations of construction.

A paucity in automated conflict resolution methods able to utilise the vast amounts of data generated from clash detection tests prevents further productivity efficiency gains from the digitalisation of design coordination and review cycles. The detection of clashes and technical design conflicts relies on either using a manual, visual inspection of 3D models (to identify "hot-spots"), or the implementation of discipline-based rules that automate the detection of 100s if not 1000s hard and soft clashes between discipline-specific 3D models appended into a federated model. Taghizadeh *et al.* (2021) claim that the construction industry is now characterised by the efforts to detect errors in the design contributions of collaborating project team members, which in turn generates an abundance of meetings, and requests for information (RFIs). Research by Akponeware and Adamu (2017) also shows that there is a link between

[1] AS ISO 19650.1:2019 Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM)- Information management using building information modelling, Part 1: Concepts and principles.

stakeholders with non-BIM specific training (or the commensurate professional qualifications) with high incidences of clashes. In addition, the structure of cloud-based common data environments (CDEs) does not facilitate clash avoidance and in fact, encourages isolated working in the early design stage by creating “digital information silos” (Akponeware and Adamu 2017). Further, justification for direct cost savings for clash detection on projects with quantifiable evidence are limited. This is largely due to the challenges associated with calculating cost savings, which are not only associated with the potential time savings (resulting from more complete and higher quality design and construction documentation), but also the potential consequences or knock-on effects of design coordination issues identified during construction. From this perspective, the cost of additional procurement, demolition, re-work caused by redesign and significant interruptions to the project schedule are difficult to calculate.

A common problem that frequently arises on projects resides in the varying approaches and maturity levels of collaborating engineering disciplines, which results in poor quality and inconsistent spatial geometry across a set of discipline-specific 3D models. Poor model quality and inconsistencies in modelling standards is typically first detected when a test of ‘hard’ or ‘soft’ clash batches are run using software such as Navisworks Manage^{TM}, Revizto^{TM} or Solibri^{TM}. The major difference between the two types of clash detection lies in the extent of the detected interference: hard clash detects a physical collision between two model objects; soft clash alerts on an excessive proximity between two objects that could generate issues during execution/installation or maintenance (Akponeware and Adamu 2017).

The utilisation of BIM has made it possible to detect clashes earlier (and avoid them) in the design process (Rokooei, 2015, Akponeware and Adamu 2017). Collaborative efforts can be focused on clash detection, clash avoidance, and technical design conflict resolution prior to construction (Chahrour *et al.*, 2021). The detection and resolution of hidden technical design conflicts within each discipline-specific model is only made possible due to the intelligent, information-rich objects contained in 3D models. Thus, according to Chahrour *et al*. (2021), the main benefits of implementing BIM relate to cost-control and design, i.e., reduced errors, increased design and model quality, or in other words, resolved clashes (Chahrour *et al.*, 2021).

The research literature highlights the benefits of model-based design coordination and review cycles, and focuses largely on clash detection and resolution from a risk and liability perspective. However, there is a gap in both research and practice surrounding methods to support the effective and efficient resolution of clashes and design conflicts once issues are detected. Taghizadeh *et al*. (2021) investigate design review and the workflows following clash tests, and highlight the limited understanding in this regard. There is a paucity of approaches to the resolution of both technical and non-technical conflicts, and therefore a lack of risk management and liability assignment integrated as part of these workflows.

3 A Model of Digital Design Coordination and Review

Multidisciplinary design means different things to different people. The AECO disciplines participating on construction projects mean that a significant number of individuals with diverse technical engineering backgrounds are engaged in decision making, which occurs as both a siloed activity and as a collaborative one. The dominant approach to understanding design relates to communication and collaboration. Definitions of design focus on concepts such as function, behaviour and structure (Gero 1998, Tang *et al.*, 2011), or optimal design, correctness, consistency, and fitness (Hu *et al.*, 2007). Under such models of design, decision-making is often considered a rational procedure, lacking in incentives, motivations, emotions, and community (Lebedeva, 2008). This traditional viewpoint has limited applicability when a team of multidisciplinary engineering designers is considered. Models of design decision-making have also therefore been limited with regards to the influence of complex collaborative processes, which recognise design decision-making as being shaped by social, cognitive, material, and technical processes (Takai 2010, Campbell *et al*., 2019). It is therefore necessary to model collaborative design coordination and review cycles as a socio-technical process of multidisciplinary engineering design decision making occurring in a distributed and heterogeneous environment.

This research therefore claims that collaborative design coordination and review activities must be treated as a socio-technical system that accounts for the unique knowledge and individual goals of the stakeholders involved in the process, as well as the technical constraints of the design problem. From this perspective, it is possible to describe how clash detection and conflict resolution activities are influenced by social and technical interactions, and how digital workflows influence conflict resolution via technical design processes and social interactions. Multidisciplinary design coordination can therefore be seen as a process of technical co-construction in which a set of collaborating project stakeholders, working within a collaborative design environment, undertakes a clash detection workflow such as the one shown in Figure 1.

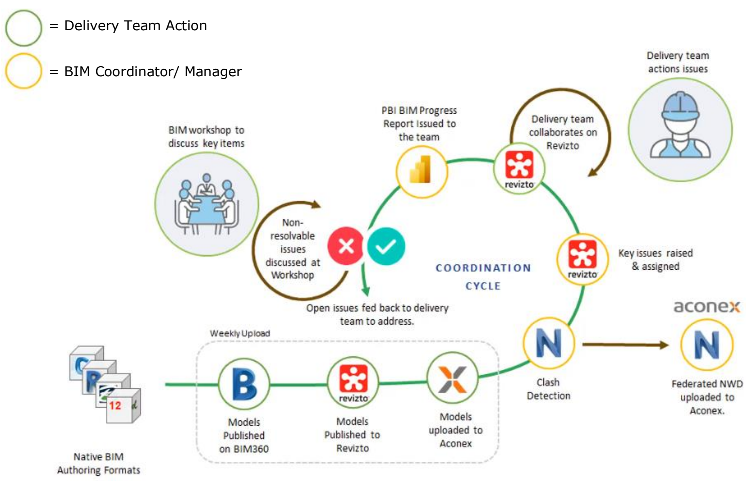

Figure 1. Design Coordination and Review Cycle

The model aims to present a sound theoretical foundation that can be used to analytically and mathematically model, simulate, manage, and optimise engineering design coordination and conflict resolution activities. The remainder of this section presents the collaborative technical, and multidisciplinary design coordination and review cycles.

3.1 A Socio-Technical Model of Design Coordination and Review Cycles

To clearly explain what is meant by the collaborative design coordination and review activities represented in Figure 1, the following concepts are defined:

- *Stakeholder*. An individual, groups of individuals, or any entities, with an interest, or possible interests, in the outcomes of the design campaign and/or of the design environment.
- *Perspective*. A collection of information that is relevant to a purpose or a goal of a stakeholder, and which acts as a “lens” or “filter” through which a stakeholder produces and consumes information. A stakeholder has many perspectives on, or relative to, an endeavour in which he participates.

- *Design coordination and review cycle*. A digital process to ensure building designs meet the functional, aesthetic, and economic requirements of project stakeholders. During the process the components of building systems are defined and routed to avoid interferences and to comply with diverse design and operations criteria.
- *Clash detection specification and workflow*. A set of goals, decisions, processes and actions, which lead to a design model (i.e., the specification of the final 3D BIM model suitable for construction in the case of building or civil engineering design), which meets the life-cycle requirements of a built asset.
- *Clash priority matrix*. A matrix that shows which disciplines take precedence based on system priority structure that presents, categorises and sorts design coordination according to the project's goals.
- *Clash and technical design conflict*. A clash can be a hard collision or soft tolerance between two objects within any combination of BIM models. A technical design conflict is a situation in which viewpoints/ perspectives and/or decisions from the same and/or different stakeholder(s) become mutually incompatible with respect to clash being resolve *and* the satisfaction of some design requirements.
- *Technical design conflict resolution*. Conflict resolution defines those techniques and methods employed to solve, prevent and avoid the occurrence of technical design conflicts.
- *Collaborative Design Environment*. The sum of technical and nontechnical infrastructure within which a design campaign is immersed. This includes, for example, physical plant, lines of communication, command and control within the organisation, corporate cultures, pertinent design codes, etc.
- *3D Model*. A three-dimensional representation of an object or surface by polygons, edges, and vertices in simulated 3D space.
- *Computational model*: A set of statements or specifications in an agreed upon language, which represents a real-world phenomenon/ artefact and can be used to illustrate, explain, understand, evaluate, record, predict or control that phenomenon/ artefact.

3.2 Design Coordination and Conflict Resolution / Management

In a design coordination review cycle, stakeholders perform both technical and social roles based on their unique perspectives. Figure 2 shows the elements and relationships in a design coordination and review system. The technical design process, social interaction, conflict resolution strategies, and perspective model are the critical components within the socio-technical decision-making process.

Technical roles are conducted as a technical decision-making process while the social roles are represented as social interactions. They are formed when stakeholders interact with other members involved in the design coordination review cycle. By making technical decisions based on their technical roles, participants create, modify, and evaluate the 3D model’s features. The recognition of social roles, which are typically influenced by project organisation structures, norms, and culture, considers how technical decisions are coupled with social-interactions that occur as part of design coordination meetings or via online interactions in the CDE. Knowledge representation is therefore also a critical aspect of the model, as for stakeholders this process is key to capturing the reasoning behind technical design decisions.

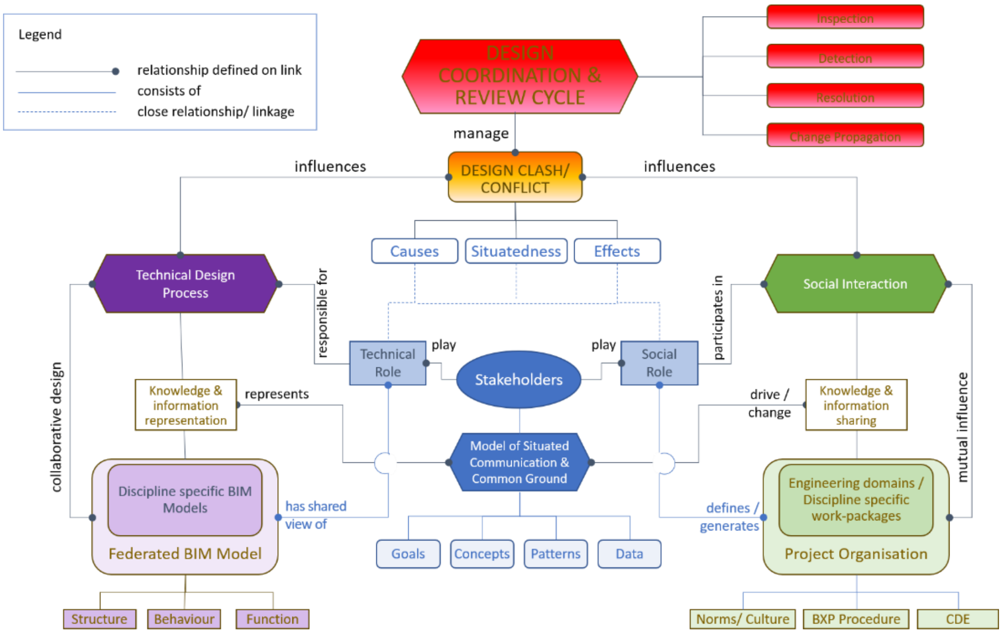

Figure 2. Model of Design coordination and review

The 3D federated model is an effective information sharing mechanism that accelerates the process of achieving shared reality. However, during the design coordination process, various conflicts (outside any potential hard or soft clash detected) may occur due to multiple task interdependencies and perspective differences. When treating engineering design as a purely technical process, these types of conflicts are usually regarded as being abnormal and to be avoided. To resolve technical design conflict, different approaches have been proposed by building utility functions for designers, by categorising conflict resolution knowledge, or by capturing design rationale. The development of the clash priority matrix is one such example of technical design conflict management and avoidance.

The socio-technical model of collaborative design coordination and review highlights the importance of clash detection, technical design conflict identification (e.g., as a part of a proposed change), and conflict resolution strategies, and enables the study of defining phenomenon. Although research has produced considerable automated approaches to clash detection, and extensive conflict management strategies (from both a technical perspective and a social science perspective), there is still no systematic and effective approach to managing how clashes and technical design conflicts are resolved using both a technical and social approach. When treating design coordination and review as a socio-technical process, conflicts can be systematically and explicitly dealt with as a resource to drive social interactions and technical design innovation. To manage conflict at its root cause, social interaction should be considered as a controllable parameter to build common ground and affect and change design perspectives. In the design stages, clashes and technical design conflicts should be treated as a motivation to identify the deficiencies among the design team and to generate solutions, while at the late stage they should be prevented or resolved to achieve greater efficiencies, productivity, and constructability.

3.3 Perspectives, Communication and Common Ground

Each stakeholder participating in a continuous design coordination and review cycle has their own set of attributes, which must include: (a) themselves, (b) aspects of the project organisation and the environment they perceive they are operating in, (c) their perception of the perspectives of the other stakeholders within the environment, or development of common ground, (d) situatedness, and (e) information sharing, or communication (Kannengiesser and Gero 2002). Each of these five attributes includes aspects related to technical viewpoints, managerial viewpoints, and social-interaction viewpoints. As technical design decisions are being made to avoid or resolve clashes, they are under the influence of social interactions. As a result, additional technical design and non-technical conflicts can occur as a knock-on effect. Technical design conflict resolution is therefore a key “process control” that enables the 3D BIM model and the design coordination process to adapt and evolve to a state that is understood and accepted by all stakeholders involved in the review.

To reach an understanding of the technical design conflict and negotiate a valid resolution across different disciplines, the content of a communicative action has to fit into some common context, else communication is likely to fail resulting in a lack of understanding or a misunderstanding. Establishing “common ground” therefore consists of “mutual or shared knowledge about the context” (Kannengiesser and Gero 2002). Common ground can also be seen as a process of co-construction undertaken by collaborating stakeholders. A technical co-construction necessitates negotiation of design goals and adaptive evolution of the design coordination process. As a convergence gradually emerges toward a consensual validation of their perceived reality, the resolution of the technical design conflict can be confirmed. When inconsistent realities evolve and merge into a consistent global reality, non-technical conflicts at different levels of abstraction can occur among stakeholders. These conflicts could be managerial or social interaction in nature. Their effective handling plays a central role in determining the overall effectiveness of a design coordination and review cycle. Thus, as convergence occurs through co-construction, the design process can be driven by technical considerations allowing mental constructs such as mappings, decision analysis and game theoretic methods to provide useful ways of implementing design coordination and review models in support of clash and technical design conflict resolution.

4 Towards a Game Theoretic Approach to Design Coordination

The multi-disciplinary nature of design coordination and review cycles adds to the difficulties of clash and technical design conflict resolution. It is widely agreed that if project stakeholders can increase their level of communication and collaboration, the clashes identified in design coordination and review workflows can be reduced and technical design conflicts can be potentially avoided. It is important to identify solutions that can satisfy all (or the majority) of the stakeholders involved, whilst considering all perspectives, and developing common ground. One such technique introduced to mitigate or resolve disputes is game theory (Peldschus, 2008).

4.1 Application of Game Theory in Construction

Game theory is essentially the mathematical study of strategic decision-making. In game theory, interacting choices of players result in overall outcomes with respect to players' preferences (Piraveenan, 2019). A game can be defined as mathematical objects including a set of players (two or more), a set of possible strategies taken by players and a determination of player's payoffs for each combination of such strategies. Knowing the capabilities of game theory in providing planning insights - not unavailable in traditional methods - has gained recent attention for solving project management problems (Piraveenan, 2019). In such approaches to game theory, the interacting choices of players result in overall outcomes concerning players’ preferences. However, the resulting outcomes might have been intended by none of the players. Game theory should therefore be seen as a tool that uses mathematical modelling to allow dispute resolution. Game theory is about the perceptions and realities of stakeholders when there is a conflict or disagreement and is used to determine which decisions are more effective in cooperation or non-cooperation between competitors.

Game theory has important applications in construction management (Peldschus, 2008). Construction activities mainly involve dealing with people, negotiating, and finding a solution that keeps the project going. In these negotiations, game theory can be an impressive tool for project management (Bočková *et al.*, 2015). All competitors are eager to cooperate as a coalition because this will decrease costs and increase profits (Teng *et al.*, 2019). A comprehensive literature survey on applications of game theory in project management can be found in (Sun *et al*., 2021). Teng *et al*. use cooperative game theory as the method for analysing profit distribution among the designer, construction contractor, owner and BIM consultant (Teng *et al.*, 2019). In the construction industry, evolutionary game theory has also been widely used to analyse the behavioural evolution mechanism of BIM adoption (Jia *et al*., 2021). Evolutionary game theory is different from game theory. It assumes that bounded rationality not only considers the limited rationality of individuals but also dynamically adjusts their strategies through learning and imitation. It describes the dynamic evolutionary process among the core competitors and better defines the formation process of equilibrium. Based on prospect theory and evolutionary game theory, Jia *et al*., discussed the adoption of BIM among stakeholders in PPP projects. In other words, the mechanism of each competitor on BIM adoption is indicated by game theory and BIM. Appling evolutionary game theory, behaviours evolution of BIM application in integrated facility management organisation, was analysed (Jia *et al.*, 2021). Using game theory, Yuan and Yang propose a model of two firms that are potential BIM adopters under support from the government (Yuan and Yang, 2020). Cooperative game theory can also propose potential solutions to mitigating disputes over liability. An evolutionary game model was constructed between government and enterprises and owners and contractors on BIM diffusion in prefabricated buildings (Jia *et al.*, 2021). Liu (2020) applied cooperative game theory and the liability game model to analyse and respond to the problem of "How to mitigate design issues while all the parties involved are satisfied with the result?" (Liu, 2020).

Whilst there have been a number of recent efforts to develop game theory models in various forms for solving project management problems, none of the previous studies dealt with the application of game theory to resolve digital design coordination and conflict resolution problems in the context of BIM-enabled project. The broader objectives of this research are therefore to introduce a game theoretic model to provide insights to project teams, and in particular to BIM managers and engineering designers, to help manage design coordination problems arising from digital clash detection workflows.

4.2 Towards a Game Theoretic Approach to Digital Design Coordination

In exploring game-theoretic approaches to digital design coordination based on the proposed model, the research is currently engaging with leading AEC companies that have moderate to high levels of maturity in the implementation of model-based design coordination and review cycles. Using a case study approach, the criteria for resolving clashes are being identified using a mixed interview and literature-based research methodology. A weighting approach can then be used to prioritise defined criteria in which, the more important, the higher weighting.

In the application of game theory, to support how clashes are addressed, and how any potential conflicts in proposed design changes are resolved, the problem can be formulated as a collaborative game. It is assumed that all stakeholders involved (or players) provide the correct information and approach design coordination in accordance with the discipline-specific technical criteria, as well as non-technical project organisation (social and managerial) criteria. Starting from any specific discipline, there may be *n* design alternatives for a specific clash and *m* pre-defined criteria, which forms an $m \times n$ matrix. This matrix is also produced for other disciplines. Finally, a game matrix is created by merging these matrices. For simplicity, assuming that there are only two disciplines involved in the design change the payoff matrix is written as in which P_n^C represents the payoff values for the first discipline while it takes the *n*[th] criterion. The game theoretic framework ensures finding the optimal solution.

$$\begin{bmatrix} (P_1^C, P_1^A) & (P_1^C, P_2^A) & \cdots & (P_1^C, P_m^A) \\ \vdots & & \ddots & \vdots \\ (P_n^C, P_1^A) & & \cdots & (P_n^C, P_m^A) \end{bmatrix}$$

Each design collaborator (e.g., structural, mechanical, electrical, civil, hydraulic, etc…) is a player in a cooperative game. While a number of approaches are being explored, the use of the Nash equilibrium in ongoing research investigations is being utilised.

5 Future Work and Concluding Remarks

With the maturity of BIM in the construction industry, design coordination and review cycles based on automated approaches to clash detection have gained increasing attention in industry and research alike. Although there is a rich literature on clash detection and its benefits, few studies have explored and developed new approaches to the resolution of clashes and related technical design conflicts. This research aims to address this gap by developing the foundations of game theoretic approaches clash resolution. This paper presents the first steps towards a model of the design coordination and review cycles as a socio-technical decision process. The proposed model attempts to overcome the limitations of existing methods by considering clash detection and technical design conflict resolution relative to the perspectives and potential competing interests of stakeholders. This ongoing research project is currently developing a categorisation of the different aspects of technical and non-technical conflicts related to (a) design coordination goals, (b) clash detection processes, and (c) model quality metrics. The aim is to identify mappings between the different types of technical conflicts that arise, and the conflict management strategies developed in the social science and organisational management literatures. It should be emphasised that conflict management involves not just the avoidance, detection, and resolution of technical conflicts, but the prevention and control of conflict between completing technical and non-technical issues. Of significance is the consideration of the measurement and monitoring of the rate at which conflict resolution occurs so that the convergence of stakeholder viewpoints and creation of common ground can be reached in an effective and timely manner.

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Towards Detailed Digital Examination of Masonry Railway Bridges Using Terrestrial Laser Scanner

Arijit Sen[1], Saeed Talebi[2]*, Song Wu[1] and Mark Shelbourn[2]

[1]School of Architecture Design and Built Environment, Nottingham Trent University,50 Shakespeare Street, Nottingham NG1 4FQ, UK.
[2]School of Engineering & the Built Environment, Birmingham City University, Millennium Point, Curzon Street, Birmingham B4 7XG, UK.

arijit.sen@ntu.ac.uk; Saeed.Talebi@bcu.ac.uk; song.wu@ntu.ac.uk; Mark.Shelbourn@bcu.ac.uk
* Corresponding author

Abstract:
Masonry railway bridges make up a significant number of the UK railway network. These bridges require regular condition assessments by transportation authorities to identify and evaluate defects that can result in structural failures. Common defects in such masonry structures are spalling, crack, bulging, joint defects and loss of section. The conventional bridge examination process is highly dependent on visual inspection, that is, an inspector should be on site and, as a result, such inspection can cause health and safety concerns as well as traffic interruption for a significant period. Digital examination process can replace the visual examination and it can subsequently reduce the number of site visits, traffic interruptions, and health and safety concerns. It can eventually speed up the examination process and improve the efficiency of inspectors' work. Terrestrial laser scanner (TLS) can be used to identify defects and analyse their severity on the surface of bridge structures. The point cloud dataset captured by TLS can be analysed using commercially available software packages to identify defects and assess their severity. However, a review of the literature reveals that despite the importance of masonry railway bridges, there is scarce literature focused on exploring and comparing different software solutions for the purpose of defect detection and analysis in such bridges. Therefore, this exploratory research aims to demonstrate the applicability of digital examination for masonry railway bridges through the application of TLS. This paper contributes to knowledge by establishing a practical basis to identify defects in masonry railway bridges using commercially available software tools.

Keywords:
Digital Examination, Masonry Bridge Defects, Point Cloud Data Analysis, Defect Detection.

1 Introduction

The U.K.'s transport network contains a large number of masonry bridges, and these bridges are highly durable and require moderate maintenance because of their arch constructions (Wiggins, 2018). Around 47% of the railway bridge asset in the UK are masonry structures (Orbán, 2004) and in Europe, it is around 60% of total railway bridges (Jing et al., 2022). Although these bridges do not require much maintenance, a periodical inspection is necessary to ensure that the bridges are in operable condition. Current bridge inspection procedures are highly relying on a physical visit to the site of a bridge and manually inspecting the condition of the bridge by an expert engineer. It is not only time-consuming but also triggers other issues such as traffic interruption, the closure of a road or a lane, risk of working overhead or underneath a bridge (Talebi et al., 2022). Also, the process requires significant planning, pre-visit to the sites carrying out safety equipment and staff travelling to the site. The digital examination can facilitate bridge condition monitoring more quickly and cost-effectively than the traditional physical inspection processes with a significant reduction in traffic closure and risk of working at height and under-bridge inspections. A study on four US bridges by Wells and Lovelace (2017) shows that digital examination using Unmanned Aircraft System (UAS) can be successfully performed in full compliance with National Bridge Inspection Standard (NBS). Instead of physical inspection, capturing digital information of an asset and analyzing that later is the key aspect of digital examination. A range of techniques could be used to capture digital data such as Terrestrial Laser Scanning (TLS), 360-degree imaging devices, Close Range Photogrammetry (CRP), Infrared thermography (IR) and Ground Penetrating Radar (GPR) (Abu Dabous and Feroz, 2020). Terrestrial laser scanning (TLS), also referred to as terrestrial LiDAR (light detection and ranging), acquires XYZ coordinates of numerous points by emitting laser pulses toward these points and measuring the distance from the device to the target. Popular laser scanners in the market include FARO, Leica, Surphaser, Topcon and Trimble. Bespoke software packages (e.g. SCENE software for FARO laser scanners) are generally required for managing and analysing the data because of the large amount of data stored in a TLS point cloud. 360 imaging cameras are designed to capture high-resolution spherical immersive images for efficient visual documentation of an environment. 360 imaging cameras are usually lightweight and easy to transport and deploy. Individual 360 images can be linked together to create a virtual tour (similar to Google Street View) to enable users to move between captured positions. 360 imaging cameras can be mounted on a standard tripod, vehicles or under a UAV for aerial data capture (Rausch et al., 2022). For example, iSTAR FUSION 360 Degree Rapid Imaging Panoramic Camera is a 360 camera that can be mounted on a tripod. It has 4 pre-calibrated sensors delivering a full spherical image. GPR generates a subsurface image using electromagnetic energy, and an infrared camera produces images based on the reflected infrared radiation from an object. Unmanned aerial vehicles (UAVs) are a class of aircraft that can fly without the onboard presence of pilots. Unmanned aircraft systems consist of the aircraft component, sensor payloads and a ground control station. When it is remotely controlled from the ground, it is called RPV (Remotely Piloted Vehicle) and requires reliable wireless communication for control. UAVs are classified based on altitude range, endurance and weight. It can support a wide range of applications including examination of the top of bridges, aerial photography, geographic mapping, and disaster management. The smallest categories of UAVs are often accompanied by ground-control stations consisting of laptop computers or mobile devices as well as other components that are small enough to be carried easily with the aircraft in small vehicles. In recent years, increasing research efforts and developments are improving UAV for various applications and reliability. Also, a shortage of skilled onsite crew members is a bigger problem. It is widely accepted that a minimum of three staff members is required to operate a UAV (Elghaish et al., 2021). Each instrument has its advantages and drawback. For example, infrared thermography can quickly produce thermal distribution in a structural element; however, the negative impacts of absorption of thermal energy within daytime should be mitigated by capturing thermal images within certain hours of a day (normally 2 hours after the sunset); 360-degree images can provide information about the surface condition; however, this technique is not suitable for subsurface defects and so on. A significant amount of research work is done in the field of construction and building engineering for the detection of bridge defects from high-resolution visual images and point cloud data; however, many of those do not consider masonry bridges due to their complex surface texture. Therefore, this paper aims to demonstrate the feasibility of digital examination for masonry railway bridges using TLS. The research reported in this paper attempts to answer to the following question: how the analysis of 360 images and point cloud data can be used to identify defects and quantify their severity respectively in masonry railway bridges?

2 Literature Review

Masonry defects in built structures are generally categorised as bulging and leaning of walls, failure in bonding and defects in joints, development of cracks, corrosion on the surfaces and defective cavity walls (Noy and Douglas, 2005). Cavity walls are not part of bridge structures rather it is found in buildings. Considering reference documents of the Network Rail in the UK, the masonry bridge defects can be classified as i) bulging, ii) crack/fracture/ring separation, iii) spalling, iv) joint defect and v) loss of section (Network Rail L3 / CIV / 006 Part 1E, 2019). The same document outlines the way to further classify these defect categories into several severity levels based on the dimension and location of the defects. Therefore, it is necessary to understand the specific measurement requirements for each defect for the development of an effective digital examination framework for masonry bridges. Table 1 shows the defect types and their corresponding measurement requirements for detailed examination of a typical masonry bridge.

Table 1. Defect types and measurement requirements for detailed examination. (Source: Network Rail L3/CIV/006 Part 1E, 2019, pages 23-30)

Measurement requirements	Defect type				
	Bulging	Crack/Fracture	Spalling	Joint defect	Loss of section
Length	Yes	Yes	Yes	No	Yes
Width	Yes	No	Yes	No	Yes
Depth	No	No	Yes	Yes	No
Area	Yes	Yes	Yes	Yes	Yes
Distortion angle	Yes	No	No	No	No

It is found in Table 1 that there are three basic types of measurement required to complete the detailed inspection process. These are:

i) Area measurement for the estimation of surface area covered by a particular defect.

ii) Linear measurement for the quantification of length, width, and depth of a particular defect.

iii) Angular measurement for the magnitude of distortion angle.

There is a significant application of digital technologies found in the literature concerning bridge inspection. Peng et al. (2020) and Wang et al. (2020) demonstrated the use of high-resolution 2D images captured using an Unmanned Aerial Vehicle (UAV) to monitor cracks in concrete structures. Rau et al. (2017) developed a graphical user interface-based system to detect cracks and spalling on concrete bridges from a high-resolution image. Yan et al. (2021) demonstrated the use of visual images (RGB) and lidar data captured using UAV to generate a point cloud model of the bridge and quantify cracks on concrete structures (Talebi et al., 2021). Tian et al. (2021) propose a method for measuring force in cable bridges using UAV-captured data and computer vision algorithms which shows good agreement with the traditional measuring methods. Rhee, Choi et al. (2019) conducted research to show the condition of concrete bridges by analysing GPR-captured data to detect water penetration. Kushwaha et al. (2018) used TLS and CRP to generate point cloud data and analyse deck linearity deformation and deck thickness measurement in different bridges. In an extended study, the authors used GPR to generate subsurface profiles for the detection of water penetration, crack voids and rebar y conducting subsurface profile analysis (Kushwaha et al., 2020). Ayele et al. (2020) used UAV-driven photogrammetry to construct 3D models which were analysed to identify cracks and to measure the width and length of the cracks. Kim et al. (2018) used photogrammetry to construct 3D models which are collected using a UAV drone. In a comprehensive review of the application of laser scanning technology in the civil engineering and building engineering domain, Rashidi et al. (2020) have shown that TLS technology and point cloud data analysis has been successfully implemented for condition monitoring of structural assets throughout the globe. UAV has two major applications namely 3D model construction and automatic damage detection with some limitations such as significant data processing time with the need for high-power computing, the requirement of skilled and trained persons etc. (Ayele et al., 2020). However, with the rapid development of cloud computing technologies high computing power and big data processing are no longer significant challenges.

3 Methodology of Digital Bridge Examination

The proposed digital bridge examination process involves three steps namely data capture, data processing and data analysis as presented in Figure 1.

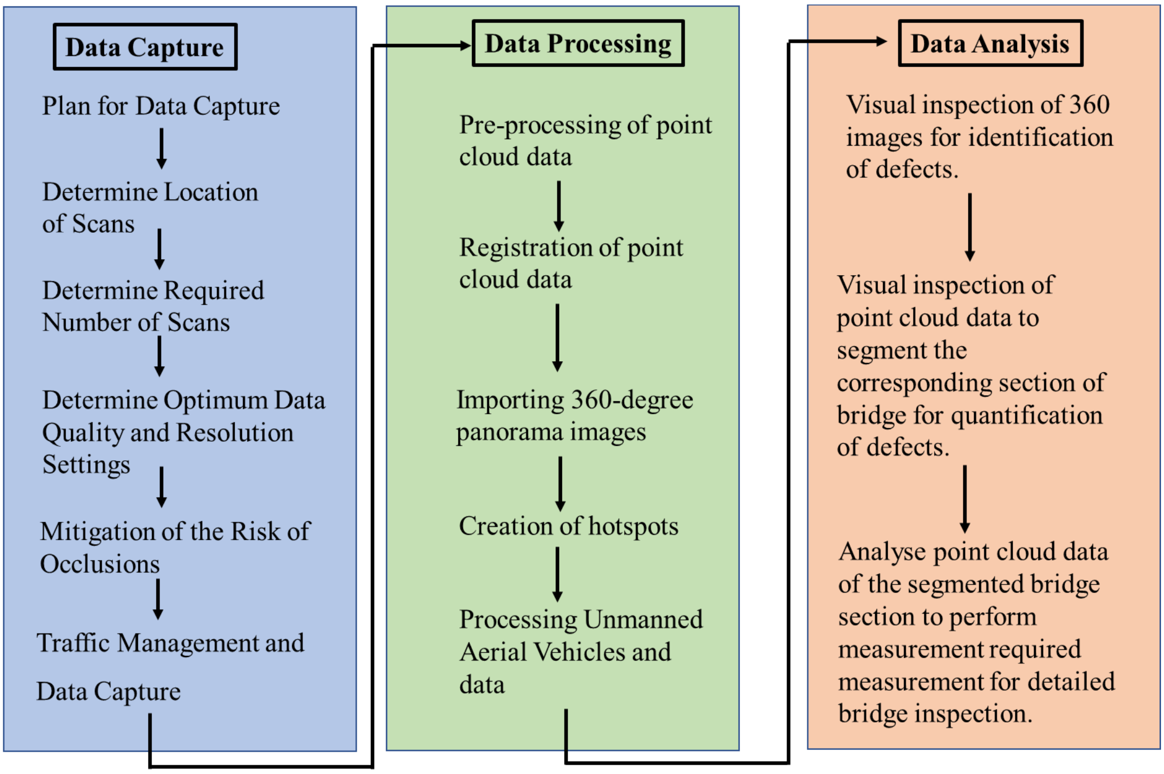


Figure 1. The proposed digital bridge examination process

The data capture activities start with proper planning for data capture which includes the determination of scan locations, determination of the number of scans required, optimum data quality and resolution setting, mitigation of risk of error, traffic management and data capture. The basic parameters of quality and resolution need to be correctly selected to obtain an accurate as-built data set. Having higher resolution and quality can increase the accuracy of data sets but they also significantly increase the time required to capture data. It is recommended to have more scans at lower scanner settings, rather than having a lower number of scans with higher settings. There are limitations which can have an impact on the workflow and the quality of the final data set. The most frequent instances are vegetation, vehicles and pedestrians obscuring capture, poor light, flooding, damp/rain, litter, animals, difficult terrain, limited safe working space, parking restrictions, narrow footpaths, existing structures and compass error. Vegetation and obstructions are common problems at many sites, obscuring data and preventing access in some cases. At structures where vegetation is an observation constraint occluding part of a structure from view, scans are taken in varying locations to capture as much of each structure as possible. Occlusion in data from obstructions is mitigated as much as possible by scanning in varying locations to capture as much of each structure as possible. A compass error occurs when the TLS detects a strong magnetic field, indicating the compass direction would not be accurate in a scan at that location. Strong magnetic fields can be caused by a variety of electromagnetic devices such as telegraph lines and large motors. Moving the TLS away from the suspected source of the magnetic interference or alternatively, turning compass data off to allow a scan to be completed (FARO, 2019) can resolve the error.

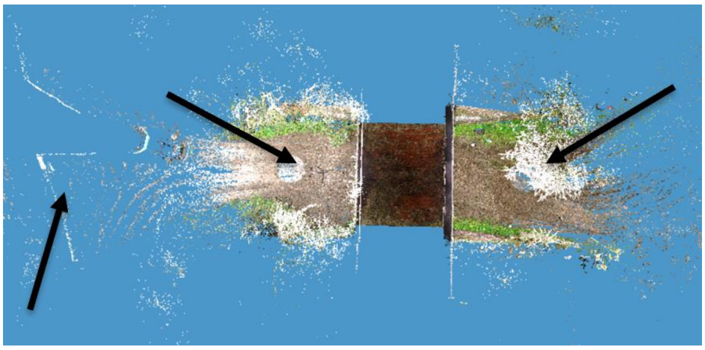


Figure 2. Example of noises in a point cloud dataset.

The data processing step includes cleaning and registration of point cloud data, importing 360 panorama images and creating a hotspot, and processing UAV data. Generally, raw data points acquired by TLS contain noise, which affects the registration and later the data analysis. The noise can be reduced using filters or manually. Data cleaning is a vital step to accelerate the point cloud registration workflow. In Figure 2, an example of noise in the point cloud dataset has been given. Point cloud processing software tools mostly have different filtering functions; however, the accuracy level is not often great. Hence, manual effort is required to clean the point cloud data. The registration process could be either target based or targetless. In target-based registration, pre-processing may be used to identify targets automatically (Sabbaghzadeh et al., 2022). For this purpose, artificial targets, spheres, checkerboards or circular flat targets can be used. The current project uses sphere and checkerboard targets as they may also be fitted automatically using automatic object detection, whereas circular flat targets can only be fitted manually with the object marker or from a selection of scan points (Da Rocha et al., 2018). The panoramic images captured by the TLS/360-degree camera can be used to display the defects found during the digital examination of the structure, and their exact location on the structure (Elghaish et al., 2020). Compared to a regular visual examination report, the virtual environment interface offers an interactive and easy-to-understand format. “3D Vista” is a tool that has been used to create an interactive panoramic virtual environment in the current project. The UAV capture RGB data can be processed in the following steps: a) Align and match points in Nadir images, followed by adding Ground Control Points (GCPs) and referencing them; b) Align and match points in Oblique 1 images, followed by adding GCPs and referencing them; c) Align and match points in Oblique 2 images, followed by adding GCP’s and referencing them; d) Merge the Nadir and Oblique images; e) Create Point Cloud; f) Create 3D model, and g) Create Orthomosaic.

4 Implementation of the proposed method

The proposed methodology for the digital inspection of masonry bridges is implemented on six different railway bridges in England. TLS-captured point cloud data, 360 images and UAV-captured point cloud data are collected for analysis to detect and quantify the defects mentioned in Table 1. Point cloud data is captured with a resolution of 10240 × 4267 pixels and point distance of 6.136 mm/10 m. 360 images are captured with resolution of 2748 × 3664 pixels. FARO Focus 3D (X330) TLS scanner was used for point cloud data capture and ISTAR 360 panoramic camera was used for 360 image capture. The registration process of TLS captured point cloud data is accomplished using FARO SCENE software. Figure 3 shows the cleaned and registered point cloud data of one of the bridges used in the project.

Figure 3. Cleaned and registered point cloud data of a masonry bridge.

Figure 4-a shows the flat representation of 360 images of the same bridge shown in Figure 2. Figure 4-b shows the folded representation of the 360 images shown in Figure 3-a in a virtual tour environment.

(a) (b)

Figure 4. (a) Example of a captured 360 image (flat image), (b) Example of a 360 virtual tour (folded image)

Figure 5-a shows the UAV-captured processed point cloud data from another bridge from the top side of the track and Figure 5-b shows the combined TLS and UAV point cloud data of the same bridge after data cleaning and registration. The point cloud data and the 360 images are used for the inspection of bridges. The detection of defects has been performed by examining the visual image, and the corresponding point cloud data has been used for quantification of defects. An open-source software called CloudCompare is used to perform the analysis of point cloud data for this project as CloudCompare software has demonstrated the capability of efficiently analysing point cloud data and it has been widely used in several research endeavours in this field (Girardeau-montaut, 2016).

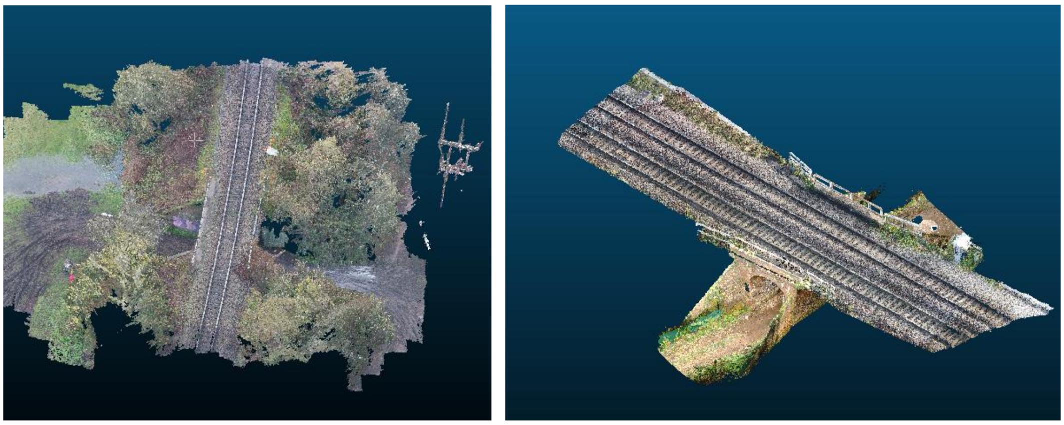

(a) (b)

Figure 5. (a) captured data by UAV from the topside of a track, (b) image of combined UAV and TLS captured point cloud data.

Figure 6 shows examples of crack detection and joint defect detection from 360 image and point cloud data. On the top left of Figure 6, window 'A' shows the presence of a crack and window 'B' shows the presence of joint defects. On the bottom right image, point cloud data of the corresponding bridge section is shown with crack and joints defects highlighted. The scalar field representation of the analysis result at the right of the image and it shows the corresponding areas of crack and joint defect in a clearer way.

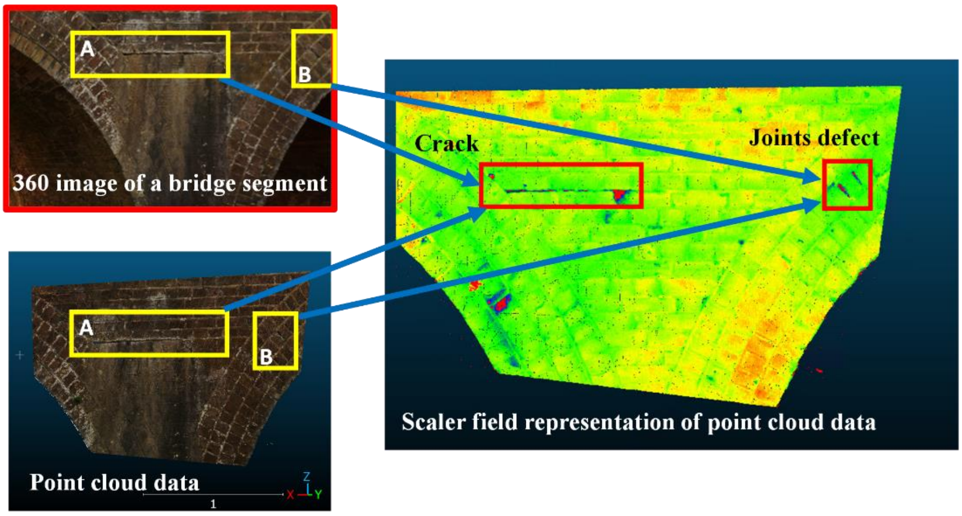
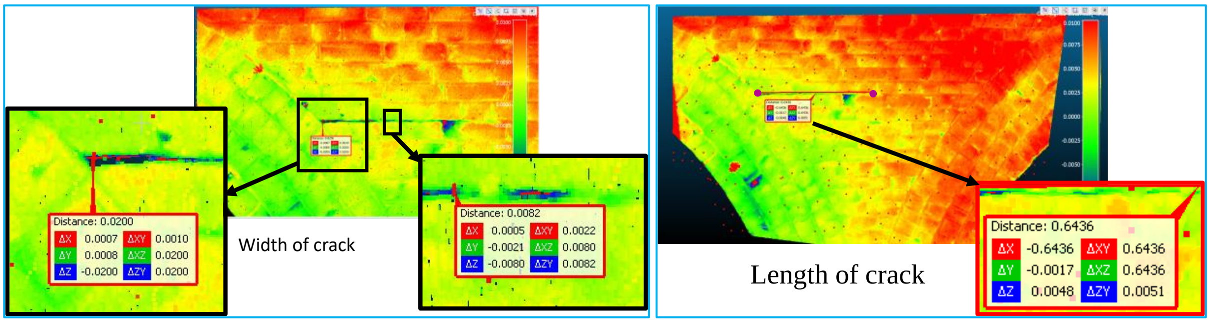


Figure 6. Detection of crack and joint defect.

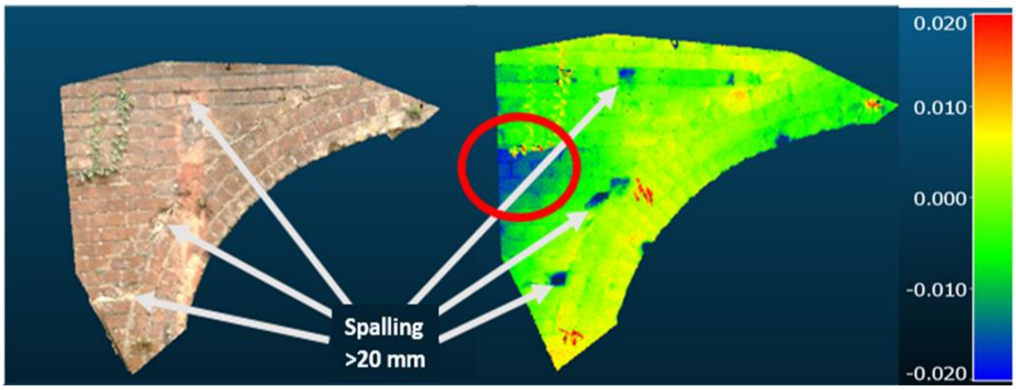
Figure 7-a and Figure 7-b show examples of measuring the width of the crack and the length of the crack from point cloud dataset. CloudCompare software allows users to estimate the distance between any two picked points from a point cloud (Girardeau-Montaut, 2015). Using that tool, the linear distance between two selected points can be measured and which facilitates the length and width of the crack as shown in Figure 7. This tool can be used to measure the linear distances required according to Table 1. Detection of spalling can be achieved from visual inspection of 360 images; however, the quantification requires some additional analysis to be performed using point cloud data. The technique implemented for the analysis is to create a reference surface that represents a healthy state of the masonry structure and then estimates the deviation of point could data from the reference surface. Bulging and loss of section can be quantified similarly.



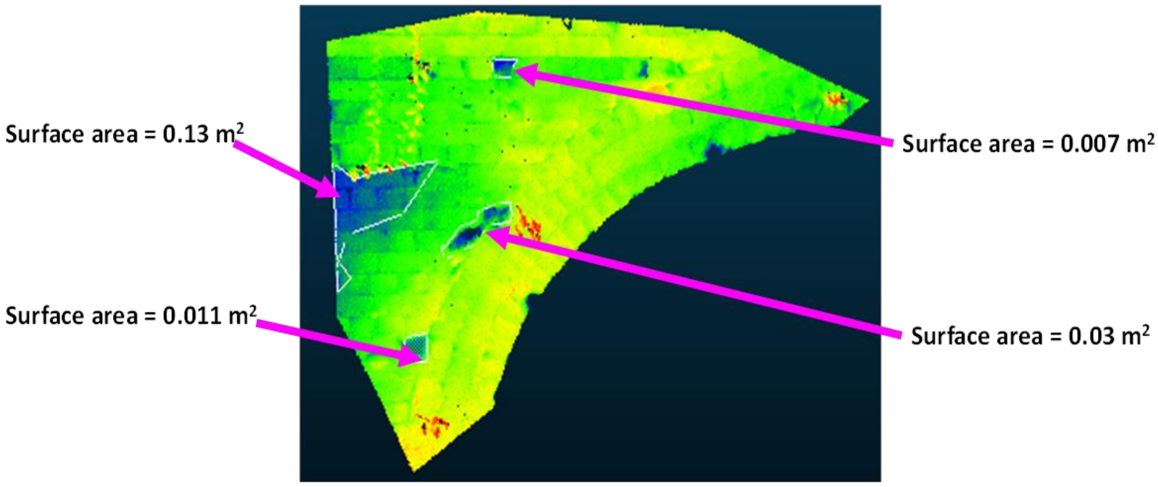
(a) (b)

Figure 7. (a) measurement of the width of the crack, (b) measurement of the length of the crack.

Figure 8-a shows an example of spalling detection using the proposed method at less than 20 mm depth and Figure 8-b shows the quantification of spalling in accordance with the measurement requirements presented in Table 1. The linear measurement related to the depth of spalling can be achieved from the colour bar associated with the scaler filed representations in Figure 8-a. Measurement of any area can be performed in CloudCompare by bounding that area with a polyline and extracting the estimated area from its property pane. Figure 8-b shows an example of area measurement for spalling.



(a)



(b)

Figure 8. (a) detection of spalling from point cloud data, (b) quantification of spalling.

5 Conclusion and Further Research

Adopting digital inspection for monitoring masonry bridges would enhance the safety and quality of the inspection process, and it would reduce the time required and cost associated with the inspection process for large multi-spanned bridges (Talebi et al., 2022). Point cloud data and 360 images obtained from TLS scanning would facilitate the shift toward digitalisation of the masonry bridge inspection process. Literature shows that significant research has been conducted in this domain; however, these are mostly concentrated on concrete structures, or those studies are limited to the laboratory environment. In this paper, a methodology for the digital inspection of masonry bridges is presented and the proposed methodology is implemented in the field (five different railway bridges). The results established the feasibility of implementing this method considering 360 image and point cloud data analysis for masonry defect detection and measurement respectively. It also shows the practicability of using point cloud data and 360 images to digitalise the masonry bridge inspection process. Detection and measurement for all the defects presented in Table 1 are not demonstrated in the current paper due to the absence of some defects in the available data set. However, it is expected that the proposed method can be successfully implemented for all detection and quantification of all defects as these would be the extension of similar processes. The current research considers using CloudCompare software only; hence, future research will focus on the ability of other popular point cloud software to perform similar analysis.

6 Acknowledgement

The research is supported by the Network Rail under Shift2Rail programme, In2Track3 project. The contents of this publication are the sole responsibility of its authors and cannot be taken to reflect the views of Network Rail. Point cloud data obtained from In2Track2 project of Network Rail under Shift2Rail programme is used in this paper.

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3D Printing Technology as an Effective Solution for Sustainable Residential Construction in New Zealand

Tatiana Poletaeva[1], Don Amila Sajeevan Samarasinghe[2*], Lorraine Skelton[3] and Zechen Guan[4]

[1, 3]Otago Polytechnic Auckland International Campus, Auckland 1010, New Zealand

[2, 4]School of Built Environment, College of Sciences, Massey University, Auckland 0632, New Zealand

POLET1@student.op.ac.nz; D.Samarasinghe@massey.ac.nz; Lorraine.Skelton@op.ac.nz; Z.Guan@massey.ac.nz

* Corresponding author

Abstract:

The construction industry contributes to approximately 6% of the global GDP but consumes extensive resources and generates about 30% of the world's carbon emissions. New Zealand's construction industry is significant to the economy but slow to innovate. Emerging digital manufacturing technologies such as 3D Printing has been involved in the manufacturing sector and are becoming popular in the construction industry as a sustainable solution to high carbon emissions. However, an effective method to comprehensively improve the sustainability of building construction has not yet been widely applied. This research explored the overseas experience of 3D printing construction and its sustainability aspects. It identifies how 3D printing technology could be used to improve the current challenges in New Zealand construction. The study recommends how 3D printing technology could be used in New Zealand residential construction for improving its sustainability. Qualitative analysis was chosen as the methodology of this primary research, which included two sets of semi-structured interviews. The first set included interviews with local companies to determine their knowledge, fears and expectations of 3D printing technology. The second set consisted of interviews with overseas companies, where the main focus was on the analysis of the advantages and disadvantages experienced by participants. Thus, the results from both participation groups (experienced overseas and local construction companies) helped to identify the possibilities for 3D printing adaptation in the New Zealand market, and any gaps this technology could cover. 3D printing can be more appropriate for start-ups for small and medium-sized businesses in New Zealand. The technology is environmentally friendly and allows for the use of recycled materials, can use local material for printable products, and can decrease construction waste and CO_2 emissions Portland cement has a high level of pollutants, and many overseas companies are trying to replace it with other materials including products generated by 3D printing. 3D printing improves Health and Safety conditions primarily because of the automatisation of the work process. Time and cost-efficiency also have become an essential part of economic sustainability, so 3D printing technology can give a quick return on investment.

Keywords:

Building Construction, 3D Printing Technology, New Zealand, Sustainability

1 Introduction

As the fifth-placed industry in the New Zealand economy, the construction sector during the Covid-19 epidemic still contributed 6.2% of the national real GDP and provided work for more than 250,000 people (MBIE, 2021). However, the construction industry in New Zealand also struggled with several issues that had a cumulative effect such as a skill shortage, materials shortage, lack of innovation and delays in the supply chain (Samarasinghe and Wood, 2021). According to Ayodele et al. (2021) and Jayathilaka (2020), these issues result in construction procedure delays and work process suspensions, which eventually affect the project net profit (the total profitability of a company after deducting all expenses from total revenue).

Furthermore, the traditional construction method in New Zealand lacks a sustainable attitude towards nature and the environment, and health and safety. For instance, plasterboard and lumber, the common materials used in New Zealand construction, will produce up to 50% of overall landfill waste during demolition at the end of the construction life cycle (Domingo and Batty, 2021). In addition, there are approximately 4350 cases of work-related accidents and injuries at construction sites in New Zealand each year (Citizens Advice Bureau, 2021). Therefore, the construction industry needs the introduction of radically new technology so it can attain sustainability (Tian and Samarasinghe, 2021; Rotimi et al., 2019). This study proposes using 3D Printing as an alternative to traditional construction methods. Compared with traditional building methods, 3D printing technology has significant advantages in sustainability (Olick, 2021), health and safety, and economics (Carey, 2021). There are three research questions in this study,

RQ1: How can 3D printing technology lead to sustainable construction?

RQ2: How can 3D printing technology be used to improve the current challenges in New Zealand construction?

RQ3: How could 3D printing technology be used in New Zealand residential construction for improving the sustainability of local residential construction?

Thus, in order to address these research questions, this study analyses the advantages and disadvantages of 3D printing technology based on a literature review and interviews to identify the possibility of implementing this technology in the New Zealand residential construction market. Through interviews with local companies and analysis of the experience of overseas 3D printing companies, this study aims to identify gaps in the sustainable environment, health and safety, and economics in the New Zealand construction market. The study explores the overseas experience of 3D printing in residential construction in terms of its sustainability impacts. In addition, the study identifies ways to adapt 3D printing technology to New Zealand residential building construction for achieving stronger sustainability in the environment, health and safety, and economic aspects.

2 Literature Review

2.1 Framework

The framework of this study is the 11th goal of the 17 Sustainable Development Goals (SDGs) of the United Nations, which mainly refers to urban infrastructure and making cities and human settlements inclusive, safe, resilient and sustainable (United Nations, 2021). The accelerating urbanization process has compelled the New Zealand Government to regularly improve urban infrastructure and improve national urban policies (Ministry of Housing and Urban Development, 2020). Hence, the implementation of new method (3D printing technology) may be promoted widely into the local market. The integration of 3D Printing allows for the digitisation of design to provide users with reliable and digital functions, reduce harm to the ecosystem and improve human and economic factors (Singh et al., 2021; Hossain et al., 2020).

2.2 Environmental Impacts

The advantages of 3D printing include lower construction lifecycle costs, fewer energy and resource requirements, and lower CO_2 emissions, all of which align with the eleventh SDG (Gebler et al., 2014). 3D printing technology not only supports the use of recycled materials but also provides efficient and environmentally friendly construction due to decreases in waste compared to traditional methods (QOROX, 2020; Kronast, 2021; Leaman, 2020). Furthermore, 3D printing technology could allow for reusing and repurposing materials and resources, eliminates inventory, and uses fewer raw materials due to design optimisation (All3DP, 2021). Moreover, 3D printing technology can enhance the structural integrity of buildings, which means it can provide superior resistance to natural disasters (Abraham and Hemalata, 2020). For instance, 3D printing technology could prevent building damage during earthquakes and thus could save lives (Carey, 2021).

2.3 Social Impacts

3D printing is an innovative technology that creates different requirements and working conditions for teams working in the office, and those working directly with the robot on the construction site. With the growth of 3D printing implementation, there is increased demand for talented professionals to help businesses expand their competitiveness in the market. The main motivation for additive manufacturing employees to change jobs is better career opportunities (Alexander Daniels Global, 2021), and prospects in the 3D printing field will attract manufacturing employees seeking opportunities for exploration and development. Moreover, 3D printing is a friendly environment for women and young specialists. Based on statistics, about 12 per cent of women worldwide working in this field as speakers and representatives of the companies and their products, as well as occupying designer and draughtsperson positions (Alexander Daniels Global, 2021). In addition to the construction industry, experts from the aerospace, automotive and medical industries have also shown great interest in the 3D printing field (Wohles Associates, 2020). 3D printing technology could improve the health and safety conditions in the construction industry by replacing the labour force with robots to decrease the number of injuries in the workplace (Castenson Villas, 2021).

2.4 Economic Impacts

3D printing is part of digital technology, which has become more attractive and popular around the world. Automatization, decentralisation, and flexibility are essential for adapting to changeable market requirements and customer needs (Alexander Daniels Global, 2021). Some 3D printing technology providers observed flexible and low-risk preferences by construction companies, which mainly focus on demand-driven, localised production, and avoid any pre-financing of products so as to minimise production delays or prevent over-production (Wohles Associates, 2020). Moreover, some technology suppliers have already started to support customers in digitalising their entire supply chain, thus making settings globally scalable and supply chains more sustainable (Alexander Daniels Global, 2021). Start-ups are another factor that supports the implementation of 3D printing technology around the world. Solver (n.d.) argues that start-ups accelerate the pace of innovation and increasingly make up a significant proportion of the overall additive manufacturing landscape and attract enormous investment. In addition, 3D printing technology enhances economic benefits due to its ability to reduce building costs, develop workflows, and avoid additional expenses (Kronast, 2021; Leaman, 2020). For instance, 3D printing technology is expected to reduce costs by US$170-593 billion by 2025 (Gebler et al., 2014). Improved workflow, shortened timetables, and less labour were the key causes of the cost drop in the construction industry (Mighty Buildings, 2021).

2.5 Summary of Literature Review

Table 1 illustrates the key findings about 3D printing technology from the literature review.

Table 1. Key findings from the Literature Review

Research Area	Key findings	Sources
Background: History of 3D printing	Fastest-growing innovative technology	Background: History of 3D printing
Framework: 17 Sustainable Development Goals of UN	Global goals for improving the general conditions of the planet Fighting against the climate change and global warming Voice for the need of environmental protection, infrastructure development, urban area improvements, health and medical field development, social stability, economic growth and improving the educational system	All3DP, (2021); Statista, (2021); Carey, (2021); Flattery, (2020); Gebler et al., (2014); Gulseven et al., (2020); Hossain et al., (2020); Ministry of Housing and Urban Development, (2020); Singh et al., (2021); United Nations, (2021); Xu and Gao, (2021)
Research questions in sustainability and 3D printing in construction	Innovative and eco-friendliness Reducing energy consumption and CO2 emission Faster construction with the use of recycled materials Sustainable construction business	Alexander Daniels Global, (2021); All3DP, (2021); Ayodele et al., (2021); Carey, (2021); Domingo and Batty, (2021); Gebler et al., (2014); Hossain et al., (2020); Jayathilaka, (2020); Kronast, (2021); Leaman, (2020); Ministry of Business, Innovation and Employment, (2020); Pastia, (2020); Paul et al., (2020); QOROX, (2020); Rotimi et al., (2019); United Nations, (2021); Xu and Gao, (202)
Prefabricated 3D printing and in-situ 3D printing	Transportation challenges for prefabricated 3D printing Breakneck manufacturing speed (up to 10 houses in less than 24 hours using recycled materials on a construction site) for in-situ 3D printing	Alexander Daniels Global, (2021); Carey, (2021); Chen and Samarasinghe, (2020); Everett, (2021); Hossain et al., (2020); Leaman, (2020); Pastia, (2020)
The impact of 3D printing on the environment	Advantages: Construction waste reduction Reduced energy consumption Reduced CO2 emission Seismic resistance Use of recycled materials Construction waste reduction up to 99% Disadvantages: Transportation emissions	All3DP, (2021); Carey, (2021); Everett, (2021); Gebler et al., (2014); Olick, (2021); Pastia, (2020); QOROX, (2020) Leaman, (2020); Paul et al., (2020).
The impact of 3D printing on the society	Advantages: Improving health and safety conditions Reduced mistakes during the work process	All3DP, (2021); Carey, (2021); Hossain et al., (2020); Kronast, (2021); Leaman, (2020); Mighty Buildings, (2021); Paul et al., (2020); QOROX, (2020); SQ4D, (2021)

	Disadvantages: Reducing worker opportunities through robot replacement Increasing unskilled labour gaps	Abou Yassin et al., (2020); Hossain et al., (2020); Mighty Buildings, (2021); Noktehdan et al., (2015)
The impact of 3D printing on the economy	Advantages: Reducing building costs, increasing workflow and avoiding additional expenses Reducing construction time Providing more opportunities for investors Disadvantages: Increasing unemployment rate High cost of technology implementation	Alexander Daniels Global, (2021); All3DP, (2021); Arch20, (2021); Carey, (2021); Gebler et al., (2014); Hossain et al., (2020); Kronast, (2021); Leaman, (2020); Mighty Buildings, (2021); Okwudire and Madhyastha, (2021); Olick, (2021); QOROX, (2020); Solver, (n.d.); SQ4D, (2021); Zhao et al., (2019) Hossain et al., (2020); Noktehdan et al., (2015); Zhao et al., (2019)
Current barriers of implementing 3D printing in New Zealand construction	New Zealand Building codes and other compliances The need for vibration resistance for earthquake-active areas Shortage of materials, skills and labour in New Zealand	Abraham and Hemalata, (2020); Alexander Daniels Global, (2021); Ayodele et al., (2021); Statista, 2021; Carey, (2021); Citizens Advice Bureau, (2021); Domingo and Batty, (2021); Flattery, (2020); Henrickson, (2020); Hewitt et al., (2021); ayathilaka, (2020); MBIE, (2020); MBIE, (2021); Ministry of Housing and Urban Development, (2020); Objective lists, (2021); Pastia, (2020); Paul et al., (2020); QOROX, (2021); Rotimi et al., (2019); SQ4D, (2021); Xu and Gao, (2021); Zhao et al., (2019)

Table 1 clearly shows the significance of 3D printing technology and its influence on sustainable housing. Firstly, numerous studies, such as Abraham and Hemalatha, (2020), Alexander Daniels Global, (2021), and Hager et al., (2016), have demonstrated that 3D printing technology occupies a strong position in the construction field and can alleviate material and skill shortages. This technique satisfies the United Nations' standards for sustainable development (All3DP, 2021; United Nations, 2021). In addition, the advantages and disadvantages of the 3D printing technology at the economic, environmental, and social levels are also shown in Table 1. Finally, according to the literature review on current barriers in New Zealand construction, 3D printing technology has the potential to be an effective solution to issues in the New Zealand construction industry.

3 Research Methodology

There are five stages to this study. First stage is to understand the research background of 3D printing through the literature review. The second stage is to identify research gaps pertaining to the New Zealand construction market. The third stage is data collection, which involves conducting interviews with top management of international and New Zealand-based construction firms. In next stage, this primary research is assessed by qualitative data analysis, with thematic analysis used as an additional tool. The thematic method allows for the examination of patterns of meaning in a data set of interview transcripts and focus group responses (Joffe, 2012). Thematic analysis takes an array of data (which can often be quite large) and groups them by similarity. Finally, this research investigates the potential and prospective implementation of 3D printing technology in the New Zealand construction market based on the results. In total, 15 participants were approached for this research: nine specialists were experienced in 3D printing in foreign countries, and six participants were from local construction companies. Moreover, one of the local participants belongs to the first construction company to begin implementing 3D technology in New Zealand. Most participants were chosen based on their work position; that is, mainly project managers, CEOs, researchers, and developers. The responders of both parts of the surveys were qualified specialists with at least five years' experience in the construction and science fields. There were two sets of questions for the local and overseas companies which differed from each other but adhered to the topics from the three areas of sustainability: environment, society, and economy. The set of questions for the local construction companies consisted of 12 semi-structured questions, while the set for the foreign companies experienced in 3D printing had 13 indicative semi-structured questions.

4 Findings

Table 2 shows the interview results of this study. The research results were shown in simplified letters to improve cleanliness and readability. The letter "P" represents "Positive effect/Yes". The letter "N" represents "Negative effect/No". "D" means "Discussible". "N/A" means "No answer". "PM" represents "Project manager". "R&D" means "Researcher and developer". "S" means "Supplier". "SS" represents "Specialist" and "C" means "CEO".

Table 2. Participants' data analysis

	Local NZ companies						Overseas companies								
	Expectations						*Real experience*								
Participants	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15
Experience	C	PM	PM	PM	PM	C/ PM	PM/ S	C	SS	SS	PM/ S	C/ PM	R&D	PM	C/ PM
RQ1: Environment aspect															
Less construction waste	P	P	P	P	P	N/A	P	P	P	P	P	P	P	P	P
Less CO_2 emission	N/A	N	P	N/A	P	N/A	N/A	P	P	D	P	P	P	P	P
Matching local standards	P	P	N/A	P	P	D	P	P	P	P	P	P	P	P	P
Earthquake resistance	P	N	P	D	P	N/A	P	P	P	P	P	P	P	P	P
Flood proof	N/A	N/A	N/A	N/A	P	N/A	P	N/A	N/A	P	N/A	P	N/A	N/A	P
Hurricane proof	N/A	N/A	N/A	N/A	N/A	N/A	P	N/A	N/A	P	N/A	P	N/A	P	P
Shape freedom	P	N/A	N/A	N/A	P	N/A	P	P	P	P	P	P	P	P	P
Concrete	P	P	P	P	P	N/A	P	N	P	P	P	N	P	P	N
Recycling	P	P	P	N/A	P	N/A	P	N/A	N/A	P	P	P	N/A	P	N/A
Any adaptable material	P	N/A	N/A	N/A	P	P	P	P	N/A	P	D	P	D	N/A	P
RQ2: Social aspect															
Better health and safety conditions	P	P	P	P	P	N	P	P	N	P	P	P	P	D	P

Increased unemployment rate	N	N	N	N	N	P	N/A	N/A	N	N/A	D	P	N	N	P
Fewer employees	P	P	N	N	P	P	N	N	P	D	N	P	N	N/A	P
RQ3: Economic aspect															
Time effectiveness	P	P	P	N/A	P	N/A	P	P	P	P	P	P	P	P	P
Cost effectiveness	N	P	D	P	P	D	P	P	N	D	P	P	D	P	P
High transportation cost	P	P	P	N/A	P	P	N/A	P	N/A	N	P	P	N/A	N/A	N
Higher salary for workers and management team	N/A	P	N	N	P	N/A	N/A	P	N/A	N/A	N	P	D	N	P
High customer demand level	P	P	P	N	P	N	P	P	P	P	P	P	P	P	P
Timber construction is a part of NZ culture	P	P	P	P	P	P	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Prefabricated 3D printing	P	P	P	P	P	P	P	P	N	D	D	N	P	P	P
In-situ 3D printing	P	N	P	N	N	N/A	P	N	P	D	P	P	P	P	N

According to Table 2, different respondents have different views on the impact of 3D printing on environment, society, and economy, but most of them are optimistic about the effect of 3D printing technology.

As for the environmental effect, five respondents from New Zealand construction companies thought that 3D printing could decrease the construction waste, but one respondent held a negative attitude on reducing carbon dioxide emissions. However, all overseas respondents insisted that 3D printing had a positive influence on the environment due to less construction waste, matching construction standards, and earthquake resistance. Most overseas respondents believed 3D printing technology has the ability to reduce CO_2 emission and only one respondent maintained that this effect needs to be further discussed. Respondents from New Zealand Construction anticipate that 3D printing technology will support multiple printing materials like concrete and recyclables. The majority of respondents with actual experience gave a positive response, despite the fact that two respondents stated they needed to investigate further.

As for the social effect, five New Zealand respondents expected 3D printing technology to improve health and safety in construction projects, and seven overseas respondents indicated that the application of 3D printing technology could reduce the risk of accidents in actual projects. The majority of local respondents were concerned that 3D printing technology would raise unemployment. The overseas respondents have differing views on the impact on the unemployment rate. Three respondents thought it could result in fewer employees, yet four respondents believe the integration of 3D Printing in construction will not affect the unemployment rate, and one respondent believed that further discussion is necessary.

As for the economic effects, most local respondents hoped 3D printing technology would speed up the construction process and decrease the project cost. However, they worried that high transportation fees will increase the project cost. In response to these expectations and concerns, overseas respondents provided similar answers. Firstly, all respondents believe that 3D printing technology is conducive to saving construction time and reducing engineering costs and meeting customer needs. In addition, three respondents maintained that transportation costs were too high, but two respondents held the opposite view. The remaining respondents did not give an answer on this question.

5 Discussion

The results of this study shows that the expectations of local corporations are often reasonable, according to the experience of overseas companies. 3D technology is advanced and promising from the point of view of sustainability in the environmental, social, and economical areas.

5.1. The Impact of 3D Printing on the Environment

3D printing will shorten the printing cycle, minimise the requirement for building materials, and eliminate resource waste. Firstly, 3D printing technology can calculate the exact number of materials required in a fully designed house in a Building Information Modeling (BIM) model, which will minimize the number of materials required in the construction process. However, 3D-printed buildings need to comply with local regulations. Different environmental factors require different regulations for materials and printable styles. Based on local construction industry regulations, 3D-printed constructions can well resist the impact of disasters such as earthquakes and hurricanes. A number of examples from other countries verified this point. In addition, 3D printing also supports the reuse of recyclable materials. Some 3D printing companies are working on creating new and different materials based on locally available (waste) products for future sustainable developments and CO_2 reductions. However, the impact of 3D printing technology may be limited by the characteristic of materials because concrete or timber will generate pollution or waste during the construction life cycle. For instance, carbon dioxide emissions from manufacture and demolition are increased when printing concrete with a high Portland cement percentage.

5.2. The Impact of 3D Printing on Society

The 3D printing technology is CE certified and fully tested. 3D printers will replace construction workers for high-intensity work such as aerial work, moving heavy objects, and working in harsh environments. Moreover, 3D printing technology could lower the number of human errors by automating operations. 3D printing technology will improve the health and safety condition on construction sites through decreasing the amount of time when workers are at risk by substituting humans with machines. Therefore, worker fatigue will be alleviated with fwere working hours. It is worth noting that although 3D printing technology substitutes machines for labour, this does not entail that unemployment will rise as a result. On the contrary, 3D printing technology conforms to the safety awareness of contemporary youth and incentivises the younger generation's active participation in the building sector. 3D printing technology could also create new job opportunities and improve the current labour pool.

5.3. The Impact of 3D Printing on the Economy

The economic impacts of 3D printing turned out to be the most debated and contradictory. On the one hand, the application of 3D printing technology will significantly lower project costs since it will shorten the construction timeframe, save onsite labour requirements, and increase job efficiency. As an innovative technology, 3D printing technology can attract customers and improve the market competitiveness of enterprises. However, the greatest barrier to the popularization and application of this technology is the high cost of printing materials. Businesses have to pay high fees when they are unable to obtain the materials directly from the local construction market. Although a printing-generated building frame can save costs to some extent, 3D printing technology cannot reduce material costs and decoration costs. The cost of printers and printing materials may not be able to compensate for a lack of adequate market demand. Therefore, the number of projects using 3D Printing has a positive correlation with the level of economic benefits generated.

5.4. Prefabricated 3D Printing and In-Situ 3D Printing

The research results indicate that supporters of both printing methods are split evenly. Prefabricated printing was backed by respondents who thought it would increase production efficiency and save more time by avoiding the need to remove the printer. However, in-site 3D printing at construction sites could reduce the probability of product damage and cost during transportation. It can also reduce material consumption and avoid repeated printing. One respondent even mentioned that some 3D printing companies could offer containers complete with printers and small cranes to prevent disassembly and boost production effectiveness.

5.5. Current Barriers in New Zealand Construction

The implementation of 3D printing technology in New Zealand's construction industry will face huge obstacles. The initial costs of 3D printing technology, such as the investment in printers and high-paid skilled workers, will discourage corporate executives from investing in the technology (Samarasinghe and Wood, 2021). Moreover, timber is the mainstream material in the current New Zealand construction industry; therefore, enterprises will face huge risks and economic losses if 3D printing materials cannot meet customer needs. In addition, 3D printing materials are considered unsuitable for large-scale commercial, industrial, and high-rise buildings. This limits the promotion of 3D printing technology. Furthermore, standards in the construction industry in New Zealand are very complex because of the variety of products used in structural and cladding systems. In addition, some disadvantages of 3D printing could become an issue for the New Zealand market, such as a limited range of available materials, restricted building sizes, a reduction in manufacturing jobs, creating only some separate structure parts, copyright issues, and transportation (Leaman, 2020; Pastia, 2020). Finally, different building codes could become snags when implementing this technology in New Zealand, and it will time to prove compliance with seismic stability and wind resistance standards through local councils. Regulations in the New Zealand construction industry are complex, so it may take a long time for calculations and practical tests to confirm the stability of the buildings made through 3D printing.

6 Conclusion and Further Research

As a foundational part of the New Zealand economy, the construction sector is plagued by issues including resource waste, elevated hazards with respect to health and safety, and excessive building prices. This study discovered through literature review and interviews that 3D printing technology is an effective solution to various problems in the current New Zealand construction industry. Although 3D printing technology will be more suitable for small and medium-sized start-ups in New Zealand, this technology not only provides new opportunities for these companies to open up new niche markets but also improves the market competitiveness of start-ups. 3D printing technology will facilitate the application of recyclable materials, reduce resource consumption, and reduce carbon emissions, all of which will improve the sustainability of New Zealand constructions. Moreover, 3D printing technology will improve the health and safety conditions on construction sites by using machines instead of labour force, and the study results indicate it will not affect employment in New Zealand's construction industry. Last but not the least, while 3D printing technology can save construction time, increasing of this technology in New Zealand may be limited by the demand in the local construction market and supply in the local materials market.

This research focuses on the development prospects and advantages of 3D printing technology. However, as an emerging manufacturing technology, the specific application of 3D printing in New Zealand still faces many problems. This study does not give solutions to these problems. Therefore, future research should explore solutions for different issues and establish efficient manufacturing methods for the realities of the New Zealand construction industry.

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Opportunities for Application of Disruptive Technology in a Disaster Management System to Address Gaps in Australian Bushfire Response

Marianna Cheklin[1*], Leila Moslemi Naeni[1] and Catherine Killen[1]

[1]School of Built Environment, University of Technology, Sydney
PO Box 123 Broadway NSW 2007, AUSTRALIA

marianna.cheklin@student.uts.edu.au; leila.mosleminaeni@uts.edu.au; catherine.killen@uts.edu.au
* Corresponding author

Abstract:
Australia has recently experienced increasing instances of natural disasters, including floods, drought, and bushfires. The Bushfires in 2019-20, also known as Black Summer, were particularly impactful. This led to an in-depth governmental investigation of its management via Royal Commission and Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO). Key recommendations for an improved disaster management system included removing silos, improve data accuracy and sharing, and using a systems design approach. In response to these reports, this paper explores how disruptive technology- blockchain, intelligent systems, and Intelligent Internet of Things (IIOT)- can be used to improve disaster response, particularly as it applies to bushfires in Australia. The method used to explore this was, first, a review of government reports on the 2019-20 bushfires to identify disaster management gaps and recommendations. Subsequently, a review of available literature was conducted to find how disruptive technology was being applied to disaster management systems. Finally, this paper explores implications of disruptive technology and presents potential next steps in research toward the future creation of a prototype.

Keywords:
blockchain, disaster management system, intelligent internet of things, intelligent systems

1 Introduction and Justification

Disaster management (DM) is defined as the coordination of prevention, mitigation, and response to disaster to support the public (Qadir et al., 2021). It involves carrying out actions such as monitoring, preparedness, planning, prevention, relief, and recovery (Kaur et al., 2022). A disaster management system is a set of interconnected tools, techniques and processes required to manage disasters. Effective disaster management in Australia, and globally, is crucial to preventing loss of life and other disaster impacts. This paper narrows the focus to disaster management system for disaster response (DMSR), the coordination of effort during a disaster to respond to emergencies, understanding risks, and allocating resources to perform impact mitigating actions.

1.1 Black Summer – The 2019-20 Australian Bushfires

This research was inspired by the Australian natural disaster that was the 2019-20 Bushfires, also known as Black Summer. A bushfire, or wildfire, is an uncontrolled fire fuelled by vegetation. Australia is prone to bushfires due to its hot and dry climate (Mark Binskin, 2020).

The unprecedented scale of the fire required advanced and urgent cooperation, as multiple fires raged across Australian States. Multiple government jurisdictions needed to work together to respond.

An Australian Royal Commission is a government-independent body which performs an inquiry into matters deemed of high national importance, often where significant failings are found in responsibility to the public. The CSIRO is Australia's national science agency. Both these bodies were engaged to review gaps in the Black Summer bushfires and make recommendations for improvements. This paper addresses gaps and recommendations for Australian DMSR as identified by the Royal Commission 2020 (RC) (Mark Binskin, 2020) and CSIRO (CSIRO, 2020b) . We then review and analyse recent disruptive technologies which may contribute to close gaps identified.

1.2 Australia's Disaster Management - Current State

The current Australian bushfire management approach is mainly qualitative, relying on expert insights to make judgements, and using experienced coordinators to make complex judgements in real time (Zarghami and Dumrak, 2021). Recent research has veered toward the need for a quantitative approach to supplement this (Zarghami and Dumrak, 2021), where accuracy can be increased with real time complex decisions supported by big data and data analysis. Zarghami and Dumrak (2021) argue traditional qualitative approaches to bushfire management will no longer suffice given the scale and increasing complexity of recent disasters. This is reiterated by the Royal Commission, which highlights the lack of accurate information being passed between parties (Mark Binskin, 2020). Recently, this recognition has sparked research interest in supplementing technology, in particular, intelligent systems, to support complex human decision making (Zarghami and Dumrak, 2021).

Australia's current disaster management bodies are many and siloed (Mark Binskin, 2020, CSIRO, 2020b). Australia's bushfire coordination effort is performed largely by impacted government (usually at state and local government level) jurisdictions, supported by several specialist bodies, including National Council for Fire and Emergency Services (AFAC), Emergency Management Australia (EMA), Australian Institute of Disaster Resilience (AIDR), and the BNHCRC (Bushfire and Natural Hazards Cooperative Research Centre) (CSIRO, 2020a). Additionally, the CSIRO reports that technology platforms used for disaster management vary between states and territories and perform different functions (CSIRO, 2020b).

1.3 Royal Commission and CSIRO – Gaps and Recommendations

On 28th October, 2020, after the devastating national impact of the 2019-20 Bushfires, the Royal Commission published its comprehensive recommendations for improving effectiveness of natural disaster management in Australia (Mark Binskin, 2020). Importantly, the Royal Commission acknowledged the likelihood of increased natural disaster occurring due to climate change, in particular due to rising sea levels and rising temperature (Mark Binskin, 2020). Further, future disasters will be more complex and more difficult to manage(Mark Binskin, 2020).They conclude that a more comprehensive disaster management approach is needed (Mark Binskin, 2020).

The Royal Commission report provides evidence-based gaps which form a starting point to improve the Australian bushfire response (Mark Binskin, 2020). The recommendations, though touching a wide variety of technology, are general, and do not provide a unified view of a potential response system. These identified gaps, and subsequent key recommendations, together with those of the CSIRO's, will be used as a basis for the remainder of this paper.

Recommendations by the CSIRO (CSIRO, 2020b), Australia's national science agency focus more on technology and systems. New and emerging technology can be incorporated to potentially improve effectiveness of disaster management systems. This is echoed by the CSIRO report into the future of emergency management in Australia (CSIRO, 2020a, CSIRO, 2020b). A summary of recommendations is presented in the Results section. This paper proposes three disruptive technology areas that addresses the recommendations from CSIRO and Royal Commission, based on review of recent related literature: Intelligent systems, blockchain, and IIoT.

2 Research Methodology

The methodology for this paper centres around finding peer reviewed research and Australian Government official documents. The intent is to perform gap review in the current Australian Bushfire DMSR, given government documents, and investigate how related recent disruptive technology innovations may address them. Figure 1, below, summarises the methodology used to perform the literature review.

Scopus and Google Scholar search databases were selected, as they offered a broad selection of relevant research with full text links. Research paper searches were limited to peer reviewed articles and book chapters published since 2015. However, Scopus and Google Scholar searches did not contain official Government reports, so the search was widened to include official Australian Government departments and agencies websites.

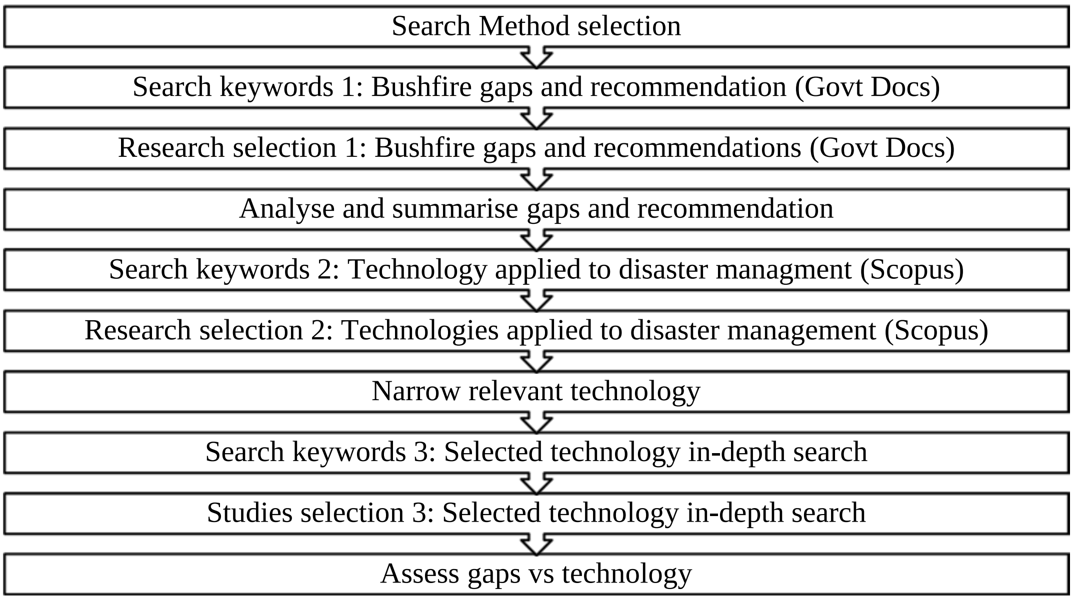

Figure 1. Research Methodology

Once the databases were selected, a comprehensive review was performed of available documentation around the 2019-20 Australian Bushfire disaster response gaps and recommendations. The purpose of the review was to identify and codify both gaps (what was done poorly, what was missed), and proposed recommendations for resolution in an updated DMSR. Two Government requested reports formed the basis for gap and recommendations analysis, the Royal Commission and CSIRO reports in response to 2019-20 Black Summer (CSIRO, 2020b, Mark Binskin, 2020).

Next, a search was done via Scopus and Google Scholar to review what recent technology was applied to bushfire DMSR or global natural disasters in general. A filter removed all non-peer reviewed papers, and any papers prior to 2019. The search was also limited to journals and conference proceedings. The initial search term used was “disaster management system”. The resulting 6196 documents provided an overview of common recent technology used around the world and locally. Titles were reviewed for themes. It allowed for narrowing the disruptive topics to three commonly and recently researched areas: blockchain, intelligent systems, and IIoT. Once all relevant target papers were identified and reviewed, analysis were performed, with attention to addressing earlier identified gaps and recommendations. The results present below highlight, first, the recommendations found in the first round of searches into Australian Government reports, then how each technology area can address them.

3 Findings and Discussion

3.1 DMSR Gaps and Recommendations from Royal Commission Report

Three important gaps, were identified by the Royal Commission report (Mark Binskin, 2020). The first area identified as an issue is the siloed systems, processes, and resources. This makes it difficult to get approval between borders and to share resources (Mark Binskin, 2020). The second is incorrect or incomplete data provided during response communication. This delays response or results in incorrect actions, putting lives in danger (Mark Binskin, 2020). The third gap is the ineffective use of resources (Mark Binskin, 2020). This gap identification is also supported by the report from the National Bushfire and Climate Summit of 2020 which states that the Australian Defense resources were under-utilised in Black Summer disaster (Ltd., 2020). The suggestion is that the capabilities of resources be assessed and coordination improved where resource engagement is concerned (Ltd., 2020) .

In response to these gaps, the RC and CSIRO made key recommendations post Black Summer 2020, as summarised in Table 2 (Mark Binskin, 2020, CSIRO, 2020b). First, both reports emphasise the need for a national approach to disaster management, with closer collaboration between jurisdiction and coordinating bodies, facilitating more effective sharing of resources and collaboration (Mark Binskin, 2020, CSIRO, 2020b). This addresses gap 1, the need to improve collaboration and reduce siloes, by providing a unified platform for communication, policy definition, and information sharing. This recommendation also addresses the second gap, incorrect or incomplete data sharing, because it provides a central data platform which is consistent to all stakeholders. The recommendation addresses the third gap, ineffective use of resources, by providing a central pool that can be prioritised across jurisdictions. The second recommendation is to improve data quality, minimising misinformation and preventing errors due to incorrect or incomplete data (CSIRO, 2020b, Mark Binskin, 2020). The last recommendation, to incorporate a systems approach to improve DMSR risk analysis and analytics, is solely reported by the CSIRO (CSIRO, 2020b). By improving relevancy of data, it implies the removal of siloed data sharing, thus addressing gap 1. The second gap is directly addressed by this recommendation. Resolution of the third gap is implied, since accuracy of underlying data promotes better resource allocation decisions.

Finally, CSIRO proposed that systems thinking is required. Systems thinking, using a multi-disciplinary and risk-based analysis approach would address all three gaps. The systems thinking approach views a system as an ecosystem of interconnecting components, that all work together and impact one another, rather than individual (siloed) parts. It requires multi-disciplinary knowledge sharing to improve decision making throughout the system. It would also entail a risk-based approach to prioritise critical decisions.

Table 2. Royal Commission and CSIRO Recommendations (Source: Royal Commission, 2020;CSIRO, 2020)

Id	**RC** (Mark Binskin, 2020).	**CSIRO** [5].
1	A nation-wide approach to disaster management is needed, with improved coordination and cooperation between government bodies and regions. (Pp 23).	A harmonised and collaborative national approach is required to achieve global best practice. (Pp 8)
2	Data needs to be comprehensive, accurate, consistent, timely, shared and nationally consistent. (Pp 103)	Data Availability is a key disaster management enabler. (Pp 8)
3		Systems thinking to deal with complexity. This includes for multi-disciplinary approach and a risk-based analysis. (Pp 8)

In the next section of the results, we review each technology area – blockchain, IIoT and intelligent systems – to investigate how these recommendations can be addressed.

4 Disruptive Technology Addressing Gaps and Recommendations Identified by the Royal Commission Report

4.1 Blockchain

Blockchain is a distributed, decentralised, and immutable public ledger, with a peer-to-peer network topology (Chowdhury et al., 2022). Data blocks, stored in a distributed manner, are linked in a chronological data chain (Huang et al., 2020). Although blockchain was originally created for financial transactions and digital currency, since the introduction of smart contracts, it has been adapted to serve other areas such as supply chain management, and now, potentially disaster management (Hunt and Zhuang, 2022, Chowdhury et al., 2022).

Blockchain has the potential to address all three recommendations from the Royal Commission and CSIRO. Firstly, the peer-to-peer communication, together with smart contracts technology, provides a platform for national collaboration in a DMSR. Abunadi and Kumar (2021) proposed a blockchain disaster management system for streamlining covid-19 responses and highlighted the secure, consistent, and transparent information as an important benefit.

Collaboration between coordinating parties and the public is another innovation offered by blockchain research, addressing the first recommendation. One innovative study proposed a way of enhancing resource management during a disaster by enabling a sharing economy via blockchain (L'Hermitte and Nair, 2021). In their model, the traditional resources available to coordinators in a disaster is extended to include community resources, which may include emergencies supplies and tools, to people assistance in an impacted region (L'Hermitte and Nair, 2021). An obvious advantage resulting from this would be additional resources closer to the source of impact. Another recent study proposed a blockchain system that targeted resolution of inter-organisational barriers in humanitarian supply chain (Ali Ihsan Ozdemir, 2021). It concluded that the key area that blockchain could contribute to was building trust between siloed parties.

Blockchain also improves data accuracy, availability, and reliability in accordance with the second CSIRO recommendation (CSIRO, 2020b, Mark Binskin, 2020). System and data resilience is one key advantage provided by blockchain (Chowdhury et al., 2022). The distributed nature of the blockchain network supports stability and security, meaning that it is difficult to overtake or interfere with the network and the information it holds. An immutable, distributed transaction ledger further supports secure real time transactions, as modifications are not possible. Generally, the blockchain can support the distribution of information in near real time without sacrificing control (Talley, 2019).

With the distributed nature of the blockchain, data and processing are carried out on multiple redundant nodes rather than on a central server, so the system itself can recover if a node is inoperative. Blockchain could form the foundation for inter-jurisdiction communication, providing a stable platform for critical information exchange (L'Hermitte and Nair, 2021).

Blockchains (particularly via immutability and distributed storage) also provide data traceability and data integrity (Huang et al., 2020) which is a crucial foundation for a DMS. Effectively, this makes the data passed around the system tamper-proof. In terms of addressing gaps, data being tamper-proof and transparent enhances data integrity and accuracy overall. By default, the blockchain was built to have full visibility of all data communication, which again, enhances data integrity.

Lastly, as evidenced by the recent research examples, by applying systems thinking to disaster management, blockchain can provide a holistic system for DMSR, and therefore address the third recommendation (CSIRO, 2020b). Blockchain facilitates the third recommendation by the CSIRO, having a systems approach with foresight and risk management. At its core a systems approach provides a quantitative, logical interconnected structure solution to problems. Because blockchains carry tokenised value, it is possible to quantify risk in a DMSR. For example, several fires may be developing in various areas, and limited resources would need to be allocated. The blockchain DMSR could provide a value to risks calculated in the background, to prioritise an area for resource allocation. These values could be passed through the blockchain and updated continuously.

4.2 Intelligent Systems

An intelligent system responds to real world events, recommending next steps and continuously adjusting parameters automatically in real time for optimal outcomes. Prior generations of software relied on business rules which were translated into a strict set of logical pathways to a conclusive action. Meanwhile, intelligent systems incorporate big data, AI and machine learning in order to analyse, interact with other systems and self-learn to make recommendations (Avvenuti et al., 2018, Bukhari et al., 2022). Machine learning looks through data to find patterns to optimise an outcome. Artificial intelligence learns by mimicking the neural pathways of human. It generally provides higher accuracy than machine learning. Human intervention by humans may be required as AI training of the system may not cover all scenarios, and to enhance the “senses” of the system (Avvenuti et al., 2018). An intelligent DMSR has the potential to address the second recommendation for improved accuracy of information made by the CSIRO (CSIRO, 2020b) by relying on objective learnings to quantify risks and optimise recommended responses to those risk scenarios. An intelligent system often uses real time input such as sensors and real time data extraction (for instance, live weather reports). In the bushfire DSMR scenario an intelligent system would take information about various risk scenarios from existing data sources, human input, sensors, and other provided information to make recommendations for response.

In addressing the third CSIRO recommendation, a systems thinking approach to risk and forecasting (CSIRO, 2020b), there are multiple examples of applying intelligent systems to disaster scenarios risk assessment and response. We identified three overarching interacting areas: risk assessment, response action selection, and resource allocation as shown in figure 2.

Risk scenario assessment involves, in existing bushfire areas, determining the relative risk bushfire to population (including human life, wildlife and natural flora and fauna, business).

The risk assessment manages two things: firstly, the movement of bushfire and extent of impact that will entail, and secondly, the current impact of bushfire under way in terms of damage being done to the region. Recent disaster management risk assessment research has moved to artificial intelligence and machine learning to improve accuracy of risk evaluation and prediction. Looking at risk assessment, Zhang et al. (2018) (Zhang et al., 2018) simulated an improved neural network algorithm for predicting flood levels forecasting and flood damage. Importantly, the model showed improved accuracy over older comparison models. Other recent research is centred around finding optimal bushfire prediction. Research found that by combining weather, satellite data and weather sensors, bushfire risk could be predicted (Ma et al., 2020).

The second interactive aspect of the intelligent decision support for DMSR is response scenario selection. There are multiple options for response, such as warning, evacuation, calling on various resources to fight the fire. Difference in risk and availability of resources could result is a difference in response scenario selection. An intelligent system prototype used stochastic game network to evaluate optimal decision in an emergency in order to minimise industrial loss (Kaur and Bhatia, 2021). Other research concentrated on using AI to uncover optimal decisions in managing crowds according to risk scenario (Alawad et al., 2020).

The third interactive aspect of DMSR is resource allocation. This manages resource depending on risk analysis, resource availability and response scenario selection. One study proposed combining intelligent systems with crowd sourcing in a emergency management scenario (Avvenuti et al., 2018), which, while adding complexity of information, vastly increases the scope of available information. With big data and analytics, this data can be more easily sorted and used in a DMSR. A bushfire DSS would require assessing fire risk in real time across targeted risk areas (which can be most of the country, but especially areas with heavy foliage). The feeds would need to include geospatial information systems (GIS), real time weather information (temperature, wind direction, humidity), IIoT devices (including heat sensing drones and other sensor devices) and human reports.

4.3 Intelligent Systems and Intelligent Internet of Things (IIoT)

IoT refers to connected devices that can communicate with systems. Examples that can be applied to a DMSR are sensors, aerial devices, robots and satellites. Unmanned Aerial surveillance (UAV) can be used to retrieve real time images of fire for analysis, the locations often being too dangerous or cumbersome for human access (Nosouhi et al., 2022). Wireless sensor networks (WSN) are a recent innovation in sensor technology being lightweight, low-cost, easy to deploy, and scalable (Dixit and Jindal, 2022).

One study uses machine learning to find an optimal network route to decrease delay in communication from the WSN and improve energy efficiency (Dixit and Jindal, 2022). Though prone to latency, Satellite information provides infrared radiation (analysis of hotspots) across a broad expanse of land in one view (Nosouhi et al., 2022). Where human life would be endangered by response action, a robot may be utilised. Unmanned ground vehicles (UGV) (Alamouri and Gerke, 2019) and robots are deployed in disaster scenarios, providing up to date information at the scene. Some examples include progressing through impacted areas and providing visual and other feedback, performing robotic firefighting, and performing rescue operations. The range of public smart devices is broad, and can include smart phones for emergency alerting, which is widely used already in Australian bushfires. It can also include special in-vehicle GPS and radio devices independent of smart phones to track and manage traffic during a disaster (Liu and Wang, 2019).

IIoT incorporates machine learning and AI into IoT. It is the amalgamation of AI, machine learning and big data with connected devices (Qiu et al., 2022). Various machine learning approaches have been applied recently to bushfire susceptibility mapping, including random forest, support vector machine and logistic regression (Hosseini and Lim, 2021).

There is an overlap between intelligent systems and IIoT in that they both include AI as a central component. where IIoT focuses specifically on how devices can interact with AI to provide analysis, intelligent systems encompass a greater scope of end-to-end management, with AI-powered decision support. However, IIoT is crucial for an intelligent bushfire DMSR, since IoT based risk analysis would be a starting point for many decisions such as resource allocation to priority risk scenarios. IIoT addresses the second Royal Commission and CSIRO recommendation to provide more comprehensive data availability by producing better quality data analytics (Chowdhury et al., 2022, Mark Binskin, 2020, CSIRO, 2020b), especially around risk and impact analysis, including predictive analytics. The following review aspects of IIoT which contribute to this.

IIoT has powerful predictive capabilities. Another bushfire prediction method using NASA’s Earth Science dataset (ESDIS), identified forest fires using ANN-MLP (multilayer perception) AI algorithm to provide high detection accuracy of up to 99.67% (Kumar and Kumar, 2020). This was significantly higher than the KNN machine learning algorithm used for comparison (Kumar and Kumar, 2020). Yet another recent study proof of concept was developed using a robust IIoT (UAV and satellite information) in early risk detection for bushfires used machine learning anomaly detection (Nosouhi et al., 2022), though some cost constraints must be overcome in order to implement this nation-wide (Nosouhi et al., 2022).

Rather than relying on historical data, a recent study used deep learning time series analysis, using multi-model data with deep learning, fusing image and weather data, in order to detect bushfire using near real time with a 93.4% accuracy rate (Phan et al., 2020). The data captured was spatial, temporal and spectral in addition to weather data to provide a more complete picture of near real time risks (Phan et al., 2020). As expected, when temperatures rise over a short period in a weather sensor, and if the weather is already hot and dry, this provides the highest risk of fire (Phan et al., 2020). This is a significant step toward having a DMSR risk assessment in real time (Phan et al., 2020).

Potential impact needs to be measured continuously in real time. This would measure to what extent an area would be impacted by loss of property, loss of wildlife and loss of human life, and that includes population, population density in impacted (Sanka and Cheung, 2021) areas, amount of foliage and changing weather conditions that may move the fire to a denser location. This would enhance the risk scenario assessment in real time for decision support.

An innovative development in technology research combines IoT driven by blockchain (BIoT). In this approach, the blockchain provides a platform for inter-device communication and distributed data storage (Kaur et al., 2022). A 2022 publication proposed applying blockchain based IoT to disaster management (Kaur et al., 2022). The idea is to build resilience into a network of IoT devices such as sensors and allow them to share information in real time (Kaur et al., 2022). There are three layers in the disaster response BIoT model which includes data gathering with installation of sensors, connectivity of smart IoT devices, data processing, analysis and storage (Kaur et al., 2022).

From a DMSR improvement perspective, a national standard and protocol for the use of IIoT would need to be created in order to address the first recommendation by RC and CSIRO (Mark Binskin, 2020, CSIRO, 2020b), that is, the creation of a single national platform for disaster management. IIoT easily addresses the second recommendation of improving data accessibility and quality provided by RC and CSIRO (Mark Binskin, 2020, CSIRO, 2020b). IIoT provides advanced data analysis that can be applied to risk predictions, as the presented research highlights. The outcome of combining IIoT into a DMSR would make more accurate information more readily available to decision makers, disaster responders, government agencies, and other participating parties (Kaur et al., 2022).

5 Conclusion and Further Research

This paper presented an exploration of disruptive technology that may be applied DSMR, addressing gaps and subsequent recommendations identified by the Royal Commission and CSIRO after the 2019-20 Black Summer bushfires. From the results, the potential for technology around intelligent systems, IIoT and blockchain to improve DMSR is encouraging. Our research found that each identified disruptive technology area potentially contributes to these recommendations.

As discussed in the results section, Intelligent systems and IIoT has the potential to address all three recommendations by centring decision making around increasingly accurate data. In that way not only can decisions be made in real time, but predictive analytics can be used to forecast risk. This leads to an enhanced risk-based decision approach, looking at complex systems through systems thinking lens, as per CSIRO recommendation 3. This technology requires accurate data for training of the system to support decisions, which addresses recommendation 2. Data-based decisions cannot operate in siloes, addressing recommendation 1.

Blockchain is flexible enough to facilitate jurisdiction governance authority where required, whilst also making public access to critical system access readily available. This serves to address the first recommendation in that it provides a national, unified disaster management system. System democratisation supports multi-disciplinary involvement, increasing the quality of decision making as outlined in recommendation 3.

There are, of course, other necessary factors that determine successful bushfire management not covered in this paper. The importance of building natural-disaster proof housing and infrastructure is highlighted by the Sendai framework (Nations, 2015). CSIRO stresses the importance of addressing climate change (CSIRO, 2020b). Using preventative measures prior to the requirement for response is also crucial. This includes public education, education of coordinators and public agencies, and research (CSIRO, 2020b, Mark Binskin, 2020).

While presenting a potentially viable option for advancing natural disaster management in Australia and beyond, there are further steps that must be taken to achieve deployment of such an enhanced system. The first step for future research is to create a full model for review. While this report presents an overview of available options for the deployment a DMSR using intelligent systems, IoT, and blockchain, the next level of analysis would analyse the best of each technology and find innovative ways to meld those into one system. Opportunity for future research into Intelligent DMSR would include reproducing some of the results found overseas in Australia, adapting and amalgamating technology found here, and looking at the latest research or address implementation challenges, to create a unified DMSR model. The second future step is a functional prototype in collaboration with Australian disaster coordinating agencies that can be tested and reviewed by experienced experts. Beyond this, the same principles explored in this paper can potentially be applied to other areas of disaster management.

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Developing Machine Learning Models for Building Rehabilitation Cost Prediction

Wai Kin Lau[1*], Nipuni Sumanarathna[1], Yung Yau[2], Daniel Chi Wing Ho[1] and Tsz Chung Tse[1]

[1]Department of Environment, Faculty of Design and Environment, Technological and Higher Education Institute of Hong Kong (THEi), 133 Shing Tai Road, Chai Wan, HONG KONG SAR

wkelau@thei.edu.hk; nipuni_s@thei.edu.hk; yungyau@ln.edu.hk; danielho@thei.edu.hk; lawrencetse@thei.edu.hk

* Corresponding author

Abstract:
The ageing of building stock is taking place in high-rise, high-density cities such as Hong Kong. To handle the ageing building stock problem, redevelopment may not be a sustainable solution, while building rehabilitation has long been neglected. Without timely and proper maintenance, dilapidated buildings are urban time bombs that threaten public safety and health. Implementing building rehabilitation, however, is easy to say than done. It requires concerted efforts from different parties, a culture of building care, and financial and other input. Worse still, lack of knowledge and collusive tendering have made the implementation more difficult. Modelling and predicting building rehabilitation cost to provide cost transparency and certainty is a way to accelerate and facilitate rehabilitation works in multi-storey, multi-ownership residential buildings. This study, therefore, seeks to identify factors affecting building rehabilitation cost from a review of previous works and interviews for developing building rehabilitation cost prediction models using machine learning techniques. The use of measures/indicators for evaluating and comparing different building rehabilitation projects is also investigated. The development of the pilot models, the research plan and the preliminary findings are presented in this paper.

Keywords:
Building rehabilitation, high-rise residential buildings, Hong Kong, machine learning, predictive modelling

1 Introduction

Ageing of building stock is similar to population ageing in many ways and is happening. Population ageing first happened in more developed regions and later developing regions, and so does the ageing of building stock. In the midst of building stock ageing, the number of new constructions and demolitions falls, the median age of buildings rises, and buildings will last longer than before. To extend the service life of aged buildings, building rehabilitation returns buildings to a condition through repair, replacement, restoration, improvement, and upgrade is necessary and inevitable.

Since the World War II, Hong Kong has transformed into a manufacturing centre and then an international financial centre. This would not be possible without the influx of immigrants and several construction booms providing space to accommodate people and industries. Buildings constructed between the 1960s and 1980s are already in their 40s and 50s, and by 2046 half of the private building stock will be 50 years old or more (HKIS, 2017). As far as sustainability is concerned, building rehabilitation which prolongs building life and slows down urban decay, will be a more sustainable than urban renewal involving demolition and redevelopment. It is, however, not easy but requires cooperation, coordination, initiative and financial input from individual owners. The Mandatory Building Inspection Scheme (MBIS) that came into force in 2012 may have accelerated building rehabilitation. Lack of a building care culture, lack of knowledge and information about building rehabilitation, and malpractice simultaneously inhibited building rehabilitation.

Despite the ageing trend, building maintenance and rehabilitation are less-studied subjects. Maintenance, as defined in BS3811: 1993, is “the combination of all technical and administrative actions, including supervision actions, intended to retain an item in, or restore it to, a state in which it can perform a required function”. For rehabilitation, it is “the process of returning something to a good condition” (Cambridge Dictionary, 2022). As can be seen from the definitions, building maintenance and building rehabilitation are similar in nature, yet the latter has a broader scope encompassing activities to conserve, rehabilitation or reuse existing buildings. In previous studies, the term building rehabilitation was often used without a clear definition (e.g. Alba-Rodriguez *et al*. 2017). In Hong Kong, building rehabilitation may refer to actions taken to improve living conditions in-situ and, at the same time, extend the lifespan of buildings and resist urban decay (URA, n.d.). For this paper, building rehabilitation means extensive repairs and maintenance to an existing building and improvements complying with statutory and present-day standards, in contrast to localised repair and maintenance.

To address the issues of lack of knowledge and information in building rehabilitation, and course of, to facilitate building rehabilitation in Hong Kong’s private residential buildings, several research questions are asked: (1) What are the suitable measures/indicators to provide transparency to the public and for comparing and evaluating different building rehabilitation projects? (2) What determines and affects building rehabilitation costs, and why do the costs vary considerably across rehabilitation projects? and (3) Since predictions using machine learning techniques are more common these days, how can these techniques be used to develop models for accurate prediction of building rehabilitation cost? For this paper, a literature review and interviews with building professionals were conducted to gain insight into the research questions. The preliminary findings, together with the research plan to develop machine learning prediction models, are presented.

2 Literature Review

2.1 Unit Rates and Measures/Indicators for Construction Projects

A fundamental question before looking further into measures/indicators for construction projects is: why measure and benchmark? Identification of suitable measures/indicators for building rehabilitation project is driven by a lack of (cost) information of building rehabilitation and then to evaluate and compare the performance of building rehabilitation projects. For new building works, unit rates and construction cost data are available (e.g. Arcadis (2021) and RLB (2021)), and they are important in construction cost estimation. An initiative was taken by Urban Renewal Authority (URA)’s Building Rehabilitation Platform (2021) to draw up 25 typical rehabilitation works items in the common area and their rates from previous URA rehabilitation projects (Tables 1 and 2). With the common unit rates, estimation and cross-checking of building rehabilitation costs will be difficult.

Table 1. 25 reference unit rates drawn up by Building Rehabilitation Platform
(Source: Building Rehabilitation Platform, 2021)

Category and typical work items	
Preliminaries - Site preparation and preliminaries (% of work value) - Scaffolding (m^2)	External elements and other physical elements - Repair works for external rendering (m^2) - Renovation works for external wall paints (m^2) - Supply and fix communal condensated water disposal pipes for air-conditioners with fittings; uPVC (m, net length of main pipes)
Structural elements - Repair works for concrete structure (m2)	Window repair and replacement - Replacement works for windows at staircases (FRR not less than half-hour)
Fire safety elements - Supply and fix fire service water pipes with fittings (m) - Supply and fix fire service water pumps (set) - Supply and fix fire service hose reel with fittings (set) - Supply and fix fire service water tank; fiberglass (set) - Replacement works for public wooden doors and frames; single leaf (FRR not less than 1 hour) (no.) - Replacement works for stainless steel doors and frame; single leaf (FRR not less than 1 hour) (no.) - Supply and fix fire-rated enclosures (FRR not less than 1 hour) (m^2) - Supply and fix emergency lighting (set)	Drainage system - Replacement works for external soil and wastewater disposal pipes; complete with vent and branch pipes with fittings; uPVC (m, nett length of main pipes) - Replacement works for external rainwater disposal pipes with fitting; uPVC (m, nett length of main pipes) - CCTV survey of underground drains, including high-pressure water jetting and survey (40 flats or below) (item) - CCTV survey of underground drains, including high-pressure water jetting and survey report (above 40 flats) (item) - Replacement works for underground drains (m)
Works to roof - Rooftop waterproof works (m^2) - Repair works for water tank waterproof (m^2)	Renovation of common area - Renovation works for internal wall paints in public areas (m^2) - Repair works for internal rendering (m^2)
Plumbing works - Replacement of fresh water pipes with fittings (m, nett length of main pipes) - Replacement of flushing water pipes with fittings (m, nett length of main pipes)	

Table 2. Reference unit rate of typical building rehabilitation works items (2019 Q1 price, selected)
(Source: Building Rehabilitation Platform, 2021)

Category of typical work items	Typical work items	Measurement unit	Reference unit rate (Range)	Reference unit rate (Average)
Preliminaries	Scaffolding (Erection and removal)	m^2	\$185-\$270	\$228
External elements and other Physical elements	Repair works for external rendering (Patch repair)	m^2	\$310-\$730	\$520
	Renovation works for external wall paints	m^2	\$145-\$245	\$195
Structural elements	Repair works for concrete structure (patch repair)	m^2	\$660-\$2,140	\$1,400
Fire safety elements	Replacement works for public wooden doors and frames; single leaf (FRR not less than 1 hour)	no.	\$5,000-\$6,600	\$5,800

Among the many literatures on performance measurement and benchmarking of construction projects, Chan and Chan (2004) proposed a framework and a set of key performance indicators (KPIs) from the literature for measuring construction project success. In measuring megaproject performance, Toor and Ogunlana (2010) argued that non-traditional measures such as safety, efficient use of resources and effectiveness are becoming more critical than completion on time, within budget and according to specifications. In measuring and benchmarking construction industry performance, KPIs capturing economic, satisfaction, profitability, predictability, etc., have been used in the UK for two decades (Constructing Excellence, 2018). Regarding the performance of building maintenance projects, Lam et al. (2010) pointed out that time, cost, quality, functionality, safety and environmental friendliness are the components to benchmark project success. Although no KPI of these components was suggested by Lam *et al.* (2010), their weightings were determined, with environmental friendliness and cost being the two most heavily weighted components. In Table 3, some key findings from the review on measures/indicators and KPIs measuring construction projects are summarised.

Table 3. Findings from the review on measures, indicators and KPIs used to measure construction projects

	Measures/indicators and KPIs for construction projects
Chan and Chan (2004) (for project success)	Objective measures:- Time: construction time, speed of construction and time variation Cost: unit cost, percentage net variation over final cost Value and profit: NPV Safety: accident rate Environmental performance: application of ISO14000, EIA score, no. of complaints Subjective measures Quality, functionality, user expectation and satisfaction, participant’s satisfaction
Construction Excellence (2018) (for construction industry performance)	Client satisfaction – product, service, value for money Contractor satisfaction – performance overall, provision of information, payment Defects Predictability (Cost and time) Profitability Productivity Respect for people Performance (Product and construction process)
Toor and Ogunlana (2010) (for mega projects)	On time Under budget Meets specification Efficient use of resources Doing the right thing (Effectiveness) Safety Free from defects (High quality of workmanship) Conforms to stakeholders’ expectations Minimised construction aggravation, disputes and conflicts
Lam et al. (2010) (for maintenance projects)	Environmental friendliness Cost Safety Time Quality Functionality

2.2 Factors Affecting Construction and Maintenance Cost

The factors affecting building rehabilitation cost is a little-studied subject. Reference is made to the factors affecting construction and maintenance costs to find suitable predictors of building rehabilitation cost. El-Haram and Horner (2002) suggested 24 factors affecting the maintenance cost of local authority and housing association housing. The factors are grouped into building characteristics, tenant factors, maintenance factors, political factors and other factors. Ali *et al*. (2010) took a similar approach as El-Haram and Horner (2002) to study the factors affecting maintenance costs in the Malaysian context. Building characteristics were found to be significantly affecting housing maintenance costs. Among the construction cost prediction studies reviewed, building characteristics and project-related variables were often used to predict construction cost, and characteristics of the parties and management-related variables such as procurement method were less used predictors. Though not used for predictive modelling, Elhag *et al*. (2005)' work identified the cost-determinant variables that were perceived to have high degree of influence on construction projects. In Table 4, the factors affecting building maintenance cost and the predictors of construction cost in previous studies are shown.

Table 4. Factors affecting construction and maintenance cost and predictors of construction cost

	Factors affecting maintenance cost
El-Haram and Horner (2002)	Building characteristics – Age, function, location, size, height of building, type of structure, finishes, services, construction materials and method of construction Tenant factors – High expectation of tenants, improper use of the property, vandalism by the tenants, delay in reporting failures, complete failure to report problems, inability to gain access to the property Maintenance factors – Selection of sub-optimal maintenance strategy, budget constraints, poor workmanship, poor quality of spare parts and materials, poor maintenance management, poor failure reporting procedures, failure to execute maintenance at the right time, failure to apply opportunity maintenance, interdepartmental boundaries, poor budgetary control, accelerated maintenance work due to poor budgetary control Political factors – Right to buy policy, new health and safety regulations, poor management decision system Other factors – Third-party vandalism, tenant complaints through different channels, poor or lack of training, energy cost in the case of income support tenants
Ali *et al*. (2010)	Largely the same factors suggested in El-Haram and Horner (2002) highlighted the importance of building characteristics, removed factors relevant to Malaysia, such as the right to buy policy and interdepartmental boundaries
	Independent variables used for construction cost prediction
Chan and Park (2005)	Level of technological advancement, level of specialisation required for contractors, whether public sector standard conditions of contract are used, whether the project is a residential project, contractor's ability in financial management, contractor's technical expertise, owner's level of construction sophistication (Only significant variables are reported here)
Emsley *et al*. (2002)	Project strategic variables: contract form, duration, procurement strategy, purpose, quality of building, tendering strategy Site-related variables: site access, topography, type of location, type of site Design-related variables: air conditioning, ceiling finishes, frame type, function, GIFA, height, internal doors, internal walls, internal wall finishes, no. of lifts, no. of storeys above ground, no. of storeys below ground, mechanical installations, piling, protective installations, roof construction, roof finishes, roof profile, shape complexity, special installations, stair types, substructure, structural units, upper floors, wall-to-floor ratio, windows
Low *et al*. (2006)	GIFA, function, duration, mechanical installations, piling, internal wall finishes, frame, site access, protective installations, internal walls, substructure, wall/floor ratio, special installations, external walls, floor finishes, height, units, electrical installations (Largely similar to Emsley et al. (2002), only variables included in regression models are reported here)
Skitmore and Ng (2003)	Contract time, contract cost, sector, project type, contractor selection, contractual arrangements
Stoy and Schalcher (2007)	Median floor height, ratio of ancillary area for services, construction duration, compactness of the building

Koo *et al*. (2011)	Construction duration, delivery method, type of multi-family housing, no. of households, site location, non-working days, total floor area, no. of stories above ground, no. of stories below ground, size of household, land ratio

2.3 Prediction of Building Rehabilitation Cost

The use of regression techniques to predict construction is common and has long been used in academic research. In more recent studies, methods such as Artificial Neural Networks (ANN) and case-based reasoning are used to develop construction cost prediction models. Considering the prediction method(s) used, the data, independent variables in the model and the predictive power, the findings from an exemplary review of construction cost prediction studies are summarised in Table 5.

3 Research Methodology

Machine learning techniques will be used to develop building rehabilitation cost prediction models, involving typical steps of data collection, data preparation, model selection, training, evaluation, parameter tuning and prediction. The input variables are determined by a literature review and interviews with building professionals, and some findings from the literature review have been presented above. To gain insight for developing building rehabilitation cost prediction models using machine techniques, interviews with construction professionals were conducted. During the interviews, questions relating to the high-cost items in a building rehabilitation project, the factors affecting their costs, circumstances that tenderers will submit a higher bid, risks entailed in building rehabilitation projects, etc., were raised to obtain input from building professionals for selection of suitable independent variables. Only those who specialise in building rehabilitation were invited to participate in this interview. From July to October 2022, three face-to-face interviews with two Building Surveyors and one Building Engineer were conducted. All interviewees are senior management in building surveying and engineering consultancy firms with experience in building rehabilitation projects. They shared valuable insight for the development of the building rehabilitation cost prediction model.

This study followed a systematic approach to select the most suitable machine learning algorithms to develop cost prediction models. First, the type of data to be used, labelled or unlabelled, was considered. Since the labelled data is available, supervised machine learning techniques are considered. Semi-supervised learning has also been considered but not adopted as there is no need to narrow down the training data set manually. Then, a review of commonly adopted machine learning algorithms, particular for cost prediction in built environment, was conducted. Traditional supervised learning algorithms such as Support Vector Machines (SVM), Decision Tree (DT) and Random Forest (RF), as well as contemporary supervised learning such as Deep Neural Networks (DNN), are selected in predicting building rehabilitation costs. Although frequently adopted in previous studies, machine learning algorithms such as ANN and Multiple Linear Regression (MLR) are not considered for the present study. As ANN and DNN are two similar algorithms, the one with higher prediction accuracy, DNN, is selected for the present study. MLR, on the other hand, was disregarded due to its incapability to relate nonlinear relationships between variables, and better alternatives are available (Shoar *et al*., 2022).

Table 5. Prediction methods, data, independent variables and accuracy of previous construction cost prediction studies

	Method	Data	Independent variables used	Significant independent variables	Predictive power of models	Mean absolute percentage error (MAPE)
Al-Momani (1996)	Multiple linear regression	125 school projects in Jordan	Cost of project at awarding the contract, variation orders, final area (in m^2), actual completion date, specified completion date, length of time extensions, highest bidding cost, lowest bidding cost	Cost of project at awarding the contract, variation orders, final area (in m^2)	$R^2 = 0.88$	-
Emsley *et al.* (2002)	Linear regression and neural network	288 building projects	41 variables grouped under project strategic, site related and design related variables	GIFA, function, duration, mechanical installations, pilling, internal wall finishes, frame type, site access, protective installations	R^2 from 0.556 – 0.789	16.6% - 27.7%
Skitmore and Ng (2003)	Standard regression and crossvalidation regression	93 construction projects	Contract time, contract cost, sector, project type, contractor selection, contractual arrangements	-	-	-
Boussabaine and Kirkham (2004)	Regression techniques	16 sport centres	Internal finishes, cladding type and condition, roof covering, structure systems, hall size, age, ratio of glazing to external cladding (in %), pool size, facility rating, total ground floor area, total number of users per annum, total maintenance cost per annum	Gross floor area, pool size, facility rating, number of users	-	-
Stoy and Schalcher (2007)	Regression	290 residential projects	-	Median floor height, ratio of ancillary area for services, construction duration, compactness of the building	R^2 from 0.508 to 0.633 Adjusted R^2 from 0.493 to 0.621	-
Koo *et al.* (2011)	Advanced case-based reasoning	101 multi-family housing projects	Construction duration, delivery method, type of multi-family housing, no. of households, site location, non-working days, total floor area, no. of storeys above ground, no. of storeys below ground, size of household, land ratio	-	87.4% (Prediction accuracy)	-
Monteiro *et al.* (2021)	Traditional least squares multiple linear regression and non-linear regression	13 residential and 10 office building projects	Floor (Underground, above ground, total, ratio), area (underground, above, total, ratio), cost category weight (%) (structure, architecture, technical installations, site overheads), total cost index, margin index, price (initial, final), unit price (initial, final), cost deviation (%), duration (days)	Above ground area, underground area, area x crisis, area x type, above-ground floors, total floors, floor ratio, crisis	R^2 from 0.505 to 0.97	-

Even though multiple machine learning algorithms were shortlisted for this study, DNN was selected to develop the pilot models. Inspired by the neurological system in resolving problems and making predictions, Neural networks have frequently been adopted as a machine learning algorithm for a while. Deep learning (DL) (i.e., DNN) is one of the neural network algorithms which addresses the issue by building multiple layers of abstraction. As a typical neural network architecture, DL architecture consists of several components such as layers (i.e. input, hidden and output), neurons, activation functions “a”, and weights {w, b} (Akinosho *et al*., 2020). Neurons are feature detectors (i.e. a feature represents project characteristics that helps make a decision) which function in lower and higher layers. Lower layers are designed to detect basic features, and higher layers containthese features. Thus, the higher layers can identify more complex features (Akinosho *et al*., 2020). As this study targets cost prediction (regression), the DL architecture is not necessarily developed as ensemble modelling.

A number of DNN models (pilot) were developed using the rehabilitation project data available on the URA’s website before developing machine learning models using private archival data. The data sample included the rehabilitation project and cost information of 306 high-rise, private residential buildings whose rehabilitation works were completed between 2009 and 2020. A total of 20 parameters were included in the initial DNN model. Later, model variants were developed by removing parameters such as lift renovation, district, building age, number of storeys, and number of units, one or two at a time. This trial-and-error method was adopted to check the relevance of each parameter. It is planned to collect more precise data such as the number of lifts, to obtain a higher prediction accuracy. Subject to the available data, binaries were assigned for the scope of work-related parameters (e.g., concrete repair). After removing the cases with missing or unreliable data, the spreadsheet was converted to CSV format and uploaded to Jupyter notebook software. Python was used to perform the DL operations. Tensorflow was selected to develop the model architecture.

4 Preliminary Findings and Discussion

Common unit rates for estimation of building rehabilitation cost are more important than measures/indicators for evaluation and comparison of building rehabilitation projects at this stage if facilitating building rehabilitation against aged buildings is on top priority. Reference unit rates published by URA will not limit the potential of the current study but add to it. Riding on the reference unit rates, building professionals interviewed commented that the most common unit rates have been included, and they identified several high-cost items from the 25 reference unit rates. They also commented that cost measures/indicators such as rehabilitation cost per m^2 were handy but not useful, as the nature of the scope of work and the building/project characteristics could vary significantly. Coming next is to find out the causes of variance in the unit rates for the prediction of building rehabilitation cost. Other measures/indicators such as satisfaction of other parties are relevant and will be used in later stages to evaluate and compare different rehabilitation projects. In Table 6, measures/indicators identified from previous works and considered relevant to the current study were shown.

Table 6. Measures/indicators identified from previous works for evaluating and comparing rehabilitation projects

Relevant and immediate	Relevant
Project scale and characteristics measures/indicators - Gross floor area (in m^2) - External wall area (in m^2, an example of quantity of high cost items)	Project scale and characteristics measures/indicators - Site area (in m^2) - Building height (in m) - No. of flats/units - Building age (in years)

Cost measures/indicators - Common unit rates - Elemental distribution of cost	- Time since last building rehabilitation (in years) Cost measures/indicators - (Contract/actual) rehabilitation cost (in \$/per m^2, square foot or undivided share) - Cost variation = (Actual rehabilitation cost – contract rehabilitation cost)/Final contract sum x 100% Project duration measures and indicators - (Planned/actual) duration of rehabilitation project = Date of (in years or days) - Time variation = (Time for rehabilitation works – revised contract period)/Revised contract period x 100% Other measures/indicators - Accident rate - No .of complaints from residents/the general public (in nos.) - Defects - Client satisfaction, contractor satisfaction -

To find factors and predictors of building rehabilitation cost, studies on building maintenance cost are the closest references as prediction and determinants of building rehabilitation cost are little studied. From previous studies, building characteristics and conditions are thought to be a significant factor affecting building rehabilitation cost. For project scale, whether there are economies of scale in building rehabilitation is to be further investigated. For building's slenderness, whether it will be more expensive to erect scaffolding to slender buildings than short bulky buildings, has remained a question.

When the property value is concerned, it is thought to be a proxy indicator of the quality level of rehabilitation project and expectations of building owners and residents. For management-related factors such as contractual arrangement, the variance will be low as the contractual arrangement of building rehabilitation projects in Hong Kong is largely the same. Following the above and the interview findings, archival research is being conducted to collect project data for training machine models and to find determinants of building rehabilitation cost.

The research team has also started the model development process using the data available in public domain, i.e. project data of URA's rehabilitation projects. DL with more than four hidden layers has been adopted to develop the models. Different models are developed using independent variables, including gross floor area, no. of units, no. of storeys and scope of work (e.g. concrete repair and external wall re-painting/re-tiling in yes or no)). After removing some cases, data of 306 projects are used to develop the models, with 80% of the cases used to train the model (the training set) and the rest 20% used to test the model (the validation set). The prediction accuracy of the models is evaluated using Mean Absolute Percentage Error (MAPE). The parameters in the models and the MAPEs are summarised in Table 7. It is clear from the MAPE results that fine-tuning the models is needed. The small sample size and the scope of work data being binary (yes/no) may have contributed to the unsatisfactory MAPE results. The small sample size issue can be addressed by transfer learning. In transfer learning, attempts are made to transfer knowledge learned in one or more source tasks and the knowledge is used to improve learning in a related target task. For that, a similar existing trained model with a similar number of input parameters to the present model should be found. TabNet, a model architecture, is used to find a similar existing model (Arik and Pfister, 2021). A similar model with 30 parameters and a 5892-sample size was found, and 10 least affecting parameters were removed to match the URA data set. A hybrid model was then developed with five hidden layers, and again MAPE was used to evaluate the predictive accuracy. After transfer learning, the MAPE values were still high for all the models contrary to the expectations. Actual cost data and other data may be required for the scope of work-related parameters to develop DNN models with high prediction power.

Table 7. Summary of input variables of the pilot prediction models and the MAPEs

Parameters of the prediction models	MAPE of different pilot models
- Total rehabilitation cost (in HK$) (Dependent variable) - Unit rehabilitation cost (in HK$/m2) (Dependent variable) - Gross floor area (in m2) - No. of units - No. of storeys - Scope of work (binary: yes or no) o Concrete repair o External wall re-painting/re-tiling o Internal wall re-painting o Replacement of drainage pipes o Electrical installation improvements o Fire services installation improvement o Replacement/repairing of windows o Repair underground drainage o Re-roofing for main roof o Replacement/repairing of fire-rated doors o Main lobby redecoration o Replacement of fresh water pipes o Replacement of flushing water pipes o Removal of unauthorised building works o Lift renovation - Building age - District	Rehabilitation cost as the dependent variable - Model with life renovation removed: ~38% - Model with district removed: ~37% - Model with building age removed: ~34% - Model with no. of stories removed: ~48% - Model with no. of units removed: ~49% - Model with building age and district removed: ~34% Inflation-adjusted rehabilitation cost as the dependent variable - Model with life renovation removed: ~38.5% - Model with district removed: ~37% - Model with building age removed: ~37% - Model with no. of stories removed: ~41% - Model with no. of units removed: ~49% - Model with building age and district removed: ~34.5%

Without cost measures/indicators of building rehabilitation works, layman owners will have no idea how much they should pay and whether the amount is reasonable. The use of cost indicators such as rehabilitation cost per m^2 is, however, unreliable as the cost indicators are calculated from rehabilitation projects of varying nature and scope of work. Common unit rates will be more reliable and useful for all layman owners, consultants and contractors to produce realistic estimates. Identifying unit rates of major and significant rehabilitation work items and finding out the determinants of the rates are prioritised. From the interviews, external wall renovation, scaffolding and fire door replacement are considered high-cost items in a rehabilitation project. As the interviewees shared, constraints such as no temporary storage area and restricted working hours, and uncertainties and risks will result in higher rehabilitation cost. Whether location and property value will result in more expensive rehabilitation has remained a question to further explore.

The preliminary findings presented above are just part of the whole research project. More building professionals will be interviewed to provide input for developing the prediction models and to validate literature review findings. The archival research will be conducted parallel with reviewing of tender and project documents accessible to the research team. The data collected will be used to train the prediction models and investigate the variance in the unit rates. DNN, SVM, DT and RF will be used with Transfer Learning to train the prediction models.

5 Conclusion and Further Research

The first few steps to developing building rehabilitation cost prediction models using machine techniques are presented. A review of previous works was conducted to look for predictors of construction and maintenance cost. Besides, measures/indicators for evaluating building rehabilitation projects were examined, and the use of cost indicators to provide cost information may not be useful. Further investigation on the high-cost items in building rehabilitation projects and the causes of variance in the unit rates is on top priority. Interviews with building professionals have started, and the interview findings provided valuable insight into the subject and machine learning prediction model development. Based on the preliminary findings from interviews, scope of works and project scale are expected to influence building rehabilitation cost more than other factors. Machine learning techniques including DNN, SVM, DT and RF with Transfer Learning, are selected to train the pilot prediction models. Data collection from private archives is underway, and the collected data will be used to develop the prediction models.

6 Acknowledgement

The work described in this paper was supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. UGC/FDS25/E06/20).

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Challenges and Enablers for Drone Application in the Construction Industry

Janet Mayowa Nwaogu[1*] Yang Yang[1] and Albert P.C. Chan[1]

[1]Department of Building and Real Estate, The Hong Kong Polytechnic University, Hong Kong, Block Z, 181 Chatham Road South, Hung Hom, HONG KONG, CHINA

janet.nwaogu@connect.polyu.hk; jackie.yyang@polyu.edu.hk; albert.chan@polyu.edu.hk
* Corresponding author

Abstract:
Drones are employed for various applications such as inspections, surveying, mapping, and monitoring work progress. These application areas are core aspects of construction activities, thus, increasing drone adoption in the construction industry over the years. However, with the adoption of digital technologies comes factors that influence their use. This study determines the challenges and enablers of using drones in construction by reviewing existing literature and social media discussions. A total of 128 peer-reviewed articles and 460 tweets related to drone adoption in the construction industry were retrieved from the Scopus and Twitter databases, respectively. The data were analysed quantitatively and qualitatively, and themes were developed. The results showed that drone adoption challenges are related to policy issues, safety concerns, and knowledge and awareness. In comparison, the enablers include efficiency and cost reduction. By identifying the factors influencing drone adoption, strategies can be developed to effectively provide construction organisations with the best opportunities to use drones for their construction processes.

Keywords:
Drone, UAVs, Challenges, Enablers, Construction Industry, AEC.

1 Introduction

The use of drones for construction activities has increased over the years, with a more than 200% increase in one year, making the construction industry the fastest adopter of commercial drones (Jeelani and Gheisari, 2021). Commercial drones differ from military drones because they are more cost-effective and portable for civil applications such as entertainment and industrial use (Li and Liu, 2019). Drones have become an important part of industrial processes such as construction and infrastructure because of their ability to collect data faster, more economically and reach hard-to-access areas than other techniques (Greenwood et al., 2021). Depending on how a drone is operated, a number of terms are used to describe it. The terms include Unmanned Aerial Vehicles (UAVs), Unpiloted Aircraft System (UAS), and Remote Piloted Aircraft System (RPAS). UAV refers to any aerial vehicle that does not depend on an onboard pilot for flight; it can either be controlled autonomously by software or remotely (Golizadeh et al., 2019, Adepoju, 2022). However, for simplicity, the term drone is used in this paper.

Drones are equipped with high-resolution cameras, Global Positioning System (GPS), radio-frequency identification readers, laser scanners, and remote sensors, which facilitate their use for collecting data in industrial settings (Adepoju, 2022). Drones have found various uses in the construction industry. They are used to perform construction activities such as security and safety monitoring, traffic monitoring, survey mapping, site navigations, pre-construction site assessment, aerial surveying, monitoring site progress, and various forms of inspection (Adepoju, 2022). Despite their benefits and promotion among the academic community, they have drawbacks. Jeelani and Gheisari (2021) noted that drones pose new risks to the workplace. For instance, they are a source of safety concerns on construction sites and privacy concerns to the community. Their drawbacks form challenges to use and retention within the construction industry. Although there are many studies on drone adoption, areas of use and benefits within the construction industry, there is a dearth in studies examining the challenges and enablers to adoption or use within the construction industry from a sentimental analysis perspective.

Jeelani and Gheisari (2021) examined the safety challenges and risks that drones pose to people working on construction sites using an empirical survey. Golizadeh et al. (2019), using a systematic review, focused on the barriers to using drones. This study intends to fill the gap by reviewing the existing literature and social media discussion to determine what forms the challenges and enablers of drone use. To determine the aim, the objectives of the study are: (i) to determine the motivators and drawbacks of drone use; and (ii) to determine the sentiments of drone users within the construction industry. This paper analyses how drone application is conceived and consented by using academic literature and Twitter data. It contributes to the drone in construction literature in several ways. It explores Twitter Analytics to shed light on how and why the drone application is debated on one of the most influential social media platforms. It further reinforces the need for scrutiny of drone use to enable attention to what form drawbacks in order to fix them for drone adoption and retention within the construction industry. Scopus database was consulted for the data retrieval because they are the largest database for peer-reviewed studies within the field of construction and engineering (Nwaogu et al., 2020). Also, Twitter was preferred because it is the most popular social media platform with the largest free and open data source (Sharma and Ghose, 2020).

2 Literature Review

Jeelani and Gheisari (2021) examined the risks posed by drones on people working with them or around them on construction sites as well as enabled an understanding of economic, social, and personal costs associated with such risks. The identified risks were physical risks, attentional costs, and psychological impacts. Physical risks arise from errors in the drone hardware or software; errors from the flight team during navigation and flight planning (Jeelani and Gheisari, 2021). Attentional risks arise from distraction from drone noise and sightings, which can have secondary safety implications. Psychological impacts are attributed to anxiety and stress that arises from the feelings of being watched (Jeelani and Gheisari, 2021). Golizadeh et al. (2019), examining barriers to drone use, categorised them as technical difficulties, restrictive regulatory environment, site-related problems, weather and organisational.

Despite the shortcomings of drones, their benefits or advantages motivate or enable people to use them. Drones have been deduced to be used for various activities, such as security and safety management, quality management, time management, traffic monitoring, survey mapping, site navigations, site assessment, aerial surveying, monitoring site progress, and inspection (Adepoju, 2022, Greenwood et al., 2019, Li and Liu, 2019). This study defines challenges as reasons or drawbacks that prevent the use of drones for construction activities. Motivators or enablers refer to catalysts, reasons, or factors that enhance the use of drones within the construction industry.

3 Research Methodology

3.1 Scientometric review

A scientometric review of journal articles published from 1980 to 2021 was conducted. The networks were constructed through two types of analysis: co-occurrence of keywords and cluster analysis. Scientometric analysis is a quantitative technique that aids in mapping and synthesising literature in a specific field (Ali et al., 2021). Co-occurrence keyword analysis indicates the research areas explored and provides a good picture of the conceptual structure of a research field (Nwaogu et al., 2020). Cluster analysis is used to identify the intellectual base and research front within a particular unit of analysis (Nwaogu et al., 2020, Olawumi and Chan, 2018). In scientometric analysis, the node or link size reflects an item's importance or influence (Nwaogu et al., 2020). Therefore, the larger the node, the larger the influence or importance of the item. VOSviewer uses two standard attributes to determine importance: Links and Total Link Strength (TLS). The *Links* indicate the number of links of an item with other items, and *TLS* indicates the total strength of the links of an item with other items (Van Eck and Waltman, 2013).

3.1.1. Retrieval of Literature from Scopus database

Scopus database was systematically searched using search syntax (TITLE-ABS-KEY ("UAV" OR "Unmanned Aerial Vehicle" OR "drone" OR "UAS" OR "Unmanned aerial systems" OR "RPAS" OR "Remotely piloted aircraft systems") AND TITLE-ABS-KEY ("construction industry" OR "engineering" OR "AEC" OR "construction sector"). The inclusion criteria at the stage of the search were limited to: articles published between 1979 and 2022, only articles at the final publication stage, and written in the English language. The initial search produced 6408 documents. The search was refined by limiting the search with the inclusion criteria. Therefore, 960 peer-reviewed journal articles were automatically retained. To ensure that only articles relevant to AEC and the construction industry were retrieved, the abstracts of the articles were read. It was deduced that only 132 articles focused on the AEC industry. The articles were read, and only 128 met the inclusion criteria. The 128 articles were subjected to scientometric analysis and review, and the findings are discussed below.

3.2 Social Media Review

The purpose of the social media review was to perform sentiment analysis which may help to address future research directions by comparing the opinions of drone users or promoters with academic research. An online search via the Twitter database was undertaken; thus, the results might not cover the sentiments of drone users in the construction industry on all social media platforms. Sentiment analysis is the study of people's opinions, emotions, appraisals, and attitudes towards something, e.g., product, service, organisation, individual, topic, or event (Zhang et al., 2018).

The search terms used on Twitter were "drone" "construction", "drone" "construction industry". The tweets were limited to those written in the English Language. The Twitter data was collected and analysed using MAXQDA. However, MAXQDA only allows the retrieval of data within one week (De Lima, 2022). To facilitate capturing older data during the data search, all the conversations found were retweeted to the time frame in order to analyse them. The search frame was 2nd September 2022 and 9th July 2022 and contains tweets from 2020 to 9th September 2022. The tweets imported to MAXQDA were analysed using the autocode hashtags and sentiments in the MAXQDA software. The hashtag function in Twitter and other social media platforms allows people to easily follow discussions, and often, trending topics stem from hashtagged words (De Lima, 2022). Hence, the hashtag is used to determine the relevant topics or keywords in discussions related to drone use within the construction domain.

Sentiment analysis in MAXQDA uses a polarity lexicon and a set of rules to identify the sentiments of tweets (De Lima, 2022). The tweets' polarities are calculated and based on the weight, and the sentiments are classified as no sentiment, negative, slightly negative, neutral, slightly positive and positive. This classification helps to understand people's views about drone use within the construction industry. The vocabulary in the tweet is used to characterise the perception of the tweeps towards the drone concept. For hashtag and sentiment analysis, the code

4 Findings and Discussion

4.1 Findings

4.1.1 Co-occurrence Keyword Word Analysis based Scientometric Analysis

The minimum number of occurrences for keywords was set at 5; with 1453 keywords in the documents, 43 keywords met the threshold. However, to determine keywords unique to the studies, terms (including search terms) generic to the construction industry were eliminated. The keywords unique to the studies and their clusters are detailed in Table 1. The cluster theme was deduced by reading the keyword with respect to the articles in which they appeared. The network of the keywords in Table 1 had 5 clusters, 143 links, and 282 TLS (see Figure 1). The clusters signal the hotspots or research areas for drone application within the construction industry, and they were categorised into inspection and mapping, data processing and management, safety and health management, challenges and risks of drone use, and training aid.

The network frequency revealed that antennas, inspection, photogrammetry, safety engineering, accident prevention, aircraft detection, and robotics are the most co-occurring keywords in the literature related to drone use in the construction industry. The overlay visualisation further revealed that these keywords have an average publication year 2020, signalling increased consideration to use drones for safety management of on-site personnel.

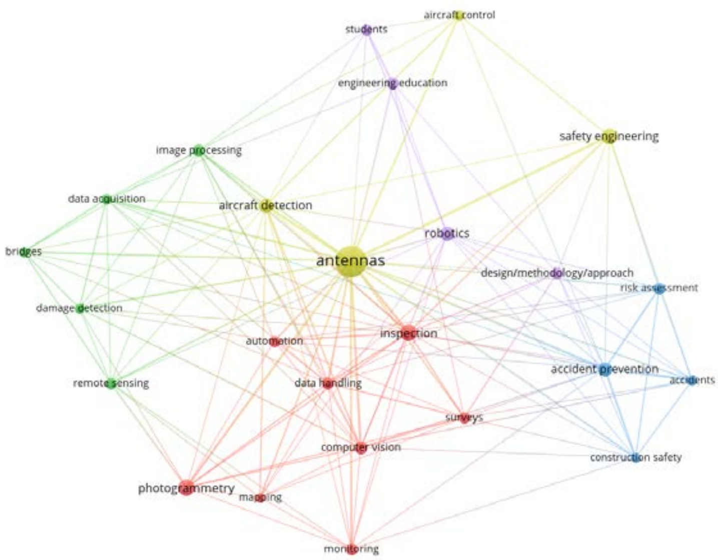

Figure 1. Research areas of drone application within the AEC industry based on keyword analysis

Table 1. Research areas where drones are applied based on keywords co-occurrence analysis

Cluster	Themes	Keyword	Occurrences	Total Link Strength	Avg. Pub. Year
1	Inspection and Mapping	Inspection	14	35	2019
		Computer Vision	9	29	2019
		Data Handling	8	25	2019
		Photogrammetry	14	21	2019
		Surveys	7	19	2019
		Monitoring	7	15	2020
		Automation	7	14	2019
		Mapping	5	12	2019
2	Data Processing and Management	Data Acquisition	6	20	2019
		Damage Detection	5	16	2019
		Image Processing	8	16	2018
		Bridges	5	15	2019
		Remote Sensing	7	14	2019
3	Safety and Health Management	Accident Prevention	11	37	2019
		Accidents	6	18	2020
		Construction Safety	5	19	2020
		Risk Assessment	7	16	2019
4	Challenges and Risks of Drone Use	Antennas	50	109	2020
		Safety Engineering	13	20	2020
		Aircraft Detection	11	34	2020
		Aircraft Control	6	12	2019
5	Training Aid	Robotics	10	19	2019
		Design/Methodology/Approach	8	12	2019
		Engineering Education	8	11	2020
		Students	7	10	2019

4.1.2 Hashtag/keyword analysis based on Twitter Data

A total of 460 tweets were retrieved from the Twitter database. Using the analyse tweet function, it was deduced that the tweets had 169 hashtags. Table 2 shows the most popular hashtags used in the 460 tweets. Among the topmost hashtags (#bullettrain, #mahsr, #nhsrcl) were related to rail project awareness in India. Aside from these hashtags and generic/search terms (drone, drones, construction, construction industry), the most popular hashtag includes "safety"; # safety was used 35 times. These hashtags represent the core topics of interest in drone use discussion on Twitter. By autocoding the tweets using 20 hashtags selected from the 169 hashtags, some topics and respective discussions within the Twitter database regarding drone applications in the construction industry could be indicated. By comparing the results from the Twitter analysis and scientometric review, it can be inferred that topic areas include drone application areas, e.g., surveying, mapping, progress monitoring, and safety. Figure 2 illustrates some exemplar tweets under the #safety.

Table 2. Most frequently used hashtags in the drone in construction discussion on Twitter

Hashtags	Frequency	Percent	Percent (without other)
#construction	134	10.11	19.94
#drone	97	7.32	14.43
#bullettrain	78	5.88	11.61
#mahsr	78	5.88	11.61
#nhsrcl	78	5.88	11.61
#drones	52	3.92	7.74
#safety	35	2.64	5.21
#building	23	1.73	3.42
#architecture	20	1.51	2.98
#uav	17	1.28	2.53
#engineer	15	1.13	2.23
#technology	15	1.13	2.23
#constructionindustry	11	0.83	1.64
#innovation	10	0.75	1.49
#ai	9	0.68	1.34
TOTAL (without other)	672	50.68	100.00
OTHER	654	49.32	-
TOTAL	1326	100.00	-

Note: "Other" consist of keywords with a frequency of less than 8

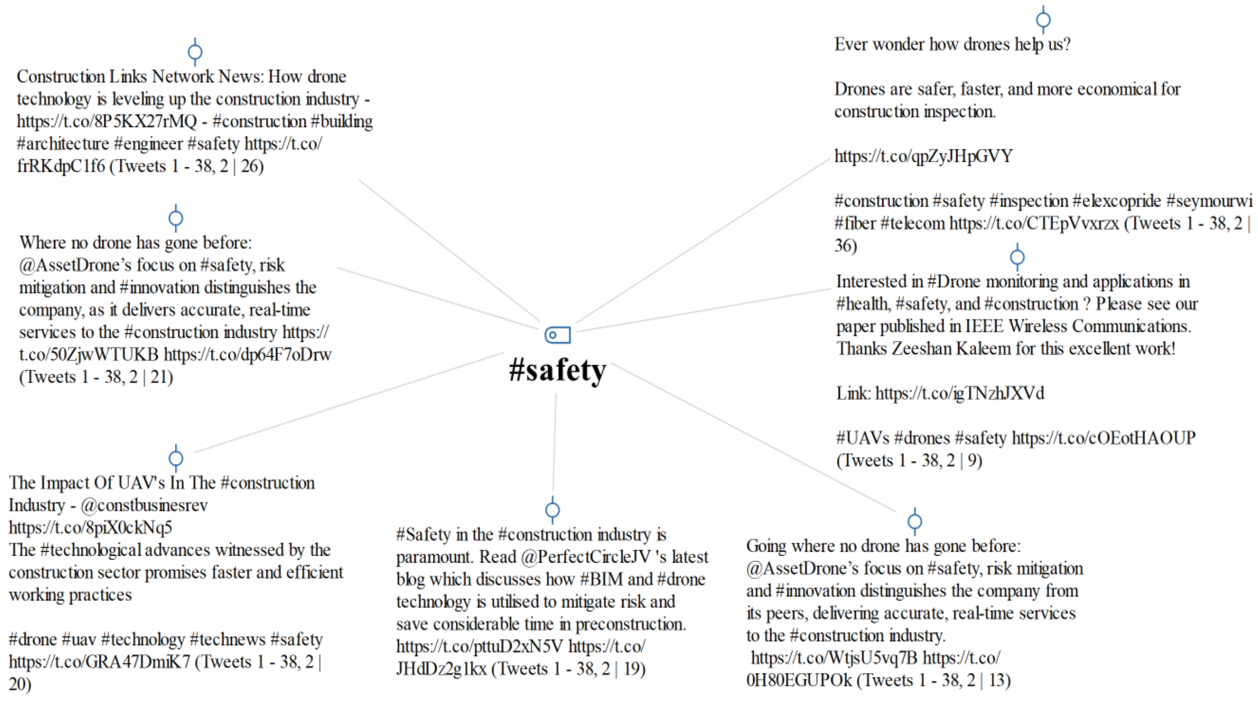

Figure 2. Screenshot of #safety and some corresponding tweets

4.1.3 Sentiment Analysis

Figure 3 shows the sentiment analysis results regarding drone discussions on Twitter. Approximately 54% (249) of 460 tweets revealed slightly positive sentiment, 39% (180 tweets) neutral sentiment, 5.7% (26) with slightly negative sentiment, and 0.2% (1) with negative sentiment. Finally, 0.9% (4) tweet has positive sentiment. Overall, the results highlight that the opinion expressed through Tweets shows that people demonstrate a positive attitude toward drone application within the construction industry. For example, as illustrated in Figure 4, some Twitter users have emphasised that drone applications can help improve health & safety monitoring within the construction industry.

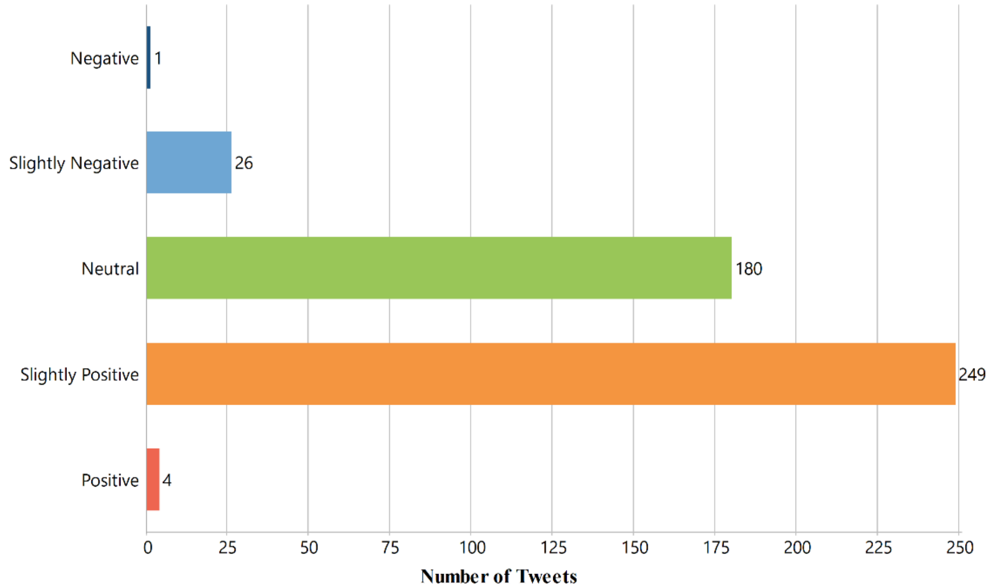

Figure 3. Sentiment analysis results of drone discussions on Twitter.

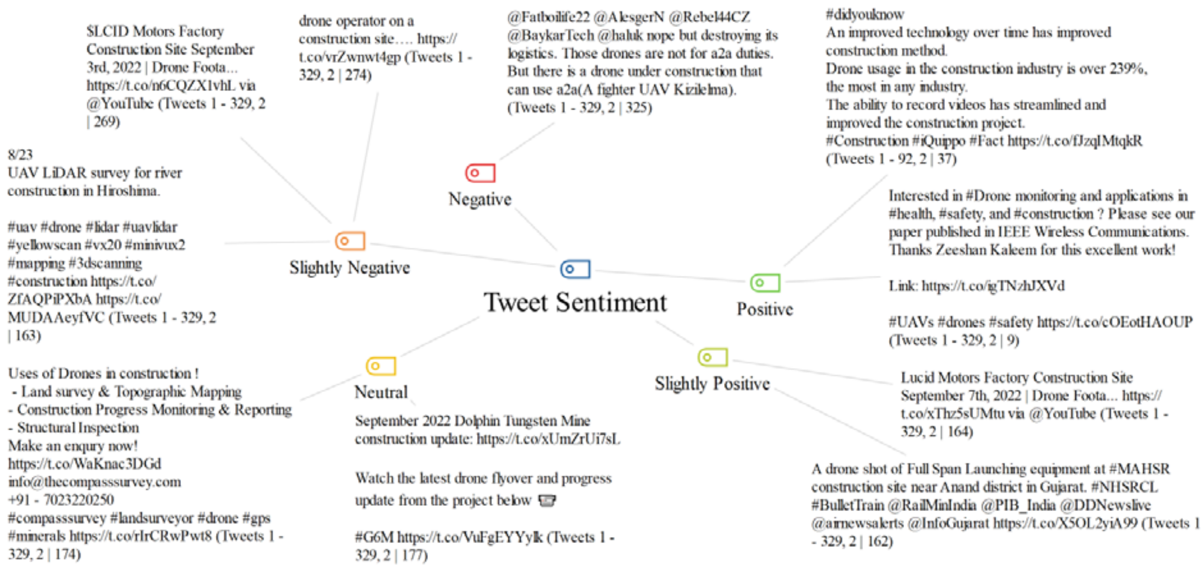

Figure 4. Exemplar tweets illustrating the identified sentiments.

4.2 Discussion

4.2.1. Twitter review and comparison with academic research

By comparing the information collected from Twitter discussion and academic literature, three patterns were deduced: (i) popular application for drones in the AEC industry, (ii) safety challenges/risk, (iii) the sentiment of the Twitter discussion appears to be directed towards use, benefits, and advertisement of service or product, or showcase of projects while opinion about drawbacks of drones are often not discussed.

(i) Popular application for drones in the AEC industry- for both types of analysis, it is deduced that the hotspots or research areas for drone application within the construction industry include inspection and mapping, data processing and management, safety and health management and safety challenges. Unlike discussions in academic research captured by scientometric review, Twitter discussions did not signal drone use for training purposes.

(ii) Safety challenges and risks of drone use - Twitter discussions rarely contained opinions about barriers and/or challenges to drone use. Specifically, Twitter discussions related to safety concerns were by academic researchers "Idris Jeelani" and "Masoud Ghesari".

"While the benefits of drones in construction are always at the forefront, their impact on human workers is seldom discussed. In our new article @MasoudGheisari and me examine the health & safety impacts of drones on construction workers. More at https://authors.elsevier.com/a/1diMW3IVV9nDgV (Tweets 1 - 329, Column: 2 | Row: 19)" "Information on our projects on "Safe Human-Drone Interaction in Construction" can be found at: https://t.co/zU7jVfO2lM Thanks to @NSF @USDOL @CPWR for supporting these projects. @UF @UFdcp @UFRinkerSchool (Tweets 1 - 329, Column: 2 | Row: 62)".

4.2.2 Motivations / enablers for Drone Adoption

The motivations or enablers of drone adoption within the construction industry are numerous. For instance, the virtual reality (VR) immersive experience built with drone-based photogrammetry could improve project communication among stakeholders during project planning, design, and construction phases. Additionally, site images captured from a drone can facilitate claims and legal processes as they can be used for litigation following an accident site (Gheisari and Esmaeili, 2019, Grosso et al., 2020). Other motivations or enablers deduced in academic literature, and Twitter analysis for drone adoption within the construction industry include effective problem identification, reduced inspection cost, accident analysis, and claims and legal. In this study, the motivations or enablers are discussed with respect to the keywords "inspection and mapping", "data processing and management", "safety and health management", and "training aid", as they represent the research focus in the literature.

i) Data processing and management: Photogrammetric models obtained from drones are an alternative to LiDAR scans (Greenwood et al., 2019, Hugenholtz et al., 2013) because drone video images are of high resolution. Thus, they give clarity and characteristics to ground surface features.
ii) Inspection and mapping: With drones, the cost of inspecting high-rise structures such as towers is reduced since the number of workers needed can be reduced (Gheisari and Esmaeili, 2019, Grosso et al., 2020). When aerial photographs are taken using drones, it is easier to identify work progress, problem areas, and maintenance needs on-site (Perez et al., 2015). Thus, time spent on inspection and mapping is reduced, and efficiency is improved.
iii) Safety and health management: It is used for accident analysis and safety performance. Images or videos collected with drones can be used to identify points of accidents. It would enable near-miss analysis, and the findings can be used to provide safety training to personnel (Gheisari and Esmaeili, 2019). When drones inspect hard-to-reach areas which typically pose safety hazards to humans, safety performance can be achieved (Grosso et al., 2020). They also facilitate hazard recognition in site equipment.

(iv) Training aid: Drones are being adopted for training purposes in tertiary institutions (Lobo et al., 2021). With drones, students can securely engage in virtual field trips without real field trips (Hernandez-de-Menendez et al., 2020). It can facilitate the acquisition of technical knowledge, development of skills in spatial visualisation, understanding of abstract things and retention among students. Additionally, drone careers such as drone piloting, software programming, design and fabrication of drones using Computer Aided Design and rapid prototyping are increasing (Lobo et al., 2021, Cañas et al., 2020). Thus, drones as training aid will prepare prospective graduates to occupy such positions.

4.2.3 Challenges to using drones in the construction industry

While there are motivations or enablers to using drones in the construction industry, several drawbacks to using them were deduced. The challenges are related to hardware maintenance, privacy concerns, lighting, regulatory hurdles, liability and legal concerns, safety concerns, technical issues, piloting and training, weather, knowledge and awareness and high capital cost.

(i) Hardware maintenance - short-term scheduled maintenance is required needed, as failure to do so may lead to motor and propeller failure (Greenwood et al., 2019)
(ii) Privacy concerns - drones are equipped with cameras, sensors, and night vision technology that could violate human rights, especially when flown without permission or in prohibited areas which makes privacy a challenge to using them (Jalinoos et al., 2020)
(iii) Lighting – lighting conditions, camera positions, and image acquisition methods limit the use of drones for inspection (Jalinoos et al., 2020). In the US, present rules indicate that drones for work or business-related tasks must be flown only during the daytime; and Part 107 of the US Federal Aviation Administration (FAA) waiver must be gotten for flights at night (Gheisari and Esmaeili, 2019)
(iv) Regulatory hurdles – acquiring proper permissions and understanding flight limitations can span months (Greenwood et al., 2019)
(v) Liability and legal concerns - liability and legal concerns related to using drones arise from personal injury and property damage that error in operation can cause; and invasion of privacy, trespassing, property rights, or insurance issues (Gheisari and Esmaeili, 2019)
(vi) Safety concerns - hazards arise from flying drones over a job site. The hazard may occur if the drone collides with a piece of equipment or birds or falls or due to human errors (Gheisari and Esmaeili, 2019, Greenwood et al., 2019)
(vii) Technical issues - technical challenges range from battery life, radio interference, and sensors to mount on drones that should be clarified before using drones on a construction site (Gheisari and Esmaeili, 2019, Grosso et al., 2020)
(viii) Piloting and training - Based on the FAA requirements in the US, only a certified pilot is required to fly drones in commercial applications (Gheisari and Esmaeili, 2019). Training is necessary to acquire the skills to fly drones safely on construction sites.
(ix) Weather - the operation of commercial drones can be affected by rain, fog, snow, and wind (Gheisari and Esmaeili, 2019, Golizadeh et al., 2019)
(x) High Capital Cost - drone technology requires high capital investment regarding acquisition, maintenance, and cost of personnel training (Adepoju, 2022, Greenwood et al., 2019).
(xi) Knowledge and awareness - Knowledge and awareness about drones and their legal or procedural requirements influences safety and privacy concerns surrounding drone use (Aydin, 2019).

Restrictive regulations regarding flight procedures make using drones a challenging task. The restrictive regulations are due to integrity, privacy concerns about the information collected and public concerns that drones are used for surveillance (Greenwood et al., 2019). The drone policy or regulations mostly discussed in the literature is the US Federal Aviation Administration (FAA) Part 107. Drone regulations have a lot to do with respect to mitigating the challenges and barriers to drone use. The drone-related regulations presently available in countries such as USA, China, and the UK are generalised and could contribute to safety and health challenges. Generalised drone policies (e.g., flight zone restrictions) can heighten unsafe conditions such as distraction and accidents, especially when used on construction projects. Every construction project is one-off as the resources, constraints, and risks are unique and would require unique regulations. For instance, the project site changes rapidly, and the sites are congested, posing unique safety challenges that are heightened when the workers have to share such space with drones (Jeelani and Gheisari, 2021). The regulations for a new site may differ from those for an active construction and engineering site because occupational safety and health risk vary with the nature of the site and type of project. Therefore, there is a need to develop industry regulations that consider the uniqueness of the construction industry and the factors that affect drones’ use on construction sites.

The shortcomings or challenges of drone use that pose safety risks on construction sites include noise and accidents. The causes of drone-related accidents include loss of control, pilot error, unplanned landing, system malfunction, flight terminations due to low battery, atmospheric conditions, and collisions with interference (Namian et al., 2021). A suggestion to reduce the probability of incidents on construction sites is that drones are flown during the off-hours or only when the premises are free. However, the suggestion may always be feasible as it defeats the purpose of using drones for some activities, such as real-time monitoring of projects for safety and total quality management. Hence, adopting cutting-edge technologies may be a more viable solution to help keep drone operations safe. In order to improve safety, cutting-edge technologies have been introduced to keep drone operations safe. The technologies include parachute, geofencing, computer vision, and Airsense (Al-Madani et al., 2018, Murison, 2019). Attention has been drawn to pilot error as a recurring reason for drone accidents (Namian et al., 2021, Lu et al., 2019). Thus, it becomes more necessary to mitigate human factors for safety improvement. To achieve this, theories on risk mechanisms, e.g., the Human Factors Analysis and Classification System (HFACS) for analysing accident causality (Lu et al., 2019) and Human Performance Model (Doroftei et al., 2020) used to evaluate the relationship between human factors and the pilot performance, would benefit the construction workplace. With the theories, latent failures that led to an incident can be identified by real-time monitoring of latent failures (Stark et al., 2013).

5 Conclusion and Further Research

This study provides a scientometric and sentiment review of the body of knowledge on drone adoption within the construction industry to deduce the motivators and challenges to drone use in the industry. A total of 128 peer-reviewed articles and 460 tweets related to drone adoption in the construction industry were retrieved from the Scopus and Twitter databases, respectively. The motivators were itemised in relation to inspection and mapping, data processing and management, safety and health management, and training aid. Four motivators and nine challenges to drone application in the construction industry were identified. This study deduced that drone policy or regulation primarily discussed in the literature is the US Federal Aviation Administration (FAA) Part 107. Likewise, the drone-related regulations presently available in countries such as USA, China, and the UK are generalised, which could contribute to safety and health challenges. Therefore, there is a need to develop industry regulations that consider the uniqueness of the construction industry and the factors that affect drones’ use on construction sites. Of the identified challenges, knowledge and awareness about drones and their legal or procedural requirements among professionals and the communities over which they fly are relatively less discussed within the construction industry. Understanding the legal requirements to operate drones commercially is an important aspect of drone use (Lobo et al., 2021). Therefore, awareness should be intensified to help drone users and the general public understand drone policies and requirements concerning the type of drone used and the activity to be carried out. More studies focused on safety management strategies, safety knowledge, and training to prevent drone-related accidents are required to identify drone-related hazards and associated safety risks in order to mitigate the safety risk of utilising drones on construction sites. The training will equip operators with hazard recognition and safety risk perception skills to prevent drone collision hazards. More studies in the construction industry focused on human physiological/cognitive responses and their impact on pilot performance are needed to mitigate human factors-related incidents. It is also recommended that researchers involved with drone application should spur more intriguing discussions surrounding drone use in the construction industry on social media, especially Twitter. This could increase the availability of qualitative data about drones' drawbacks, which pose challenges or barriers to use.

6 Acknowledgement

This study is part of research project No. is 2021.A6.181.21C funded by the Hong Kong Public Policy Research Funding Scheme.

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Deterministic and Probabilistic Risk Management Methods in Construction Projects: A Systematic Literature Review and Comparative Analysis

Ania Khodabakshian[1], Taija Puolitaival[2] and Linda Kestle[3*]

[1] Built Environment and Construction Engineering, Politecnico di Milano, Via Ponzio, 31, 20133, Milan ITALY
[2] Faculty of Built Environment, Tampere University, FI-33014 Tampere University, FINLAND
[3]School of Building Construction, Unitec Institute of Technology, PB 92025, Auckland 1142, NEW ZEALAND

lkestle@unitec.ac.nz
* Corresponding author

Abstract:
Risks and uncertainties are inevitable in construction projects, and can drastically change the expected outcome, and negatively impact the project's success. However, Risk Management (RM) is still conducted in a manual, ineffective, and experience-based fashion in practice, hindering automation and knowledge transfer to upcoming projects. The Construction industry is recently benefitting from Industry 4.0 revolution and the advancements of Data Science branches such as Artificial Intelligence (AI). This shifts the construction management processes towards digitalization and optimization. Data-driven methods, such as AI and Machine Learning algorithms, Bayesian Inference, and Fuzzy Logic, seem to be a decent solution to RM domain shortcomings and automating and optimizing the RM processes, which are being widely explored recently. These methods are divided into deterministic and probabilistic models, the first of which proposes a fixed predicted value, and the latter, embraces the notion of uncertainty, causal dependencies, and inferences between variables affecting projects' risk when proposing a predicted value. This research uses a systematic literature review to investigate and then comparatively analyse the main deterministic and probabilistic methods applied to Risk Management in the construction industry in respect of each method's specific scope, primary applications, advantages, disadvantages, method limitations, and proven accuracy. The findings will establish the recommendations for optimum AI-based methods and frameworks for different management levels- Strategic, Operational Project Management, and for large or small datasets.

Keywords:
Artificial Intelligence, Construction Industry, Machine Learning Algorithms, Project Management, Risk Management

1. Introduction

The construction industry has one of the highest accident and fatality rates, delays, and cost overruns, which are caused by uncontrolled risks. Risks occur at various levels: operational, project, portfolio, strategic, and business and enterprise levels, derived from external and internal factors, and can be: a) a Field-based risk, including financial, market, operational, political, reputational, and disaster risks, or b) a Property-based risk, including uncertainty, dynamics, interconnection and dependence, and complexity (Wu et al., 2014). Risk Management (RM), as depicted in best practices and Project Management standards, tends to be a proactive approach consisting of Risk identification, analysis and assessment, mitigation planning, and control stages (Project Management Institute (PMI), 2017) to exploit or enhance positive risks (opportunities) while avoiding or mitigating negative risks (threats) and to ensure the project's success, to meet project's objectives and constraints, and to secure the project safety. However, it is still conducted in a manual, time-consuming, superficial, and ineffective manner. Moreover, Risk Identification and Assessment, in their conventional ways, are conducted based on individual and experience-based expert judgments and seem highly personalized and context-dependant (Li et al., 2018). Therefore, knowledge transfer and model generalization remain critical issues for future projects.

On the other hand, the construction industry is experiencing a digitalization revolution thanks to the abundant production of data and the development of digital tools and data-driven decision-support systems like Artificial Intelligence (AI), Digital Twins, and the Internet of Things (IoT). These technologies prepare the technical foundation for an intelligent and ever-improving construction industry. AI is one of the key pillars of the industry 4.0 revolution and digitalization era to create an active connection between the physical and digital worlds. It includes the science and engineering techniques that aim to make machines mimic human cognitive processes of learning, reasoning, perception, planning, and self-correcting (Darko et al., 2020). AI is gaining a vast application for fostering, optimizing, and automating processes throughout the entire construction project life cycle for intelligent management of projects.

Nowadays, AI algorithms can learn from enormous real-time data generated by cutting-edge technologies like the Internet of Things (IoT), Sensors, Cyber-Physical Systems (CPS), Cloud Computing, Big Data Analytics (BDA), Text Mining, and Information and Communication Technologies (ICT) for more reliable and smart management and decision-making in the construction projects (Zhong et al., 2017). This data, if transformed into a structured and understandable form, can bring valuable insights for knowledge management in projects and economy, and society development. AI learning process takes place based on historical data records, in which the machine tries to recognize the relationships between input data and output data by constant weighting and correction. AI algorithms can analyse large volumes of data to extract insights from previous data, recognize the data pattern, generalize the rules, and make a prediction for upcoming data entries in complicated, nonlinear, and uncertain problems (Mellit and Kalogirou, 2008).

However, though its vital role in securing the project's success and ability to solve the shortcomings of traditional RM methods, AI applications in Construction RM have been limited and far behind other industries and robust AI-based RM frameworks (Chenya, 2022). AI models can improve analytical capabilities across the RM domain while offering a high granularity and depth of predictive analysis (Guzman-Urbina et al., 2018). AI-based RM systems can function as a) Early-warning systems for risk control, b) AI-based risk analysis systems using algorithms like Neural Networks for identifying complex data patterns, c) Risk-informed Decision Support Systems for predicting various outcomes and scenarios of decisions, d) game theory-based Risk analysis systems, e) Data-mining systems for large data sets, f) Agent-based RM systems for supply chain management risks, g) Engineering risk analysis systems based on optimization tools, and, h) Knowledge management systems by integrating decision support systems, AI, and expert systems to capture the tacit knowledge withing organizations in computer systems (Wu et al., 2014).

As depicted in Figure 1, an AI-based RM system aims to: a) mine and analyse real-time project data, b) conduct automatic identification, evaluation, and assessment of risks, c) conduct proactive decision-making on responses to mitigate these risks and d) share this insights and predictions in a collaborative environment for data integration like Cloud Building Information Modelling (BIM), and Digital Twin platforms (Pan and Zhang, 2021). This research focuses specifically on the “b” clause, the AI-based analytical models for risk assessment and management, and aims to study the relevant aspects of a successful AI model, i.e. input data requirements, model structure and reasoning, application scope, etc.

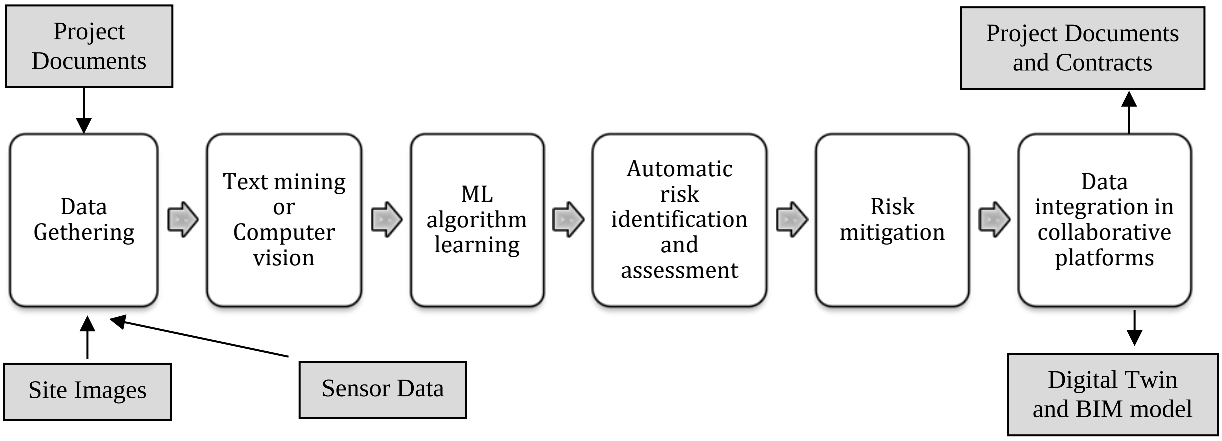

Figure 1. AI-based Risk Management framework

Most of the data-driven methods, like ML algorithms, require a significant amount of data in a structured format to learn from and make a prediction for future projects. However, risk data is usually not frequently registered or updated in project documents, is in unstructured text or image forms, has missing values and scarcity problems and is affected by different individual perceptions. Moreover, as there are a variety of risk types and individual experts might not have encountered or have sufficient knowledge of all of them, human-based risk analysis systems suffer from low accuracy, incomplete risk identification, and inconsistent risk breakdown structures (Siraj and Fayek, 2019). Therefore, AI-based methods for data structuralizing and pre-processing are required.

AI algorithms' structure, processing formats, and the role of probability in the process are other important issues to consider. The probability theory has been studied through various models within the past decades, such as Gaussian models, Pareto distributions, stochastic process theory, Markov processes, and Monte Carlo simulations (Wu *et al.*, 2014). However, an important factor that is missing in many of the previous techniques is the isolated analysis of risks and ignorance of the causal interrelations and correlations among risk factors. Assessment of the individual risk factor's magnitude, regardless of the occurrence probability of the risk events chain and the effects each risk cause to the others, may result in underestimation of the overall project risk level. Some previous studies have focused on the concept of risk paths and scenario analysis, rather than individual risk factors, which is a more accurate and realistic delineation of the reality (Eybpoosh *et al.*, 2011).

The same concept is also applicable to the AI algorithms' structure and processing format. AI algorithms can generally conduct deterministic or probabilistic analyses, as a result of which are grouped under deterministic or probabilistic model groups. Deterministic models provide a fixed prediction amount based on the effects of input variables on the output, while the Probabilistic models provide a probability-attached final value considering the interrelation and causal inferences of input variables on each other. This research aims to answer the following questions through a systematic literature review and comparative analysis between AI models:

a) In which capacities and by the application of which algorithms the RM domain can benefit from AI?
b) What are the entry data requirements for each algorithm, and in case of data scarcity and uncertainty, which algorithms are applicable?

c) What are the advantages, disadvantages, application scope, prediction accuracy, and limitations of Probabilistic and Deterministic AI models for RM?

2. Research Methodology

This research used a systematic Literature review approach, due to its comprehensive, structured, reproducible, transparent, and quantitative nature (Pickering and Byrne, 2014).As topics and domains related to the scope of this research are numerous, the systematic literature review approach helped finding the most relevant interdisciplinary publications, extract knowledge areas, and categorize their applied AI techniques, after some filtering stages. The publication search was conducted in Scopus and Web of Science libraries, as by the result of preliminary search, they had more relevant publications to the research theme. Figure 2 presents the literature search scheme, the findings of which serve as the source papers to identify and classify AI algorithms for RM. These algorithms are classified in two groups of Probabilistic and Deterministic models, based on their analytical reasoning, input data requirements, and level of intaking uncertainty, and shape an important component of AI-based RM framework in Figure 1.

The search rule was (("construction") OR ("AEC") OR ("construction industry") OR ("construction project")) AND (("risk") OR ("risk assessment") OR ("risk management") OR ("risk evaluation")) AND (("Artificial Intelligence") OR ("Machine Learning") OR ("Data Mining")), which was limited to Engineering domain, English language, and Review paper type, as a result of which 69 documents remained. Review papers had a wider variety of techniques included, often had a comparison conducted, and had the proper level of detail about each method, which was sufficient for our research scope. The abstracts and keywords of all the 69 documents were reviewed to remove the outlier publications. For instance, some publications were studying RM in other industries, some were focused on AI-methods for other purposes like data generation, and some were focused on non-AI methods. At the end of this phase, 48 final documents remained as the source papers.

A thematic and bibliometric analysis was conducted on the source papers in Bibliometrix application to identify the main areas of research concentration, common techniques, interrelation of topics, application scopes, and trending topics. It is noteworthy that a number of papers were particularly focused on health and safety risks, which are only analysed regarding the AI algorithms they proposed.

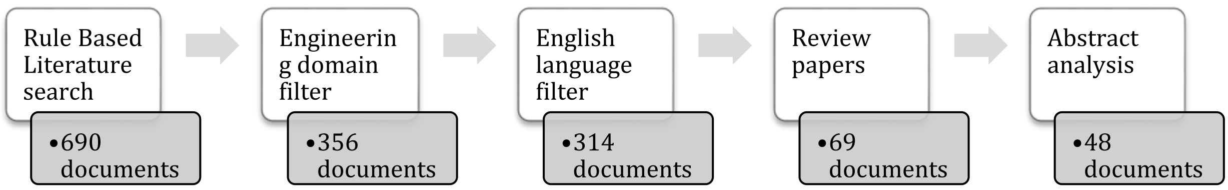

Figure 2. Literature search flowchart

3. Research Findings

3.1 Background data

Figure 3 presents the co-occurrence diagram between keywords and research areas in the source papers created by Bibliometrix application, which provides a big picture of the interdisciplinary research in the field. As marked on the diagram, the papers introduce a number of AI algorithms applicable to various steps of RM, such as risk identification and analysis, for decision making about different aspects of construction projects, such as contracts or cost. This paper focuses on the blue and green zones of the figure, i.e., risk assessment and analysis steps, and AI algorithms for each of these steps.

Furthermore, the various topics' trends were analysed based on the found literature, as a result of which, the Big Data, Machine Learning, and Deep Learning lead the current trend, followed by health, safety, and occupational risks. Decision Support Systems and knowledge based Systems used to be trending during the last decade, but are substituted by AI-based techniques that foster the decision-making.

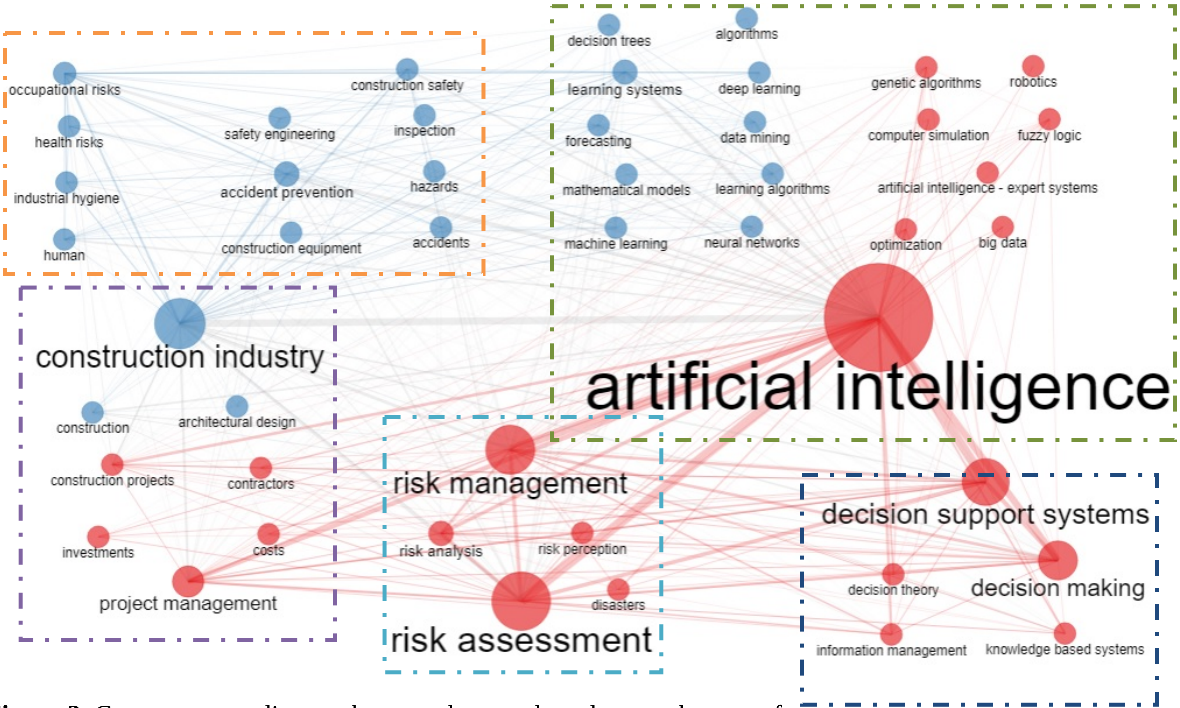

Figure 3. Co-occurrence diagram between keywords and research areas of source papers
AI algorithms Decision Support Systems RM domains
Construction Project Disciplines Health and Safety

3.2 AI-based risk data structuralizing and pre-processing

Text mining tools like Natural Language Processing and adaptive lexicon have been implemented to convert textual and unstructured risk data into structured format proper for AI algorithms (Fan and Li, 2013). Given that 80% of construction data is stored in text format in project reports, TM can extract valuable data for identifying contract risks from contract conditions, socio-technical risks from licensee event reports, and safety risks from accident reports (Xu *et al.*, 2021) for further analysis of risks. Moreover, Computer vision techniques are for detecting hazardous objects and situations that might trigger safety risks through images. Clustering and Classification methods are used to categorize risks and can be integrated with text mining methods as a proceeding step of text structurization. It is widely applied in safety and contract risk domain and various ML methods like Support Vector Machine (SVM), Linear Regression (LR), K-Nearest Neighbour (KNN), Decision Tree (DT), Naïve Bayes (NB) models are used in literature to classify the causes of the accidents (Zhang *et al.*, 2019).

3.3 AI algorithms classification for Risk Identification, Analysis, and Mitigation Planning

Various categories have been proposed for AI-based Risk analysis and reasoning methods in literature. Based on the categorization for AI application areas in the construction industry proposed by Pan and Zhang (2021), RM falls under a) the category of Expert Systems/Fuzzy logic for Knowledge Representation and Reasoning mainly formed on probabilistic, qualitative, and linguistic analysis, and b) Machine Learning for supervised learning based on either probabilistic or deterministic analysis. Samantra *et al.* (2017) classified construction risk assessment approaches as a) Probabilistic approach, dealing with risk probability and impact estimation based on historical numeric data, including Sensitivity analysis, Decision Tree analysis, Bayesian Networks, Monte Carlo simulation, etc. (Zhang *et al.*, 2014), and b) Possibilistic approach, dealing with risk probability and impact estimation based on qualitative or descriptive data including fuzzy logic (Dikmen *et al.,* 2007). The advantage of possibilistic models is that they can embrace the uncertain and vague definition of risk factors and their magnitude in a linguistic and subjective human description (Samantra *et al.*, 2017). Although called by various names, the notion and reasonings for classifying all of the methods are the same. For ease of reference, this paper calls them Probabilistic and Deterministic models. It is noteworthy that this classification basis is the risk reasoning itself, which is applicable to all phases of RM process from risk identification to assessment and mitigation planning.

3.3.1 Probabilistic Models

Probabilistic models include Structural Equation Modelling (SEM), Bayesian Network (BN), Fuzzy Logic, and Fuzzy Cognitive Map that can be integrated with other methods like Fault Tree analysis. These methods have a vast application in Expert Systems and Knowledge Representation and can have one of the bellow-mentioned risk reasonings (Wee *et al.,* 2015):

a) probability-based reasoning, referring to probability theory to indicate the uncertainty in knowledge, including fault tree analysis (FTA), SEM, and BNs.
b) Rule-based reasoning, deploying a set of rules in the "if <conditions>, then <conclusion>" format with logical connectives, like AND, OR, NOT, for analysing qualitative and linguistic data of expert opinion, including Fuzzy Logic.
c) Fuzzy Cognitive Map (FCM) learned from data or expert opinions, in which the fuzzy graph structure enables interpreting complex relationships and systematic causal propagation for immediate identification of risks' root causes in uncertain conditions.

SEM is a versatile multivariate statistical technique consisting of a schematic diagram representing causal structural relationships among multiple variables (Xiong *et al.,* 2015), and has a vast application in construction safety risk analysis with Exploratory Factor Analysis (EFA). EFA can uncover the underlying structure of a large set of variables when there are no hypotheses about the nature of the underlying structure of a model (Liu *et al.*, 2018). Bayesian Networks are a part of Probabilistic Graphical Models, which are statistical techniques based on probability and graph theory for causal inference analysis between risk variables. BNs are presented as graphs consisting of nodes, as random variables, and directed arcs as causal relationships among these variables, which is referred to as the Directed Acyclic Graphical model (DAG) (Borujeni *et al.,* 2021); and include a Conditional Probability Distribution (CPD) table, representing the influences between the nodes. The structure and CPDs can be learned through algorithms from enormous historical data, expert opinion, or both. BNs have a wide application in modelling, identifying, and analysing project-related risks like claims and contract risks, structural health, operation quality, cost and schedule overruns, and safety hazards (Khodabakhshian and Re Cecconi, 2022; Liu *et al.*, 2021).

Fuzzy Logic has a wide application in modelling qualitative and subjective data extracted from expert opinion, which allows reasoning with ambiguous information. The probability of verbal expressions are transformed into fuzzy numbers, with degrees of truthfulness or falsehood represented by a range of values between 1 (true) and 0 (false), using triangular, trapezoidal, or Gaussian fuzzy membership functions, and through four subprocesses of fuzzification, inference, composition, and defuzzification (Pokorádi, 2015). Fuzzy Logic integration with Bayesian Network, Analytic Hierarchy Process (AHP), and TOPSIS is proven to be a robust risk assessment and decision-making approach, especially when the problems are characterized by subjective uncertainty, ambiguity, and vagueness (Fayek *et al.*, 2020). A fuzzy cognitive map (Wee *et al.*, 2015) is a combination of fuzzy Logic and cognitive map, which uses subjective and vague linguistic variables from domain experts, perform a Root Cause Analysis, and model complex and dynamic systems with numerous indicators, causal dependencies, and weights. FCM forms a what-if scenario analysis for the prediction and evaluation of risks in a fuzzy weighted graph model with a tolerance of imprecision and uncertainty (Chen *et al.*, 2020).

3.3.2 Deterministic Models

A list of ML techniques applied in construction-related disciplines includes Artificial Neural Networks (ANN), Decision Trees, Logistic Regression, Naïve Bayesian Models, and Support Vector Machines. ML combines methods from statistics, database analysis, data mining, pattern recognition, and AI to extract trends, interrelationships, patterns of interest, and useful insights from complex data sets (Flath *et al.*, 2012). Deterministic Models include most of the Machine Learning algorithms. These algorithms can be used for one of the following applications in RM: a) Regression to predict continuous numerical outcomes like delay caused by a risk, including Linear Regression, Decision Trees, Support Vector Machines (SVM), and Neural Networks (NN) techniques, b) Classification to present the class of the output based on some input features like risk identification including NNs, Random Forest, SVM, and Genetic Algorithm, c) Clustering to explore data for natural groupings like finding related events causing a risk including K-means and SVM, d) Attribute importance to rank attributes based on their relationships to the target variable like identifying the most significant causes of accidents including Decision Trees and Random Forest, e) Anomaly detection to identify unusual cases based on deviation like identifying accident risks including SVM and Deep Neural Networks (Ajayi *et al.*, 2019). In contrast to other realms in construction, ML application has been limited and mainly for predicting delay risks in construction, predicting the impact of contract changes on the time and quality performance, and analyzing and modeling of incident databases for predicting H&S risks. The format of the input risk data for Risk Assessment in deterministic models can be numeric, categorical, video data, sensor data, textual data, etc., and input data acquisition approaches could be historical, real-time, or a combination of historical and real-time data (Hegde and Rokseth, 2020).

ANNs are the most applied ML method in engineering risk assessment, followed by SVM, Decision Trees, RF, CART, Naïve Bayes, K-means, KNN, Linear Regression, and BRT (Hegde and Rokseth, 2020). NNs are formed by layers of interconnected nodes using activation function, weight, and bias, which simulate the human brain structure and behavior for solving problems like recognition, classification, and regression (Bengio *et al.*, 2013). The reasoning behind these layers rely on the weights and biases assigned to each node, being learned and optimized based on Forward propagation and Backpropagation processes, with an objective to minimize the loss function as an indicator of prediction precision. They have a great performance in the presence of abundant data, capturing linear and nonlinear relationships of the data and serve as a predicting-analytical model for industrial RM control and accidents' severity assessment, to estimate the S-curve in a construction project, to analyze the causes of accidents, to predict delay risk in construction logistics (Gondia *et al.*, 2020)

DT is a supervised learning method that explores the relationships of many input attributes to an output attribute by creating a top-down branching structure consisting of a root node splitting into branches as probable outcomes. DTs do not need any assumptions regarding the independence of variables or variable values. They can process both numerical (continuous) and categorical (discrete) data and perform regression and classification. Support Vector Machines (SVM) perform regression and classification by mapping data to a high-dimensional feature space to categorize the data points by forming a separator between the categories in the form of a hyperplane. Genetic algorithms, which is an optimization and complex problem-solving method using an adaptive heuristic search, is also useful in measuring project risk interdependencies for the optimal cost solution under uncertainties (Liu *et al.*, 2013).

3.4 Comparative Analysis between Probabilistic and Deterministic models

Followed by Probabilistic and Deterministic algorithms determining and listing based on the source papers of Figure 2, an analytical comparison was made between them, regarding their reasoning basis in risk identification, assessment, and mitigation planning stages, advantages and disadvantages, application areas, and data requirements for each, presented in Table 1. The basis of this comparison was the points mentioned in source papers of the systematic literature review regarding the precision, problem type, analytical reasoning, input data requirements, level of probability included, and characteristics of each of these methods.

Table 1. Analytical comparison between Probabilistic and Deterministic RM models

Comparison Criteria	Probabilistic Models	Deterministic Models
Reasoning basis	probability-based reasoning rule-based reasoning Fuzzy logic	Forward propagation and backpropagation Loss function Weights and biases
Structure	Interconnected Graphs	Layers of neurons or branches
Learning Source	Historical Data Experts' opinion	Mainly historical data
Data Requirements	Limited amount of data Able to deal with missing values Numerical, categorical, and linguistic data	High amount of data Partial ability to deal with missing values
Probability and dependencies' role	Embrace probability in assessments Considering variables interdependencies with each other and final output	Does not embrace probability in assessments Considering variables interdependencies on final output
Prediction precision	Mid-high	Very high
Application scope	Subjective and uncertain problems with limited data	Objective and complex problems with abundant data
Application in RM processes	Risk Identification Qualitative Analysis Risk Control	Risk Identification Qualitative and Quantitative Analysis Mitigation Planning Risk Control
Advantages	Flexibility to various problems Ability to integrate qualitative and quantitative data (subjective and objective) Risk path approach Ability to include dynamic data	Quick processing and learning Ability to consider linear and nonlinear relationships among data Ability to include dynamic data

Disadvantages	Takes longer time to create the structure Not high precision if merely based on historical data High processing time in complex problems	Individual risk analysis approach (isolated) Not flexible toward change Requirement to high data volume

In general, Deterministic models have advanced structure, quicker processing time, and higher result precision in complex problems, but they require huge amount of structured data with no missing values or uncertainties. Given that documentation is in a poor condition in the industry, the data scarcity and infrequent data updates are main challenges of these models. Probabilistic models on the other hand, due to functioning in the state of data scarcity, missing values, and being closer to reality regarding the interdependencies between risk variables are more practical. They can integrate subjective and experience-based experts' opinion with objective historical data gathered from previous projects to overcome the data scarcity issue. Moreover, they benefit from the risk path approach instead of isolated risk assessment. Construction firms can refer to this study and Table 1 to choose the most proper AI model to foster their RM processes, regarding their enterprise requirements and data availability.

4. Conclusion and Further Research

The Construction RM process benefits significantly from AI in terms of automation, optimization, decision-making fostering, and standardization, as supported by the systematic literature review findings. Machine Learning and Deep Learning algorithms, with ANN, SVM, BN, and Fuzzy Logic in the lead, have found significant applications in RM research. However, in order to implement these methods in practice and to identify causes of various risks and analyze them in construction projects, abundant experience, prior knowledge, and historical data are required, which in most cases are not well documented or not easily accessible. Therefore, the data requirements, reasoning, and structure of each AI model needs to be thoroughly analyzed to choose the proper one based on the data availability of an enterprise. Furthermore, AI-based methods like text mining and computer vision can help structuralize the risk data and fairly overcome the data scarcity problem.

This study provided a systematic literature review for classifying AI algorithms that can be applied during different phases of the RM process. These algorithms were grouped under Probabilistic and Deterministic groups based on their risk reasoning, learning process, data requirements, flexibility toward data scarcity, uncertainty, integration of qualitative and quantitative data, and application scope. The contribution of this paper is providing an analytical comparison between different AI algorithms for practitioners and researchers to choose the proper AI model for a target risk problem; which, as proven by the results of previous literature, can bring many advantages in terms of automation, optimization, digitalization, and decision-making increasing the RM processes performance and projects' success rate. Moreover, an AI-based RM framework is presented, in which this study focused on the data analysis phase, and future phases are the subject of further studies. The limitation of this research was the limited number of publications for validating the proposed analytical comparison. Furthermore, the classifications provided by previous researchers for the AI algorithms were based on different criteria such as project phase, algorithms efficiency level, supervised or unsupervised learning, etc., that in some cases were incompatible with each other. Therefore, this paper had to group them under two wide flags of Probabilistic and Deterministic models to include the majority of these criteria, even if a more detailed classification would provide a more accurate comparison. As a suggestion for further studies, the provided comparative table can be discussed and validated by experts in the field or through case studies for algorithms implementation and results comparison.

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Ensuring Trusted and Traceable Construction Certifications with Blockchain: A Conceptual Model

G. Thilini Weerasuriya[1*], Srinath Perera[1] and Rodrigo N. Calheiros[2]

[1]Centre for Smart Modern Construction (c4SMC), School of Engineering, Design and Built Environment, Western Sydney University,
Locked Bag 1797 Penrith NSW 2751, AUSTRALIA
[2]School of Computer, Data and Mathematical Sciences, Western Sydney University,
Locked Bag 1797 Penrith NSW 2751, AUSTRALIA

T.Weerasuriya@westernsydney.edu.au; Srinath.Perera@westernsydney.edu.au;
R.Calheiros@westernsydney.edu.au

* Corresponding author

Abstract:

Significant failures in buildings are reported due to poor design, non-compliance to standards, and inadequate oversight, testing, and certification. Clearly traceable inspections, tests, and certifications are required to deter future failures and identify responsible negligent parties. Blockchain provides a secure, decentralised electronic ledger, which prevents unauthorised data manipulation and presents an audit trail with transparency of activities. Blockchain also contains smart contracts that can automatically execute on fulfilment of specified conditions. This paper proposes a conceptual model for a blockchain-based framework to ensure trusted and traceable certifications of construction work, materials, and related payments. The conceptual model was developed based on a critical literature review and problem analysis. Issues related to certifications, limitations of existing software systems in the construction industry, and the suitability of blockchain as a solution were identified from the literature. The conceptual model presents the stakeholders involved in certification, the high-level processes and types of construction certifications, and a blockchain framework to manage the certifications. The blockchain framework comprises of an integrated data model, process model, blockchain prototype, and distributed applications. The conceptual model was validated through an expert forum consisting of industry practitioners. The blockchain framework is expected to enhance the trust and traceability of certification data, thereby allowing the identification of reliable contractors and consultants to improve the performance of the construction industry with fewer defects and building failures.

Keywords:

Blockchain, Conceptual Model, Construction Certification, Traceability, Trust

1 Introduction

The construction industry is highly fragmented because of the many professions and organisations involved, which increases the complexity of projects (Nawi, Baluch and Bahaudin 2014). This fragmentation leads to long supply chains which are improperly integrated (Farmer 2016), limits data sharing among stakeholders in the construction industry (Hewavitharana, Nanayakkara and Perera 2019), and creates trust issues and challenges in managing processes (Wang, J *et al.*, 2017). Significant failures in compliance in buildings have been reported due to poor design, non-compliance to standards, and inadequate oversight, testing and certification (Shergold and Weir 2018). Regulators do not have the means to track and analyse information regarding certifications and compliance within the industry as a whole (Hewavitharana, Nanayakkara and Perera 2019). Furthermore, there is a lack of assuming responsibility for issues in certification (Buys 2006) and delays occur in approval of work (Maritz and Gerber 2017).

Compliance can be ensured through certification of construction material, workmanship, and work progress by various consultants in a project, such as architects, engineers and quantity surveyors. Accurate certification requires tracking complex information, including the quantity and quality of work executed by the construction contractors and numerous subcontractors (Ashworth and Perera 2018). Contractually, progress payments are made to contractors based on these certifications (Bailey 2019). All certifications should be traceable, and any negligent parties held accountable.

Blockchain technology is proposed to solve these issues. A blockchain is a peer-to-peer decentralised digital ledger of data, which contains a cryptographically linked record of all transactions executed within the network. A copy of the blockchain is stored by each computer (node) on the peer-to-peer network (Nanayakkara *et al.*, 2019). The other nodes should provide consensus to add new blocks to the blockchain, and blocks cannot be subsequently modified by a single actor, leading to immutability of data. This ensures that the authority of the network is not held by a single party, provides transparency of activities, and enhances data security (Perera *et al.*, 2020). Cryptographic methods ensure the integrity of data, creating trust and security (Belotti *et al.*, 2019). Transactions on the blockchain are validated and a timestamp is recorded. The transaction and ledger data is available for all authorised users to view. This allows users to trace records through any network node, hence auditability and traceability exist in the blockchain (Shojaei *et al.*, 2019). Users in a trustless environment can collaborate without worrying about record falsification due to these features (Perera *et al.*, 2020). Hence, a blockchain is an ideal medium to store certification data.

This paper proposes a conceptual model for a blockchain-based framework to ensure trusted and traceable certifications of construction work, materials, and related payments. The conceptual model was developed subsequent to a comprehensive, critical literature review. Issues related to work and payment certifications in construction were identified from the literature. Studies on current information and communication technology solutions for construction were also reviewed to understand the capabilities and limitations of these systems. Furthermore, the features and suitability of blockchain technology were explored as a better solution for managing construction certifications. The major findings of the literature review are presented in Section 2. The research methodology of the study is described in Section 3. The conceptual model and plan for model validation are presented in Section 4. The final section concludes the paper and proposes future research directions.

2 Literature Review

2.1 Issues related to work and payment certification

The construction industry has a number of features which differentiate it from other industries, including, the product being large, complex and immovable; using mostly bespoke, single-use designs without a prototype model; having an industry arrangement where there is separation of design from construction; and a single project can lead to high annual turnover (Ashworth and Perera 2018). It is relatively easy to enter the construction industry due to a lower capital requirement to start a construction company, and it is dominated by small and medium enterprises (Farmer 2016).

Construction projects need specific attention to maintain the quality as they are unique and non-repetitive in nature. Quality in construction projects depends on the quality of material and workmanship utilised in construction (Rumane 2017). Construction contracts include terms for materials and workmanship, compliance with approvals, regulations and standards, and fitness for purpose (Bailey 2019). The client is obliged to make progress and final payments to the contractor according to the timeframes set out in the contract. Nevertheless, issues related to payments are a significant problem that affects the industry (Stamatiou *et al.,* 2019).

Adversarial relationships among stakeholders in the construction supply chain are reported in the literature, where contractors and subcontractors are confrontational rather than cooperative (Chen *et al.*, 2020). Transfer of risk occurs through subcontracting, and benefits arise through specialisation and division of labour at the construction site (Tam, Shen and Kong 2011). However, when a project has numerous subcontracts, it can cause issues such as dividing the project authority, responsibility being fragmented, creating complications when scheduling operations, causing disputes and impairing the efficiency of the job. Smaller construction firms may lack proper work procedures, and issues in guaranteeing quality or professional competency can arise (Tam, Shen and Kong 2011). Contractors are responsible for timely payments to subcontractors, subcontractors should pay sub-subcontractors on time, and so on, along the construction supply chain. Nevertheless, payment problems persist within these contractual relationships as well (Ramachandra and Rotimi 2015).

The recommendations by Shergold and Weir (2018), in their report on improving compliance in the construction industry include to ensure private building surveyors' integrity, to collect and share building information and intelligence, to maintain adequate documentation and record keeping, and the importance of inspection regimes. Hoffman, Carter and Foster (2019) recommend independent third party checking and certification of engineering designs, on-site checking and certification that construction is as per the design at critical stages, and creation of an online database where all certifications may be viewed by a broad range of stakeholders.

The client is entitled to receive delivery of a project according to the expected scope, within the agreed-upon timeframe and specified cost (Rumane 2017). However, many studies globally have shown that this is rarely the case, with projects running overtime, over budget and/or not meeting requirements and with defects being revealed (Carretero-Ayuso, Moreno-Cansado and García-Sanz-Calcedo 2019; Forcada *et al.*, 2016; Maritz and Gerber 2017; Prasad 2019). A longitudinal study of an Australian contractor revealed that 34% of total costs of the projects sampled over six years were due to rework. Reasons for the rework included defective installation of items, not complying with specifications and standards, and insufficient oversight and inspection (Love *et al.*, 2018).

Out of all business sectors, the construction industry has extremely high rates of delinquency of payment and bankruptcy (Chong and Diamantopoulos 2020). Disputes occur due to progress payments and final payments, not only between clients and contractors but also along the construction supply chain involving contractors and subcontractors. Problems in payments occur due to not complying with payment provisions (Ramachandra and Rotimi 2015). When one party fails to pay, it cascades down the chain and causes long delays for stakeholders on lower levels to receive their payments. The causes of late and non-payment are complex and include attitudes towards payment, failure to implement proper contractual governance, hierarchical structure of the construction supply chain, industry competition, low business capitalisation, insolvency, and so on (Chong and Diamantopoulos 2020).

According to Shergold and Weir (2018), significant failures in compliance in buildings have been reported, including cladding which is non-compliant, roof construction that is not structurally sound, mould and compromise of structure due to seepage of water, and fire resisting elements that are poorly built. Inadequate oversight, poor design documentation, and improvisation by builders, as well as lack of independent certifiers have led to poor compliance and enforcement systems (Shergold and Weir 2018). Opal Tower and Mascot Towers in New South Wales, Australia were evacuated due to cracking in the building structures (Snow, Gorrey and Chung 2019). Non-compliant construction and structural design were reported to be the reason for the defects in the Opal Tower (Hoffman, Carter and Foster 2019). The inquiry into the tragic Grenfell Tower fire in London in 2017 highlighted lack of knowledge, disinterest, unclear roles and responsibilities and insufficient supervision by regulatory bodies as major reasons for failure (Hackitt 2018). There have been numerous other instances of construction failures throughout the world, which are mainly caused by non-compliance to standards, poor design, and insufficient regulatory supervision (Love *et al.,* 2020; Prasad 2019). Non-compliance to standards and design should be identified through proper inspection, testing, and certification (Velikova, Baker and Smith 2018). Recommendations have been made that conducted inspections, tests, and certifications should be clearly traceable, in order to deter future failures and identify responsible negligent parties (Hackitt 2018; Hoffman, Carter and Foster 2019; Shergold and Weir 2018), although the literature has not revealed any such systems currently implemented for industry-wide traceability of certifications.

2.2 Information and communication technology solutions for issues in the construction industry

Applying information and communication technology (ICT) to solve issues in the construction industry including inefficiencies, overruns of time and cost, quality problems, and so on, is an area of growing interest among industry and academia (Lu *et al.,* 2014). Yet, compared to other industries, the rate of integrating ICT into construction practices is sluggish. According to a report by McKinsey and Company, the construction industry is one of the lowest-ranked in terms of digitalisation (Barbosa *et al.,* 2017). Investments in ICTs by the Australian construction industry is approximately 1% of gross value added and 15% of its total investment volume (Leviäkangas, Paik and Moon 2017).

Researchers have categorised and studied software used in the construction industry including document management systems, quantity surveying software, project management software, Enterprise Resource Planning (ERP) systems, and Building Information Modelling (BIM) systems (Lu *et al.,* 2014; Redwood *et al.,* 2017). However, having separate systems to manage activities causes data redundancy and inconsistencies as the systems cannot easily share data among each other (Arnold and Javernick-Will 2013). Lack of interoperability in terms of exchanging information among various systems and organisations is affected by the fragmented nature of the construction industry (Lu *et al.,* 2014). Traditional software systems have a centralised data storage approach, which can create issues of trust, since there is no transparency. Increased security vulnerabilities also occur due to depending on a central database which may be compromised, and unauthorised changes made to the data would affect the entire system (Perera *et al.,* 2021; Rodrigo *et al.,* 2020). Data related to certification needs to be stored immutably, since it should provide a clear audit trail of work and payment certificates issued with dates and certifier details. However, using traditional software systems cannot guarantee the auditability of the data (Rodrigo *et al.,* 2020). Even cloud-based systems have security issues related to traceability of changes made to the data (Wong *et al.,* 2014). Therefore, alternative technologies which could provide these features needs to be explored. A potential solution is blockchain technology or distributed ledger technology.

2.3 Blockchain for trusted and traceable certifications

Blockchain offers a number of features such as decentralisation, security, trust, auditability, traceability, and immutability (Abeyratne and Monfared 2016; Belotti *et al.,* 2019; Perera *et al.,* 2020; Wang, Y, Han and Beynon-Davies 2019). A copy of the blockchain is stored by each computer (node) on the peer-to-peer network. The other nodes should provide consensus to add new blocks to the blockchain, and blocks cannot be subsequently modified by a single actor. This leads to immutability of data. It also ensures that the authority of the network is not held by a single party, provides transparency of activities, and enhances data security. Cryptographic methods ensure the integrity of blocks, creating trust and security. Transactions on the blockchain are validated and a timestamp is recorded. The transaction and ledger data is available for all authorised users. This allows users to trace records through any network node, hence auditability and traceability exist in the blockchain. Users in a trustless environment can collaborate without worrying about record falsification due to these features (Abeyratne and Monfared 2016; Nawari and Ravindran 2019; Perera *et al.,* 2020; Wang, Y, Han and Beynon-Davies 2019).

Blockchain contains smart contracts which can be defined as tamper-proof digital contracts that are automatically executed and enforce rules that are dependent on distributed consensus within a blockchain (Cong and He 2019). Third parties are not necessary to manage the transactions as they are replaced by smart contract code and do not require manual involvement to enforce the terms of a contract (Belotti *et al.,* 2019; Nawari and Ravindran 2019). This will result in savings in time and cost (Shojaei *et al.,* 2019). Payment terms and compliance requirements are conditions that can be enforced through smart contracts which will increase the guarantee of execution (Nanayakkara *et al.,* 2019). A challenge for implementing smart contracts in the construction industry is that uncertainties in projects create complexity that is difficult to completely translate to code (Shojaei *et al.,* 2019).

Critical reviews on blockchain in construction show that there is a great potential for blockchain to overcome significant issues in the industry in areas such as construction management, contract management, supply chain management, and payment management (Perera *et al.,* 2020; Wang, J *et al.,* 2017). Automating and executing construction contracts, payments and certification are potential applications of smart contracts in the construction industry (Shojaei *et al.,* 2019). Being able to trace the provenance of products in the construction supply chain is important for quality assurance and compliance purposes when defective products are identified. If the full history of product transactions in the supply chain is tracked through the blockchain, it enables the identification of parties responsible, and enhances the traceability and transparency of the construction supply chain (Wang, J *et al.,* 2017; Wang, Y, Han and Beynon-Davies 2019).

Certifications regarding quality of raw materials and products, and quality and quantity of work progress can be stored in the blockchain so that all relevant stakeholders know the source of the authentic information (Nanayakkara *et al.,* 2021a; Wang, J *et al.,* 2017). Since the records are tamper-proof, it will assist in enforcing compliance of work, and all modifications to data such as BIM models, certifications, and so on can be stored immutably on the blockchain (Nawari and Ravindran 2019).

3 Research Methodology

The research methodology of the study is illustrated in Figure 1 below. A critical review of literature was conducted to derive the problem specification. Literature included indexed journal and conference papers, industry reports, textbooks, and technical white papers. The first step was to identify the issues in the current practice of work and payment certification in the construction industry described in the literature. Next, current ICT solutions for issues in the construction industry and their limitations were analysed through the literature review. This provided the groundwork to evaluate the features and suitability of blockchain as a solution for the identified issues, through a further review of relevant literature. A qualitative approach of semi-structured interviews with industry experts was followed to validate the problem specification. The expert forum comprised of construction consultants in the categories of quantity surveyor, project manager, architect, engineer, and certifier, with more than five years of experience in certification of construction projects. The current industry practice of certification of the quality and progress of construction work and related payments was investigated through the interviews. Subsequently, the conceptual model for ensuring trusted and traceable work and payment certifications with blockchain was designed.

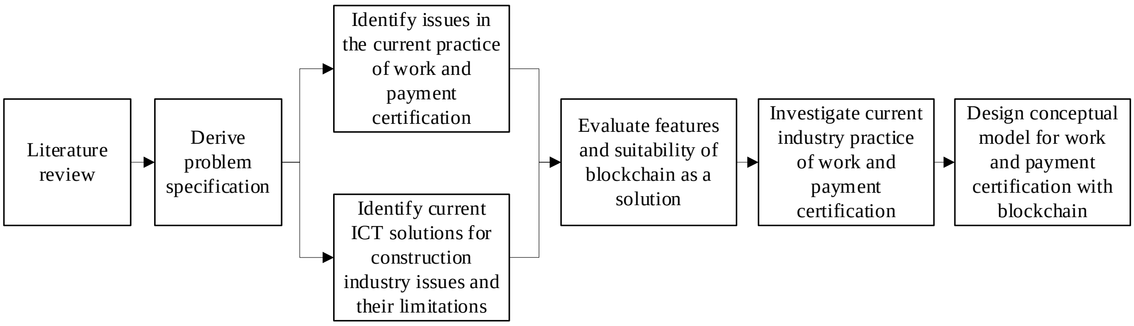

Figure 1. Research methodology diagram

4 Findings and Discussion

4.1 Conceptual model for blockchain-based work and payment certifications

The major stakeholders in a construction project are the client, main contractors, subcontractors, suppliers and manufacturers, and consultants such as project managers, architects, engineers, certifiers, and quantity surveyors. The main contractor and subcontractors carry out work on the construction project, while suppliers and manufacturers provide material for the project. Architects, engineers, and certifiers are involved in certification of the quality of material and work. Quantity surveyors certify the progress of work and amount of material on site to provide recommendations for progress payments, and create the final accounts at the end of the project. The responsibilities of project managers include managing the running of the entire project, coordinating all stakeholders, and certifying payments to contractors, subcontractors, and suppliers (Ashworth and Perera 2018; Rumane 2017). These stakeholders, high-level activities, and types of certifications are reflected in the conceptual model in the upper-left corner of Figure 2.

A blockchain framework is proposed to track all quality, progress, and payment certifications, and details of defects and other issues related to construction projects. The stakeholder details will also be stored in the blockchain to trace responsible parties for specific work or certifications. The framework will be developed by designing data models for the tasks handled by each category of construction consultant. These categories include quantity surveyor, project manager, architect, engineer, and certifier. The data models will consist of data flow diagrams and entity relationship models (Rodrigo *et al.*, 2021). Subsequently, an integrated data model will be developed to consolidate the tasks to a common platform. Process modelling will be performed through activity diagrams that reflect each consultant's certification-related activities and decisions. An integrated process model will then be created to provide a comprehensive and streamlined system to manage certifications in projects.

The framework will also contain a blockchain prototype. The prototype will be developed based on the data and process models described above. Selecting a suitable blockchain platform is an important decision to be made in this step. The suitability of the platform will depend on the requirements of the system. These requirements will inform decisions on the type of blockchain network (public, permissioned, or hybrid), consensus mechanism, cost, level of security and performance, and so on (Nanayakkara *et al.*, 2021b; Perera *et al.*, 2021). Smart contract algorithms will be written to automatically execute actions on the fulfilment of predefined conditions. For example, flagging responsible parties upon identification of defects or non-compliance to specifications or standards during the certification process. Subsequently, distributed applications will be developed as user interfaces to allow the stakeholders to interact with the blockchain prototype. Project data stored in external databases will also be able to be accessed by the blockchain smart contracts when required. The proposed blockchain framework is illustrated in the upper-right corner of Figure 2. The lower half of Figure 2 shows a simplified view of how the various stakeholders can participate in an example blockchain network. A node on the network should be connected to at least one other node. Each node will have a copy of the blockchain ledger that replicates the same data throughout the network.

The fully developed blockchain system could be used by clients and construction consultancy firms to track projects over time. As data about work, certifications, and stakeholders is immutably stored within the blockchain, responsible parties for issues that occur even after the project is complete could be pinpointed. As data stored in a blockchain cannot be tampered with, it will ensure compliance of work by contractors and subcontractors, and credibility and ownership of certifications of consultants. This is expected to lead to a reduction of defects and incidence of building failures. The availability of all certification data on the blockchain will assist industry regulators' decision-making in providing approvals such as occupation certificates. The development of a comprehensive blockchain solution will involve in-depth modelling of the activities in a construction project and the introduction of streamlined processes. The proposed prototype is expected to serve as a proof-of-concept for a comprehensive system.

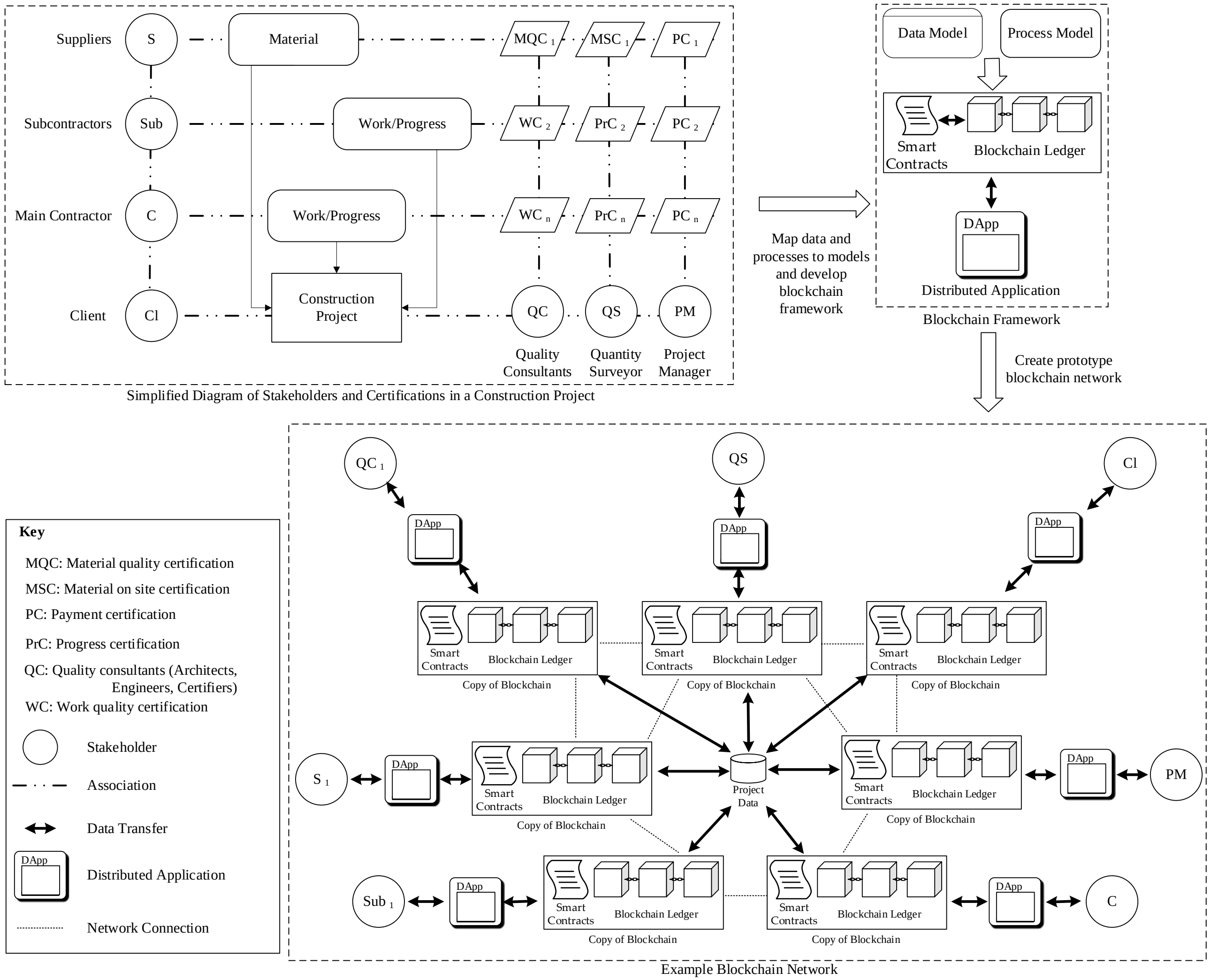

Figure 2. Conceptual model for blockchain-based work and payment certification

4.2 Model validation and enhancement

The conceptual model was validated through an expert forum consisting of industry practitioners. As described in the previous sub-section, the data and processes related to certification identified through expert interviews will be used to develop the data models and process models. These models will then be validated by experts through a multi-round Delphi interview process and revised where necessary. Subsequent to the development of the blockchain prototype and distributed applications, the entire framework will be validated by another expert forum of construction industry practitioners to ensure the research achieves the proposed objectives.

5 Conclusion and Further Research

The construction industry faces significant issues related to defects and failures in buildings. These arise due to factors such as non-compliance to specifications and standards, defective installation of items, and inadequate inspections and certification. The fragmented nature of the construction industry results in limited data sharing among stakeholders. This creates challenges in managing processes and ensuring the quality of projects. Although various software systems are used by construction stakeholders, most often, the systems used by different parties are not interconnected. This limits the ease of data exchange, decision making, and enforcement of quality standards. Identifying reliable contractors and consultants will enhance the quality of projects. Accurate and traceable certifications of the quality and progress of construction work and materials and their related payments are essential to ensure compliance to specifications and standards.

This paper proposes a conceptual model to implement a blockchain-based framework for certification of work and payments in a construction project. The framework consists of an integrated data model, process model, blockchain prototype, and distributed applications to ensure trusted and traceable certifications in the construction industry. The data and process models of the framework will be designed in the next stage of this research using data gathered through expert interviews. Subsequently, a blockchain prototype and distributed applications for construction stakeholders to access the blockchain will be developed. The blockchain framework is expected to enhance the trust and traceability of certification data. This will provide a method of identifying reliable contractors and consultants. Since the data will persist over time, negligent or unreliable parties will not be able to operate, as their performance history is available for all stakeholders to view. Reliable contractors and consultants will assist in enhancing the performance of the construction industry. Furthermore, enhanced compliance and reliability will reduce the incidence of building failures and increase longevity of buildings, thereby positively impacting clients' confidence in the construction industry.

6 Acknowledgement

This research is funded by the Research Training Program Scholarship provided to Western Sydney University by the Commonwealth Government of Australia and in-kind support from the Centre for Smart Modern Construction (c4SMC).

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Smart Adaptive Homes and Their Potential to Improve Space Efficiency and Personalisation

Thomas Goessler[1*] and Yamuna Kaluarachchi[1]

[1] Manchester School of Architecture, Manchester Metropolitan University, UK
All Saints Building, Manchester, M15 6BH, United Kingdom

thomas.goessler@stu.mmu.ac.uk; Y.Kaluarachchi@mmu.ac.uk
* Corresponding author

Abstract:
Over the last decades, population growth in urban areas and subsequent rising demand for housing have resulted in significant space and housing shortages accompanied by a loss of identity and personalisation in urban homes. This paper investigates the influence of smart technologies on small urban dwellings to make them adaptive, personalised and resilient. The study builds on the hypothesis that smart technology could increase efficiency and space usage up to two to three times compared to a conventional apartment, and could accommodate increased housing demand and give young city dwellers a new housing perspective. A comprehensive semi-systematic literature review including a review of case study projects illustrates different strategies to increase functionality and diminish the physical and psychological limitations of small spaces by making functions time-dependent and introducing furniture and division elements that adapt to user needs in real-time. This paper discusses the two main schools of thought, the idea that technology should be a silent and invisible helper versus the notion of technology as an interacting entity with visual representation. It further categorises types of flexibility and adaption regarding the size of the moving elements and the time that the transformation takes. Together with the analysis of real-world projects, results show that smart and adaptive technology can increase space efficiency by reducing the need for separate physical spaces for different activities. Smart technology substantially increases the versatility and multifunctionality of the room in all three dimensions and allows for adaptation and customisation for a variety of users.

Keywords:
Smart homes, adaptive homes, interactive architecture, micro-living, space shortage

1 Introduction

Over the last decades, the population growth in urban areas and rising demand for housing have been accompanied by a sharp increase in space shortages and loss of identity and personalisation in urban homes. According to RIBA (2013), the most prevalent cause of discontent with one's home in the UK is the lack of space. In major cities like London, the housing demand is hardly met with adequate supply, leading to unaffordable rents, urban sprawl, transportation problems and sustainability issues (Kichanova, 2019). Micro-living concepts have been proposed as a possible solution for affordable residential space, increasingly when combined with smart technology and automation. Smart can be defined as (see comment) Smart technology can help increase the quality of life, especially regarding the increase of functionality and personalisation (Radha, 2021). By doing so, housing can overcome fixed layouts for specific functions and more broadly has the potential to become smart, adaptive as well as personalisable and will allow homes to solve problems, alter furniture and layouts, make decisions and predict what users might require in advance (Radha, 2021). Architecture becomes the science of fluid dynamic structures and environments running in real-time according to Oosterhuis (2012). The intersections of different concepts that contribute to a space that acts and reacts in real-time such as smart, adaptive etc. are illustrated in Figure 1. Adaptive architecture combines the research areas of automation (making changes with the help of actuators and machines) and smart technology and includes areas like interactivity or reactivity. ‘Smart’ in this context means the integration of sensors, databases, and wireless access to collaboratively sense, adapt, and provide services for users (Kaluarachchi, 2022) in the home environment. This paper concentrates on real-time adaptiveness in small homes with the goal to link theories with real world products and categorise architectural concepts in the findings section.

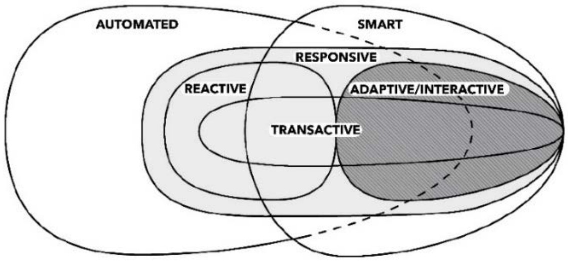

Figure 1. Terminology
Source: own graphic following Jaskiewicz (2013)

2 Research Methodology

Research methodology is semi-systematic literature and project review, identifying research opportunities for more efficient, functional and personal urban dwelling units. The literature review included a body of 410 case studies, peer-reviewed articles, working papers and reports and was compiled using EthOS, Science Direct, ResearchGate and Google Scholar as search engines and databases. A three-stage approach was deployed: First a deduplication of the various sources was carried out. Then a review of the abstracts using a CASP protocol and finally (when the full text was accessible) an analysis of the full text of the paper. The review is considered semi-systematic since after the initial systematic scoping the selection of literature and projects is based on the researcher's judgement regarding relevance. The search terms that were used are “cybernetic architecture”, “interactive architecture”, “adaptive architecture”, “adaptive interior”, “home automation”, “micro-living”, “smart home”, “smart furniture”, and “spacing saving furniture”. The inclusion criteria is that the work was published in the time between 2010 and 2022 and contains information that is relevant to the architectural perspective of adaptive spaces. This led to a reduction of the body of work to 81 articles, papers and conference proceedings. Additionally, space standards and national statistics were considered. Since projects and technology play a major role in the architectural discipline this review also considers smart furniture or homes selected to complement the literature. This allows an evaluation of theoretical strategies to achieve more space efficiency and personalisation with adaptive smart homes and to compare them with real-world examples. A semi-systematic literature and project review creates the theoretical framework for further research. This paper is part of a PhD research project and only a selection of the literature and projects are included. The protocol adopted is shown in Figure 2.

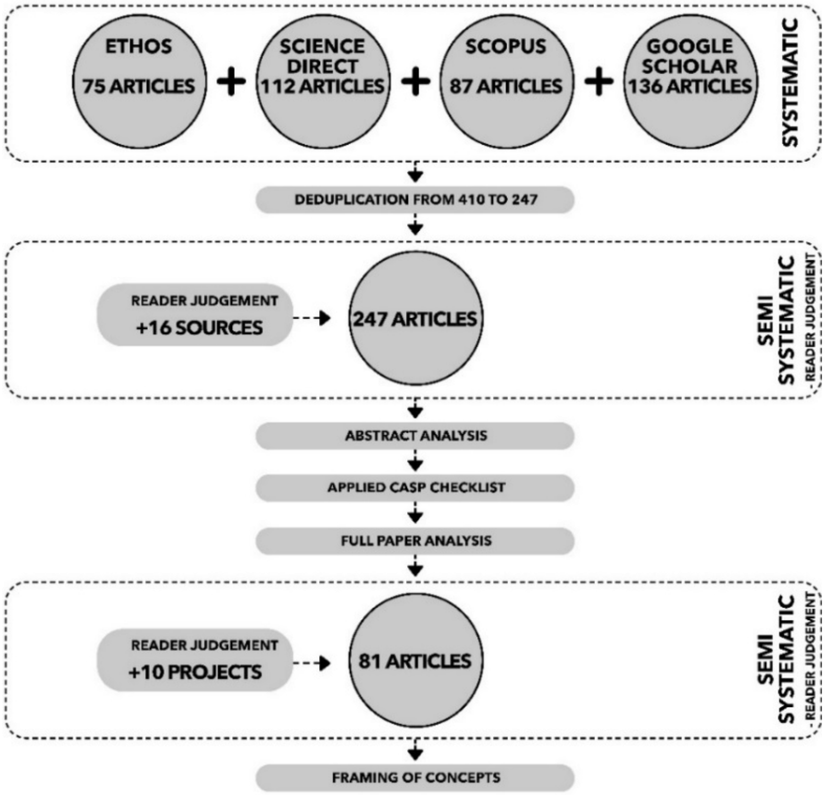

Figure 2. Literature review protocol
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3 Literature Review

The following review discusses concepts that are relevant for small adaptive homes through different lenses. Namely the architectural perspective dealing with the concept of a home, including the significance of space for well-being as well as micro living as a strategy to improve space usage. And secondly the role that technology plays to make space more interactive and efficient. Together these sections form the state of the art of adaptive and interactive spaces and lead to a categorisation of adaptive space concepts in the findings.

3.1 The home

From an architectural point of view, the concept of a home consists of physical space, the function that a space enables and the meaning of space which considers the home as a space of relationships, memories and as a representation of the resident (Canter, 1977). The literature indicates that personalisation and higher-level needs like self-actualisation have to be incorporated to achieve user satisfaction (Leitner, 2015). Today's smart homes that improve energy usage, security, remote control, automation and comfort (Gram-Hanssen & Darby, 2018) are especially attractive to young people pursuing a technology supported neo-nomadic lifestyle characterised by their digital dependence and location independence (Naz, 2016).

3.2 Reasons for adaptive micro living spaces

Most published research papers focus on needs regarding space shortage or are linked to a change in society where especially young people want to live in flexible, smart environments. According to the United Nations (2018) an estimated 55.3 per cent of the world's population lived in urban settlements in 2018 and by the year 2030, that number is expected to rise to 60 per cent. This rapid growth and the inability of many metropolitan areas to keep up with the resulting demand causes housing shortages in many of the world's largest cities. London's population has increased by 25% from 1999 to 2019, yet the number of dwellings have only increased by 15% which leads to unaffordable rents, house prices and housing dissatisfaction (Kichanova, 2019). Well-intended legislation like a 37-m^2-minimum (Mayor of London, 2018) for new-build flats in London are political attempts to improve the situation. However, such legislation is criticised for making the situation worse by architects like Patrick Schumacher (Pitcher, 2018) or researchers like Kichanova (2019) who argued that 'smart micro-housing' is the better choice for some people. Reducing size can decrease living costs, be a driver for sustainability and allow people to live in urban areas while focusing more on social life and leisure activities (Kichanova, 2019). The literature suggests that especially young people are smart micro-home users or will be in the near future (Radha, 2021).

Historically, labour was geographically bound while the introduction of teleworking has brought the freedom to work from anywhere for a group of people who are often referred to as digital nomads (Graham et al., 2017). Some studies estimate the number of digital nomads will continue to rise and reach over 1 billion in 2035 (Wiranatha et al., 2020). Especially young professionals who are working digitally while living a location-independent and often travel-reliant lifestyle (referred to as digital nomads) are looking for co-living, micro-living or smart living solutions (Wang et al., 2019). Research findings by Omar et al. (2012) show that personalisation is another important factor for housing satisfaction. According to their findings, alterations of homes do not necessarily mean dissatisfaction of the user, but rather show how people would want to make their home unique and personal.

This calls into question the efficacy of the current system for delivering homes which appears unconcerned with the unique expression of each resident. While research by institutions like the RIBA (2013) shows that lack of space is the most common cause of housing dissatisfaction, according to Foye (2017), moving to ''larger accommodation'' has no positive long-term impact on subjective well-being. Similar results are shown by other user surveys (Frijters et al., 2011; Nakazato et al. 2011). Jansen (2014) explains this outcome by saying that an increase in living space will initially close the gap between one's preferred housing situation and reality, leading to an initial increase in housing satisfaction. However, this gap re-emerges over time and causes the uplift in housing satisfaction to diminish. The concept of micro living is discussed mainly positive as a hub for aesthetic and functional refinement and innovation in the literature. Critics say that instead of constituting sustainable liveable space, they are sold above market price to increase profits (Hall, 2022; Arcilla, 2021). The literature above suggests that when all basic needs like security, safety and physical needs like warmth and hygiene are available housing satisfaction is influenced by the functionality of a space, the flexibility that it offers and only to some extent the actual size per person. New technology has the potential to increase space efficiency and personalisation and can be used to achieve real-time adaptiveness.

3.3 Technology (automation and smartness)

The semi-systematic literature review shows that most concepts build up on technological advancement as a driving force for adaptive spatial design. The state of the art in technology is highly influenced by the progress in sensors, actuators, materials and Artificial Intelligence (AI) with their role in adaptive architecture illustrated in Figure 3 below.

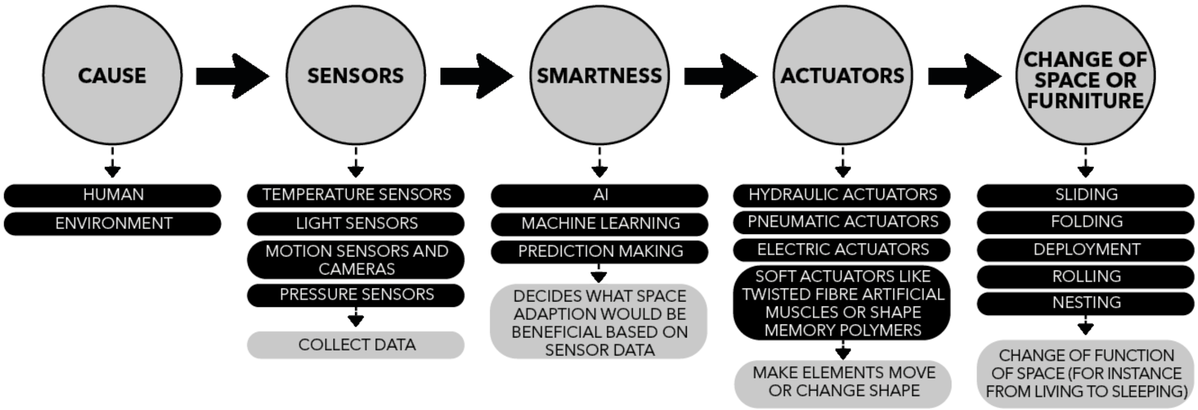

Figure 3. Technology for adaptive spaces
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Progress in AI allows machines to learn, recognize what users are doing and make predictions with very high accuracy (Yiannoudes, 2016). Machines are getting context-aware and more ambient intelligent (Yiannoudes, 2016). Ambient Intelligence is used as a term for a collection of technologies that smoothly blend into their environment to produce an unnoticeable user interface (Dunne et al., 2022). Sensors are already very elaborate in collecting multitudes of data, from temperature, humidity, solar radiance, or energy usage to human activity, sound or spatial recognition of objects (Zaro et al., 2021). The trend goes toward cableless microsensors or wearables that detect human activity with high accuracy (Haroun et al., 2021). Cutting-edge actuators can achieve almost any motion and can vary from engines to artificial muscles. Soft actuators which are materials that can perform tensile and torsional actuation are becoming increasingly elaborate and cost-efficient (De Silva, 2016). They include twisted fibre artificial muscles, shape memory polymers, hydrogels, liquid crystal polymers, electrochemical actuators utilising conducting polymers, and certain natural materials (Zou et al., 2021).

To alter space visually lights, screens and materials are developing fast and allow the ambience and colour of a room to change in real-time (Leitner, 2015). Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR) are advanced enough to offer an immersive experience that can be a solution to expand the physical space (Yang et al., 2021). Hermund & Klint (2016) show that virtual space can convey all the information that physical space can. While the literature indicates that technology is advanced enough to alter architectural space physically or virtually, the big question in the architectural discipline is in relation to the best way of adaptation and transformation. Integrated technology opens up many opportunities.

3.4 Adaptive space theories

According to Jaskiewicz (2013) adaption, which is the change of architectural space over time (both regarding the building shell and the interior layout) is in the first place linked to human needs and follows cycles of daily routines and external factors. Environments adapt to human activity, while at the same time, through a feedback loop, human activity is influenced by the spatial characteristics of the human habitat (Oosterhuis, 2012). According to Jaskiewicz (2013) and Yiannoudes (2016) adaption can be achieved by different means, depending on the time necessary for the change (Figure 4) and the entity (human or machine) making the change and can be divided into: Firstly, **reconfiguration** of space which is reassembling or changing parts of a building manually (for instance installing/removing a partitioning wall), which is time and labour intensive. Secondly, **flexibility**, which means leaving margins in the space or create open spaces. That allows users to reconfigure spaces manually, however over dimensioning leads to inefficiency (Yiannoudes, 2016). And thirdly adaption is achievable in real-time by means of **automation** with intelligent systems sensors and actuators (Jaskiewicz, 2013). The paper presented here focuses and gives more attention to this third aspect.

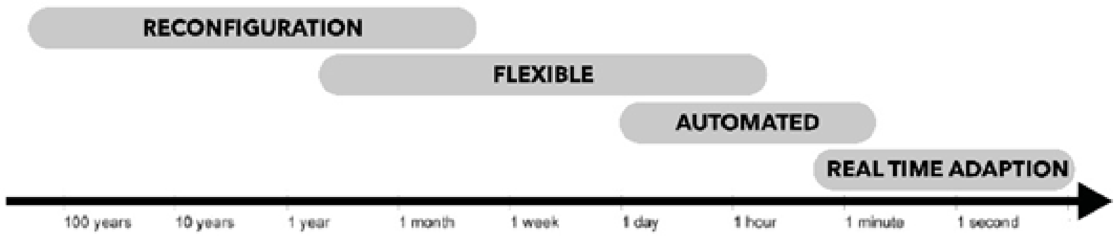

Figure 4. Time dependent space change
Source: own graphic

The adaptive systems of today are linked to smart homes and smart furniture. Historical concepts are still very relevant in the current literature that is built up on cybernetic and metabolist ideas from the 1950s and 1960s. Pask (1969) proposed that cybernetics could make buildings adapt, learn, and respond according to the interaction with users. In his work, *The Architectural Relevance of Cybernetics*, Pask (1969) described cybernetics as a transdisciplinary area that permeates divergent domains such as engineering, biology, sociology, economics, and design. He puts forward that the architect's "aim is to provide a set of constraints that allow for certain, presumably desirable modes of evolution," and determines the relevant properties between humans and systems (Pask, 1969, p. 75). Archigram, an avant-garde architectural group drawing inspiration from technology, had a more iconographic and theoretical approach toward adaptive architecture (Crompton, 2012), and they envisioned flexible and functionally indeterminate spaces where the "push of a button or a spoken command, a bat of an eyelid will set transformation in motion – providing what you want where and when you want it" (Archigram, 1967, p. 146). While Archigrams' concepts were futuristic, on the other end of the spectrum, the works of Price, Friedman and Zenetos were more elaborate examples that marked a shift towards adaptive user-centric designs (Yiannoudes, 2016).

Today, user-centric studies by Radha (2021) and the MIT Media Lab (2016) show that moving furniture elements and adaptive spaces are re-emerging in the public interest and are no longer futuristic ideas considering the technological advancement over the last decades. The research project *CityHome* (MIT Media Lab, 2016) conducted in Cambridge/USA shows that this smart furniture system could make an apartment act 2 or 3 times its size. The MIT Senseable City Laboratory (2022), which is a successor of the *CityHome* project, looks at methods for studying the built environment as layers of networks as well as digital information and the machine becoming the city. (Duarte & Ratti, 2019).

According to the findings by Radha (2021), who conducted user surveys regarding adaptive smart home prototypes in Iraq, smart houses with moving room elements have better internal space efficiency and functionality, since they make better use of time and space for a variety of activities using smart technologies and are more likely to be accepted by younger people. The paper concludes that by "incorporating smart architectural elements, increased degree of design versatility was achieved, and it was discovered that changing size, shape, reference, and layout became easier, faster, and allowed more options for organizing spaces in smart homes" (Radha, 2021, p. 15). Together the above studies show great potential and also user acceptance for adaptive elements to be integrated into existing as well as new buildings.

Yiannoudes (2016) examines architectural designs that employ computational technology to adapt to changing environments together with human demands and emphasizes that intelligence is needed for adaptive spaces acting in real-time. Ambient Intelligence is concerned with intelligence in the built environment and smart environments can then proactively respond to the needs and activities of people by utilizing adaptive systems, ubiquitous computing, and user-friendly interfaces. While the review of the selected literature shows that only a small number of researchers concentrate on the user centric design of spaces, the literature above shows the great potential to save space that are technologically feasible.

Looking ahead, research that is looking at swarm robotics and room-bots as a solution for almost indefinitely adaptive spaces shows some promising results in early studies and experiments. The Hyperbody Research Group under the lead of Kaas Oosterhuis at TU Delft did research regarding adaptive spaces, for instance, the *Muscle Project* that attempted to create a space that can change shape by contracting and relaxing artificial muscles and stretchable materials (Oosterhuis, 2001). According to Oosterhuis (2012) buildings are subject to the digital revolution and architects have to play with the unheard-of potential of the new media invading the built environment. Especially swarm architecture (a self-organized systems consisting of smaller elements) that is at the same time e-motive, transactive, interactive and collaborative is seen as the future of buildings adapting in real-time (Oosterhuis , 2012). Companies like Festo were able to create small robots (resembling for instance ants) that are able to work together like a real-world colony (Stoll, 2021). Building furniture and walls with all their properties (like softness for a sofa) is a big challenge and not feasible at the moment. However, Szot et al. (2021) developed a virtual environment to train robots to arrange objects and furniture in an apartment with reinforcement learning, which shows that the re-arrange ability can be achieved with independent robots.

Suzuki et al. (2020) developed the prototype of a room-scale dynamic haptic environment called *RoomShift* that creates haptic experiences by rearranging physical spaces with the help of a tiny swarm of robot helpers. The swarm of shape-changing robots that can freely move a variety of furniture. Spröwitz et al. (2010) try to “imagine a world in which our furniture moves around like legged robots, interacts with us, and changes shape and function during the day according to our needs” (Spröwitz et al. 2010, p. 15) While it is technologically possible to overlay physical and virtual space with VR, AR or MR and the social lives of people are more and more shifted towards the virtual space, it is questionable whether these technologies can or should replace the physical space fully (Yiannoudes, 2016). The mentioned literature indicates that technological advancement combined with architectural design opens up many possibilities.

3.5 Real-world systems

Examples of adaptive kinetic facades like the *Ocean Pavilion* by Soma from 2012, the *Shed* by Studio Diller Scofidio + Renfro completed in 2019, the *Shanghai theatre* by Heatherwick and Foster from 2017 or the *Polish House* by Robert Konieczny from 2017 are already very common today and might be further developed for the use in interiors. Products like the ones by Expand Furniture (2022), Candra (2022), Dror (2022), or the foldable and smart furniture lines by Ikea (2022) are contributing to space saving.

Smart furniture by Ori Living (2022) and Bumblebee (2022) is considered state of the art and shows how furniture is made adaptive and movable with actuators. ORI furniture emerged from MIT Media Lab’s (2016) *CityHome* project where furniture, storage, exercise equipment, lighting, office equipment, and entertainment systems are all integrated into a transformable wall system. The range includes the *Cloud Bed*, which is a ceiling-mounted bed as well as the *Pocket Studio* and *Pocket Office* which are smart walls with an integrated bed or office table (Ori Living, 2022). Whereas smart walls seem to be the most anticipated element, both ceiling and floor, mounted moving furniture is on the market and has great space-saving potential. The ORI and Bumblebee systems have the same goal, namely, to increase the functionality of residential spaces with furniture that is multi-functional, movable, and smart and change the inner layout of space automatically and in real time. Both systems offer a bed, a table and storage. One of the main differences is that ORI is mounted on floors and walls and Bumblebee is a ceiling-mounted system. The advantage of a ceiling-mounted system is that it is more flexible since the bed and storage could be installed in the middle of the room, however, the solution by Bumblebee seems to be more expensive since the movement on cables is more complex. Looking at the bed options from ORI and Bumblebee, they can both almost free up the whole space of about 5m^2 that a standard bed would use. Regarding storage, ORI can save about 50% of space usage compared to a conventional cupboard because the access area can be minimized. Systems like this get more efficient if more rows of storage are staggered, like in the *Domestic Transformer* by Chang (2007). In comparison the Bumblebee system does not need any floor space, however, due to the small volume of the ceiling-mounted boxes, there is a larger area of the ceiling necessary to achieve a similar volume. Products like the *Pocket Studio* by ORI combine a variety of functions, which can save up to 9m^2 compared to the same elements without adaptiveness (Ori Living, 2022; Bumblebee Spaces, 2022). Looking at these examples it seems feasible that a 35m^2 studio can function like a 50m^2 home.

Regarding visual adaption, art installations like *Ada* from 2019 by Microsoft show that light and sound can change in real time according to people around the installation (D'Angelo, 2019). There are also more advanced visual personalisation options like colour-changing materials (for instance *ChroMorphous* (2022), a material that changes colour and appearance on demand, developed by researchers at the University of Central Florida) and invisible screens. According to Yiannoudes (2016), the functionality of an ambient intelligent system depends on the design of the space that is supposed to host it. Architectural design and immersive smart technologies must be linked and thought of as a concise system. Combining those has the potential to make our life happier, healthier, sustainable, and more comfortable (Jaskiewicz, 2013).

4 Findings and Discussion

This literature review shows that today there is both the need (regarding space shortage) and the necessary technology for many concepts to be realised as well as the user acceptance (especially among young people) to make adaptive homes successful. Early smart furniture systems on the market seem very promising although not yet widespread and smartness becomes an important factor in every product. Obvious reasons why people would not buy such systems are high costs, system compatibility issues and concerns regarding data security (Schill et al., 2019). Visions of a dystopian future metropolis that is overcrowded, where people have become accustomed to living in cramped cellular rooms with a legal maximum size of just 3.5 square metres per person like envisioned by the avant-garde British author J.G. Ballard in his short tale *Billennium* from 1962 (Ballard, 1983) have to be addressed and the goal to make most out of the available space be emphasised (Yiannoudes, 2016). The borders between the concepts of flexibility and adaptability are blurred and many of the reviewed research projects are difficult to locate in the broader framework or to understand what they would mean for the interior of a home. Therefore, this study tries to classify strategies and divide them into categories shown in Figure 5-9 for a clearer understanding of concepts.

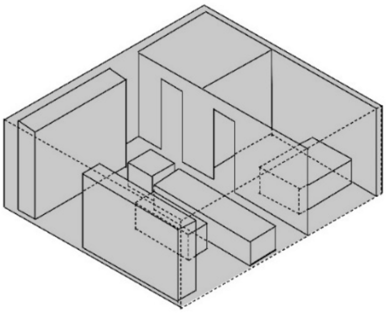

Figure 5. Standard apartment
Source: Own graphic

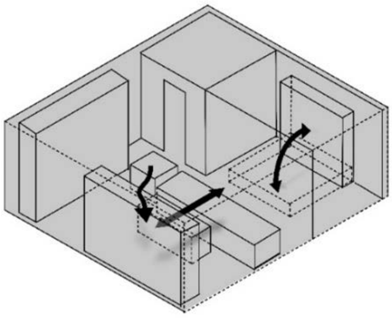

Figure 6. Micro living
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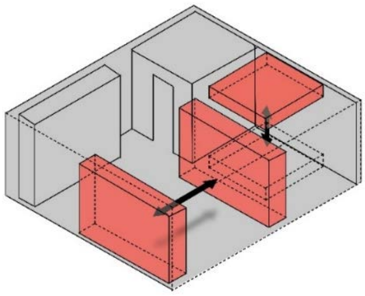

Figure 7. Big modules
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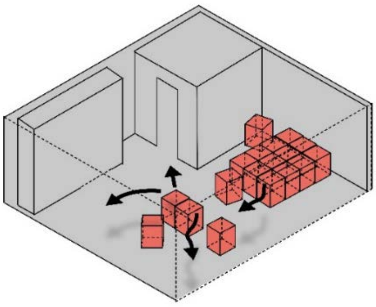

Figure 8. Small modules
Source: Own graphic

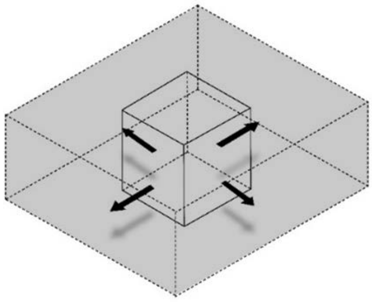

Figure 9. Virtual space
Source: Own graphic

4.1 No adaptability – standard apartment

The most common apartment type today is a conventional apartment that has room separation and loose furniture (like shown in the illustration of a 37m^2 home in Figure 5). Furniture can be replaced easily to achieve some sort of personalisation and while the furniture could be rearranged and moved, this is often not possible in reality because minimum apartments do not have the spatial flexibility to do so. Structural reconfiguration is necessary for severe functional change. While standard furniture is the cheapest option the usability of the space cannot be increased, and functions are difficult to stack.

4.2 Transformable micro-living apartment

Micro living spaces that use movable or folding elements have become common to make space more efficient. In comparison to a standard apartment, space is much more flexible and can have multiple functions in the same area. There are relatively cheap products like wall-mounted folding beds, sofa beds, stackable chairs, expandable tables or simply furniture with wheels on the market. More elaborate, often individually designed, examples also use the floor and the room height to maximise space usage with split levels or under-floor storage. While cost and space efficiency are the big advantages, the disadvantage is that changing layouts is often time and labour-intensive.

4.3 Adapting with fixed layout options (large modules)

Building upon theories by Radha (2021) and the MIT media lab (2016) this strategy offers several fixed layouts that the apartment can adapt to, with very predictable results. This approach is adopted by real-world furniture like Bumblebee or ORI which automates the movement of elements with actuators. The elements can be ceiling-mounted storage, beds or tables, movable smart walls and expandable elements. These systems have the advantage that furniture can be located in places that cannot be manually accessed by users easily like ceilings.

While furniture elements come at a higher cost than furniture that does not transform automatically it has the benefit of much bigger convenience. Space adapts by itself and can do so without any user input with machine learning and activity prediction if wanted by the user.

4.4 Adapting without fixed layout options (small modules)

This approach builds upon approaches that use small robots, bio-inspired organic systems or other small building elements. Theoretical projects like the muscle projects by Oosterhuis (2012) as well as research by Lengiewicz and Hołobut (2018) or Suzuki et al. (2020) show the potential of small robots and intelligent materials in test environments. The concept has the advantage that smaller elements always increase the freedom and adaptiveness of space and almost every change could be made. Due to complexity, technological limitations and costs these systems are harder to achieve and less accessible but could on the other hand lead to the most adaptive systems. Whole building parts could appear and disappear according to user needs.

4.5 Virtual Space

The shift of our lives towards the digital space influences architecture on many levels. Extending space virtually while only having the bare minimum like a sleeping capsule in the real world, has limitless options and allows users to live and play in a shared, permanent, and self-sustaining world thanks to the metaverse ecology. While this approach has the problem of dystopian connotation, both physical boundaries and location are irrelevant since everyone is connected with everyone else and can be anywhere (Gibson & Carden, 2018).

5 Conclusion and Further Research

This paper presents a review of existing research studies, links them with projects in the field of smart adaptive homes and attempts to categorise strategies in terms of time that the system needs to reconfigure the space and the sort and size of the elements that are used to do so. Even though a lot of research is carried out around the smart home, it concentrates predominantly on technical improvement (Solaimani et al., 2011) while there is a gap in design-related research, functional maximization and real-world implementation as already pointed out by some researchers (Radha, 2021). Pursuing the need for better space efficiency, more user-centric studies need to be executed and consider different locations of the world since results might be different. Most studies agree that modular smart house architecture should have changeable flexible or adaptive physical areas. While the lack of space is undoubted, and technology should not be the excuse to make spaces smaller per se and there is little available literature indicating how much space is enough to prevent claustrophobic conditions.

Technology has become more than creating gadgets for entertainment, fun or lifestyle and it is essential to stay up with changes in customer expectations and aspirations. Thus, architecture and interior design must employ appropriate solutions to work with, incorporate and benefit from the mentioned technologies. Increasing adaptiveness and reducing fixed residential space layouts can prevent the need for renovations and construction work for possible additions and changes which can be a driver for sustainability and resilience. However, the question of what makes a smart adaptive space successful remains to some extent. The analysis of the smart furniture systems from ORI and Bumblebee shows that while saving floor space, they lack interactivity and have high costs. Terms used for describing models of adaptability are not clearly defined or overlap. They include expressions like ‘adaptive’, ‘interactive’, ‘cybernetic’, ‘automated’, ‘reactive’ and ‘smart’ among others. The categorisation of strategies for the improvement of space efficiency can help future research to test different solutions with users (for instance in VR models). The limitation of a semi-systematic literature review is that it is restricted in the scope of depicting the whole picture since progress in the field is happening fast. For this ongoing research, surveys and experiments with users will be conducted to better understand the user perspective regarding these technologies, especially in micro homes.

The consolidation of the existing body of knowledge also shows that these new forms of urban living (together with micro-living and co-living) can and should be reflected in policies and practices. In the UK for instance the allowed minimum floor area of new apartments of $37m^2$ has been criticised since the quality of the space and its functionality might be more important than its size on paper. Therefore, research in the area of smart adaptive and interactive micro homes has the potential to improve living quality in urban areas and needs to be advanced to reflect the development of technologies.

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Case Study Observations on the Use of Digital Technologies for Onsite Project Success

Hayden Smith[1], Mary Hardie[1*] and Donald Mason[1]

[1]School of Engineering Design & Built Environment, Western Sydney University,
Locked Bag 1797 Penrith NSW 2751, AUSTRALIA

m.hardie@westernsydney.edu.au; donald.mason@westernsydney.edu.au
* Corresponding author

Abstract:
The use of digital technologies plays a significant role in the success of construction projects especially with respect to construction safety. Comparatively recent developments have helped to digitise the industry, introducing new technologies which may involve processes, techniques, software and materials. These advances have brought benefits such as reduced costs, minimised waste production, improved design sustainability and increased levels of safety, efficiency, productivity alongside improved quality assurance. The most common barrier towards adoption of these technologies is a lack of knowledge and understanding of their effectiveness. Three case studies of industrial warehouses built in the greater Sydney area are examined for insights into the relationship between the adoption of digital technologies and project success. The study of project records from these case study projects indicates a consistent use of digital tools such as Build Soft™, Microsoft Project™ and Aconex™ throughout the design and construction phases. The results also suggest possible supporting evidence for a link between project risk and project duration being impacted by the relative adoption level of the digital tools.

Keywords:
Construction management, digital technologies, industrial warehouse projects, onsite project delivery

1 Introduction

The use of digital technologies appears to play an increasing role in the delivery of projects in the construction industry in many countries. This is despite previously reported reluctance towards change from construction practitioners. Although there is a lot of evidence to support their benefits, the use of digital technologies is still not universal throughout the construction industry. According to Blismas and Wakefield (2008), the most common barrier to the adoption of new technologies is a lack of knowledge and understanding of their effectiveness and an inability to realise the many potential cost benefits they can provide to construction projects. The future adoption and implementation of diverse digital tools in construction is largely dependent on the industry's ability to overcome these constraints and realise the potential advantages at all project sizes. Understanding the effectiveness of digital tools, and how they are best implemented is key to their future increased utilisation within construction. The combination of digital tools and techniques, utilised during both design and construction, can contribute to the overall successful delivery of a project. Particularly, in safety matters, the use of digital tools provides construction companies with the opportunity to improve risk management and greatly improve their onsite project safety record. Digital tools can be defined as devices or implements that can be utilised to assist with the undertaking of a specific task or activity. Technology such as mobile-based BIM software and site wearables are just some examples that can be used during the construction phase to improve risk management through early detection of design problems. If implemented correctly, digital tools, like those mentioned above, have the potential to greatly influence the safety outcomes of a project by effectively managing risks and decreasing errors generated during design (Zhou, Whyte and Sacks 2012).

The aim of this paper is to conduct a systematic study into the use of digital tools as instanced in one company's projects in Sydney in the last decade and comment on their effectiveness in improving the onsite safety of these projects. The objectives of this study are to:

1) to speculate that a connection exists between increased levels of onsite safety and the use of digital tools during the design and constructions stages, and
2) to expand upon existing industry knowledge by conveying the benefits, to project safety, of implementing digital tools in all phases of construction via actual project examples.

This study will focus on the industrial warehouse projects. Commercial, residential and industrial construction are all very different, each with its own drivers and barriers. Focusing the scope of the research on industrial construction allows for detailed evaluation.

2 Literature Review

Even though the construction industry has seen a rapid development of digital technologies in recent years, it is still considered to be behind other industries in terms of taking advantage and adopting these advancements. According to Stewart (2017), only about half of the building industry utilises the various digital tools that are available. Some firms are missing opportunities to gain a competitive edge over their competition by not adopting digital tools that have the potential to improve project efficiency and safety. Research conducted by the McKinsey Global Institute that found that less than 40% of building firms are willing to spend more than $500 on purchases that could provide benefits in the form of internet-based or digital technologies (McKinsey Global 2017). This demonstrates the extent of resistance to change among the industry, which is creating a growing technological gap with other sectors of business (Stewart, 2017). As technology transforms the early adopters, construction firms will need to learn to adapt in order to compete in the industry. Swift advancements in construction technology have seen the introduction of digital tools ranging from remote operated aerial drones to Building Information Modelling (BIM) and 3D printing techniques. These digital tools are already being extensively used offshore in countries such as China, where a building firm has been able to design and construct a 3D printed an earthquake-resistant dwelling (Speed, 2016). The implementation of such digital tools is promoting a technologically saturated environment where these products will continue to be developed and adapted to provide further benefits as their widespread use increases.

It is important that construction firms understand the digital opportunities in the building industry and how they can be taken advantage of to increase efficiency and success. The constant development of technology is shaping the construction industry and its operation. According to Cashmore (2018), companies can make use of three different categories of digital opportunities. These are the managing of knowledge, advances in construction sequencing and project life cycle management. Collecting legacy data using BIM, making use of 3D printing techniques and the implementation of observation technology to monitor a building at each stage are all examples of these digital concepts, and the incorporation of all three is likely to be a suitable strategy to exploit these digital opportunities.

Construction project success can be greatly affected by improvements in processes and techniques that can be achieved through the adoption of new digital tools and technologies (Rem, 2017). As a result of design development through BIM, building firms are able to visualise layers of data as a 3D model, at multiple stages of the project life cycle. The design generated in BIM can be shared and viewed anywhere in the world, increasing communication via an integrated environment. Increasing communication and collaboration among management teams can significantly improve project efficiency and reduce risk through early identification of problems.

According to Sun, Man and Wang (2015), BIM can be used in situations where it is difficult to predict or calculate risk due to factors such as project size, insufficient individual practical knowledge or poor risk management tools. Their case study of a hospital building investigated BIM's risk management benefits. BIM allows users to input design data such as cost, measurements and scheduling and can estimate and identify risks to quantities, value and programme that can reduce unnecessary spending and accidents during construction.

The integration of design-based technologies such as BIM often requires adaptation of existing management processes in construction firms. Effective collaboration among building professionals is essential for the successful integration of digital technology (Merschbrock and Munkvold 2015). However, some design and management teams resist adapting to more collaborative work methods as these may require a large departure from their traditional ways of working. The study conducted by Merschbrock and Munkvold (2015) found that implementing a BIM-friendly work environment encouraged design teams to work more collaboratively and effectively. Conversely, Neff, Silfvast and Dossick (2010) argued that even though BIM offers some level of increased communication and integrative properties, many design professionals still prefer to work with paper due to its 'interpretive flexibility'. Although the introduction of new design media has the potential to provide many benefits, it can be seen as very disruptive to some personnel and to the work management landscape.

Despite this residual resistance, industry change has tended to accelerate in recent years. Kent and Gerber (2010), argued that the integration of BIM and team collaboration can be harmonised by means of Integrated Project Delivery (IPD). The American Institute of Architects (cited in Kent and Gerber 2010) defines IPD as:

> *"a project delivery approach that integrates people, systems, business structures, and practices into a process that collaboratively harnesses the talents and insights of all project participants to optimise project results, increase value to the owner, reduce waste, and maximise efficiency through all phases of design, fabrication and construction"*

The integration of digital-based tools like BIM in the construction industry is largely influenced by the level of collaboration demonstrated by design and management teams and is dependent on construction firms being able to adapt their processes to accommodate for the beneficial change.

2.1 Project Success Measurement

As early as 2003, Baccarini described how the successful delivery of a project is significantly affected by communication, the competency of the project team, realistic cost and time projections and shared project understanding. As clear intra-project communication is vital to all projects, it should be consistently prioritised by all stakeholders, at all stages of a project to increase efficiency, decrease confusion and ensure effective teamwork. A competent project team is a crucial part of construction delivery, and how well a team can communicate internally, work as a unit, be productive and maintain focus, has a large effect on the outcome of a project.

Furthermore, the estimated costing and total duration of a project needs to be realistic and achievable in order to ensure that deadlines are met and unnecessary delays are avoided. Additionally, the shared understanding of a project is crucial to its performance (Baccarini 2003).

2.2 Safety and Onsite Project Delivery

According to SafeWork NSW (2018), more than 34,000 accidents occurred on New South Wales construction sites between 2012-2015, with over 33,000 workers injured, over 2000 severe injuries and 33 fatalities. Consequently, it is imperative that construction firms understand and adhere to the applicable laws, as well as plan for all the aspects that relate to onsite safety. The adoption of work health and safety protocols are very high throughout the construction industry, says SafeWork Australia (2015). The study revealed that a large majority of Australian building firms implemented safe work methods including, reducing hazards, reporting of potential risk and the preparation of safe work method statements. This was seen to be higher in comparison to other priority industries, which could be due to the pressing demand for better safe work practices in the construction industry.

The onsite safety of a project can be attributed to multiple external and internal factors. These factors can have a direct or indirect effect on the safety and delivery of a project respectively. According to Gunduz and Ahsan (2018), project onsite safety should be a top priority among workers and should be widely enforced by firms through strict measures and procedures. The results from their research revealed 40 factors that attribute to onsite safety in construction, with adhering to safety rules, adopting Personal Protective Equipment (PPE), safety meetings and encouraging a safe work culture being the most significant. It is important that workers and stakeholders have access to adequate PPE and are made to wear it when required. It is just as crucial that management seek to create an environment that endorses safe work behaviour through methods such as, regular team meetings on safety, enforcement of WHS procedures and communication of safety expectations via signs and infographics.

Lingard et al. (2018) argues that the provision of infographics and other visual stimulants, can be implemented by firms to help promote positive thinking and attitudes towards onsite safety. The investigation found that there is a relationship between positive communication of Work Health and Safety (WHS) practices and increased identification of WHS shaping factors, and the utilisation of infographics by design professionals. Brumberger (cited in Lingard et al. 2018) states that visual stimulants familiarise viewers with different components and encourage 'out-side the box' way of proposing solutions. Therefore, the onsite safety of a project is heavily influenced by a positive safe work environment and procedures. A strong culture of safety has a significant influence on the onsite safety and delivery of a project. This culture can be fostered through the conceptualisation of safety by the site management team (Sunindijo and Zou 2013). Katz (cited in Sunindijo & Zou 2013) defines conceptual skill as one's ability to visualise the entirety of the company and stresses its importance in allowing management personnel to see the 'big picture'. Observing components from different perspectives is critical to the management of onsite safety. The analysis of over 270 survey responses found that the conceptual skill of a site management team is directly dependent on their vision of project goals and outcomes, and the coordination of the construction sequence. Sunindijo & Zou (2013) claim that these components play a big role in implementing safety management procedures, and that site managers must be aware of their effect when organising roles and responsibilities at all stages of the project life cycle.

The importance of a strong culture and climate of safety towards onsite project delivery is further conveyed by Schwatka and Rosecrance (2016). The authors express that project safety increases alongside the climate of safety, and that a management teams promise to safe work methods should be shared to all workers and not just senior members, as workers behaviour can greatly affect a projects culture of safety. A positive appreciation of safety shared by all workers helps to promote improved outcomes during construction. The research conducted by Schwatka and Rosencrance (2016), shows that managements' and workers' perceptions and commitment to safety is a big determining factor towards total onsite safety, and that safe work outcomes rely more on who implements the actions and not just what type of safe management tasks were adopted. Thus, the climate of safety is heavily reliant on the perceptions and views shared by management and co-workers towards work health and safety practices. This culture can be aided by the use of digital technologies.

Risk management, the process or method of identifying, categorising and managing potential risks to a project or workplace, has a key influence on the safety outcomes of a project. The approach of risk management is defined by The International Organization for Standardization (ISO 2009), as being the process of applying a logical strategy to the recognising, classifying and mitigating of possible project hazards and risks. Zou, Kiviniemi & Jones (2017) claim that the introduction of BIM can be used to assist with the risk management process, by allowing users to recognise risks earlier and to better monitor and mitigate hazards through improved communication of project information. Adopting BIM into the risk management process has the potential to lift onsite safety levels, through identification and managing of risks, as well as improved communication of project information between users and construction personnel.

3 Research Methodology

This study is part of an ongoing effort to incorporate the work experience undertaken by construction undergraduates as an introduction to the formal research process. The process of research does not occur within a vacuum. There are often circumstantial factors that are likely to affect the study in some way or shape, such as the outcome of the results. These factors include but are not limited to, the experience and expertise of the researcher, their interests and beliefs, and even their interaction within the physical environment. It is vital to consider these variables when conducting research as they can impact the data recorded. As stated by Popper (1989), research is an open concept that is never closed completely, it is a system that allows for and accommodates factors much like those mentioned previously. Adopting the methodology that is best suited is one way in which these variables can be acknowledged and properly accounted for.

Selecting the optimal research method is crucial to conducting a well-orchestrated study that yields accurate result data. The method of research implemented can also greatly impact the analysis of the results and the overall quality therein. The most common methodologies fall under two primary approaches to research, quantitative and qualitative. These systematic approaches represent the methods most commonly used by researchers and the like. Quantitative studies typically include research that involves numbers and quantities, and are mostly concerned with answering questions such as 'How much?' or 'How many?' (Fellows and Liu 2015). Examples of quantitative approaches include surveys, experiments and questionnaires. On the other side of the coin there are qualitative research methods, which are those that pay closer attention to the how and why? The data received is usually subjective in nature and includes methods such as, case studies, interviews and observation. It is fully conceded that this research is observational in nature. It records the work experience of the lead author as well as his subjective observations on three project sites.

3.1 Mixed Methods Research

According to Smith, Thorpe and Jackson (2012), a mixed method design is ideal in that it incorporates both qualitative and quantitative styles, however, there are important considerations that need to be made in terms of sequencing and dominance. Researchers need to make the decision as to whether qualitative will come first, or if it will follow quantitative, as well as which approach will be more predominant within the study.

The mixed method approach can be further broken down into three distinct designs known as, handmaid, partnership and compensatory designs (Smith, Thorpe & Jackson 2012). Each of these styles are examples of triangulation and implement qualitative and quantitative methods in altering sequences, with each being predominantly qualitative or quantitative or balanced. Research that combines two or more methods in order to complement one another is known as a 'handmaid' design. This design has a clear method sequence with one method being dominant over the other. Studies based on interviews or independent observation, accompanied by a questionnaire survey, are the most common examples of this approach. Studies that follow a 'partnership' design, are those that comprise of more than one method, where each share the same level of importance within the research. For example, using a survey will allow to collect a larger sample of data from responses, but will lack depth, and on the other hand, case studies and interviews will collect data from fewer sources, but in much greater detail (Smith, Thorpe and Jackson 2012). Furthermore, compensatory designs are similar in that the methods used have a balanced level of dominance. Both methods are used in order to account for the weakness of the other. A common use of this format is to support a questionnaire survey by utilising a qualitative method to explain and provide detail inferences to the result data gathered,

Case study research is an in-depth investigation into a specific topic or phenomenon (Yin 2014). Case studies take a theoretical approach to research, in instances where the use of surveys or experiments would not be appropriate. The design of a case study approach can vary depending on the researcher and the contextual factors affecting the study. The researcher must make the decision whether to elect a single case study method, or to conduct an analysis of multiple cases. Further to this, case studies can be that of an exploratory, descriptive or explanatory design, says Fellows and Liu (2015). Exploratory case study research strongly follows a theory or hypotheses which drives the investigation, with the aim being to gain an in-depth understanding of the topic. Descriptive case study research is different in that it is not primarily focused on proving or testing a particular theory or phenomenon, but more on merely detailing it. This is different again in explanatory case study research, which is concerned with answering the question of 'how' or 'why' in relation to a topic of inquiry.

Industrial warehouse projects were selected in order to demonstrate a multiple-case, replication design (Yin 2014), which is where each case is intended to reveal similar or identical findings. Thus, providing a compelling set of project cases that reinforce a specific idea or phenomenon. The case study research will consist of three case studies conducted on three different industrial warehouse projects in New South Wales, with each being completed within 1 year of each other. Each case study will overview the project and the use of digital tools throughout the duration, as well as describe the project delivery and safety outcomes.

The lead researcher for this paper had access to the full project data for the three case study buildings as a result of his employment in the building company responsible for the projects.

He was given permission to use the data for research provided that the company was de-identified. The chosen projects are three different industrial warehouses, located in the Greater Sydney area at Albion Park, Marsden Park and Hoxton Park. The research data has been collected for each individual warehouse, which was then reviewed and summarised to form the three case studies. Once reviewed, the collected data enabled creating the headings that form the principles in the Likert scale that will be used in future quantitative research to critically analyse the information. The case study method was chosen for its demonstrated suitability to previous construction research, as mentioned by Fellows and Liu (2015).

4 Findings and Discussion

The analysis of data is largely qualitative at this stage with some reference to collected quantitative records from project case studies. The major limitation of the chosen method is the possibility of a researcher bias, due the analysis of the data being conducted by the lead researcher. If there were the opportunity for a longer time frame, the ideal design would involve distributing the multiple case studies and having them ranked by several industry professionals to increase the validity of results. It is intended to carry out this process in the future. Table 1 overleaf, presents a brief summary of the data collected from the three independent project cases. General observations on the individual projects are discussed below.

4.1 Hoxton Park

The warehouse design was approximately 13,656 m2 in gross floor area, and incorporated the main trading area, trade centre, garden centre and loading dock, with the external areas boasting a 328-space carpark with associated landscaping. The total project duration was 30 calendar weeks, with only 2 weeks delay due to weather, and ran a total cost of $16 million. The initial project duration was programmed as 37 weeks but efficiency gains meant the warehouse was completed in just 30. There is evidence of adequate utilisation of digital technologies throughout the project at Hoxton Park, some of those being Buildsoft™, Microsoft Project™, Jobpac™, Google Drive™ and Aconex™. There is also a consistent use of everyday tools such as email, internet and Dropbox by each of the onsite and office team. The estimator made use of the Buildsoft Global software during the tender stage of the project, which was implemented to prepare the bill of quantities and the final tender price for the project. The project management team were able to utilise the prepared bills and pricings as a means to monitor the job costings, trade by trade.

Microsoft Project was used during all stages, by both estimating and construction departments. The software was used during the tender stage in order to prepare the initial programme for the project, which was then provided to the construction team who were then able to adjust, monitor and manage the project according to this and subsequent programmes. The other significant tool that was used during the project is Aconex. Aconex, being a procurement and project management software, was used by the construction team to create and distribute trade packages to subcontractors in an effective and efficient manner. The online software then acted as a document control tool, being used to track which documents and drawings had been sent and when, as well as to whom.

This project had multiple safety policies in place such as site safety plans and various WHS management plans for individual trades and high-risk sequences of the project, that all personnel had access to at all times. It can be seen that, the WHS officer onsite, ensured all workers complied to these policies by making them wear full PPE when required (which was almost always). There is also a record of Safe Work Method Statements (SWMS) being completed for each subcontractor and trade working onsite, accompanied by a safe work checklist as a means to monitor and identify trade risks. A constant concern during the project was the potential damage to nearby council footpaths, roads, drainage channels and manhole covers. This risk was managed through the conducting of a dilapidation report prior to site possession and again at the time of practical completion and handover.

Table 1. Summary of Case Study Projects details

Location	***Hoxton Park***	***Marsden Park***	***Albion Park***
Estimated Duration	37 weeks	28 weeks	34 weeks
Actual Project Duration	30 weeks	34 weeks	51 weeks
Weather delays	2 weeks	2 weeks	6 weeks
Gross Floor Area (GFA)	13,656 m2	13,337 m2	13,022 m2
Cost	$16M	$16M	$22M
Project Team	Project Director, Project Manager, Contracts Administrator, Project Coordinator, Design Manager, WHS Manager, Site Foreman, Leading Hand, Site Labourers x 2	Project Director, Project Manager, Contracts Administrator, Project Coordinator, Design Manager, WHS Manager, Site Foreman, Leading Hand, Site Labourers x 2	Project Director, Project Manager, Contracts Administrator, Project Coordinator, Design Manager, WHS Manager, Site Foreman, Leading Hand, Site Labourers x 2
Scope	Construction of a new single storey hardware, building supplies and bulky goods premises with associated external on-grade car parking for 328 vehicles.	Construction of a new single storey hardware, building supplies and bulky goods premises with associated external on-grade car parking for 330 vehicles.	Construction of a new 2 storey hardware, building supplies and bulky goods premises with associated external on-grade car parking for 340 vehicles.
Digital Tools Used	Buildsoft (Estimating), Buildtools (document control), MS Project (Construction programming/time management), Jobpac (procurement/invoicing), Google drive (cloud document control)	Buildsoft (Estimating), Buildtools (document control), MS Project (Construction programming/time management), Jobpac (procurement/invoicing), Google drive (cloud document control)	Buildsoft (Estimating), Buildtools (document control), MS Project (Construction programming/time management), Jobpac (procurement/invoicing), Google drive (cloud document control)
WHS Incidents	No notable incidents recorded	No notable incidents recorded	1. Injured back due to broken truck seat (1 day off work) 2. Laceration to workers lower leg from metal roofing 3. Drum roller tipped over 4. Worker rolled ankle stepping out of excavator 5. Roller backed into fence, crushing a car 6. Asbestos found in the earth
WHS Policies in Place?	Yes	Yes	Yes

4.2 Marsden Park

The project is a retail warehouse of approximately 13,337 m2 in size, with a main trading area, garden centre, trade area, loading dock and external onsite 330 space carparking with associated landscaping. The project duration was 34 calendar weeks, achieving practical completion in March 2015, and costed a total amount of $16 million. The use of digital technologies is quite consistent throughout the project, with the collected data indicating an introduction of tools such as Buildsoft, ArchiCAD, Aconex and Microsoft Project. The Buildsoft Global software was used by the estimating department during the tender stage of the project to complete the final price and bill of quantities for each of the job trades. These bills were then passed onto the construction team to assist with procurement and monitoring of trades. Microsoft Project was utilised to prepare all of the project programmes from design stage through to construction, allowing users to monitor, manage and communicate effectively, regarding sequencing of major activities and trades.

The use of Aconex on the project assisted the construction team in issuing packages to subcontractors and then acting as a document control tool, by tracking all distributed documents and drawings. A branch of this software called 'Bid Contender', was used during the tender stage of the project to distribute tender invitations to subcontractors and monitor incoming quotations for each trade. The collected data identified several WHS incidents onsite, with the most significant being a dumper truck driven into a pit, a scissor lift backed into a block wall and two instances of workers receiving cuts and abrasions from minor falls. These accidents were well recorded and included in the monthly safety reports of the site, which provided well thought out measures to prevent future risk of the same nature. It is important to mention that no loss of time was incurred from any of these incidents, and that the personnel involved were back to work the same day.

4.3 Albion Park

The final chosen project is a retail warehouse store with a gross floor area of 13,022 m2, which is comprised of the main trading area, trade centre and garden centre. The store also has an external on-grade carparking with 340 spaces and associated landscaping to the surrounding area. The project ran for a duration of 51 weeks and cost an approximate total of $22 million to construct. This project was the least effective in terms of time and cost delivery. While similar digital tools were available they were used to a lesser extent in practice. Traditional paper systems were more commonly used due to the preference of some project team members.

5 Conclusion and Further Research

The research commenced for this study is ongoing and will be the object of review and analysis. It is hoped that further detail will be presented in future publications. The present collected data shows that each project is similar in design comprising of approximately 13,000 m2. The records for each project indicate a consistent use of digital tools such as Buildsoft, Microsoft Project and Aconex throughout the design and construction phases in the first two case studies but less consistent use in the third. It can also be seen from the data, that there was a large appreciation for safety across all three projects, with each being supervised by a Work Health & Safety Officer from conceptualisation to completion and there being a record of every WHS incident or issue encountered. The results also suggest possible supporting evidence for a link between project risk and project duration, however, the case study data would require further analysis and investigation before any concluding remarks can be made. There are various themes that can be seen from the current results that suggest a link between safety outcomes and tools and techniques implemented. The results though not complete, still provide supporting evidence for the value that digital tools can provide to project delivery. The collected project data will be critically analysed to finalise and complete the results chapter of this study. If it were not for such a limited time frame, the project data could be analysed to make inferences to outcomes of not only safety, but project scheduling, cost savings, communication and efficiency as well. The time restraints on this research also limit the volume of case study data that could be collected and analysed. A recommendation that could be utilised for future research, would be adopting a design that analyses data from multiple projects across different sectors of construction, and that compares various project delivery outcomes such as, time, money and success. This research is part of an ongoing endeavour to incorporate the work experience of undergraduate students in a collective process of reflection that can lead to quantitative comparisons as well as time-based analysis of workplace change for construction students.

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Theme:

Industrialisation of Construction

A Conceptual Model to Compare the Pipeline and Sector Information in the Construction Industry

Arun Kumar Manickavasagam[1*], Mostafa Babaeian Jelodar[2], Monty Sutrisna[2], Azam Zavvari[2], and Teo Susnjak[3]

[1]Department of Civil & Natural Resources Engineering, University of Canterbury, Christchurch 8041, NEW ZEALAND
[2]School of Built Environment, Massey University, Auckland, NEW ZEALAND
[3]School of Mathematical and Computational Sciences, Massey University, Auckland, NEW ZEALAND

arun.manickavasagam@canterbury.ac.nz*; M.B.Jelodar@massey.ac.nz; A.Zavvari@massey.ac.nz; M.Sustrisna@massey.ac.nz; T.Susnjak@massey.ac.nz

* Corresponding author

Abstract:
Responding to the various issues facing the construction sector in New Zealand, particularly the imbalance between the demand (pipeline projects) and supply (the construction sector's ability to deliver), a research project has been developed focusing on the construction supply-demand by evaluating the pipeline of construction work in New Zealand. This is an integral part of the New Zealand Government funded CanConstructNZ research programme to assess and enhance the capacity and capability of the New Zealand construction sector. Due to the complex and dynamic nature of these problems, a system dynamics (SD) model for comparing information from both pipeline and sector sides is explored. In particular, the dataset from the Ministry of Education (MoE) was used as a case study example to illustrate and demonstrate the pipeline sub-model. Whilst it was demonstrated that SD holds the potential to be used as the modelling tool, future research will involve more comprehensive and holistic view of the pipeline sub-model. This includes further development of the supply sub-model thus allowing a comparison between the pipeline and sector information.

Keywords:
construction sector, case studies, data, demand, supply.

1 Introduction

The New Zealand construction sector suffers from poor productivity, high staff turnover, low skills and is constrained by a lack of innovation. Regular failures of companies lead to job losses, wasted resources and low confidence in the public sector (Wilkinson, 2017). With $42bn worth of construction projects estimated over the next 25 years (MBIE, 2017), a key question from Government and the sector is: How ready is the New Zealand construction sector able to deliver the next 25 years of construction projects?

This research is intended to enhance the sector's ability to deliver, by creating a smart system called CanConstructNZ, to model the dynamic inter-relationships of government and development needs (the proposed construction and infrastructure) against the construction sector's ability to deliver (capability and capacity including: procurement & processes, supply chain & organisations, people, and technology & tools). CanConstructNZ will provide the industry with a robust and practical way to address limitations/constraints in capacity and capability for delivery, and ensure government realises the potential of the sector for the completion of projects. The system will identify the gaps in capacity and capability to be clearly mapped against the needs of the future construction projects, providing solutions to address the difference between infrastructure and construction needs and industry delivery whilst optimizing solutions so that future construction projects can be delivered efficiently, effectively, sustainably and safely.

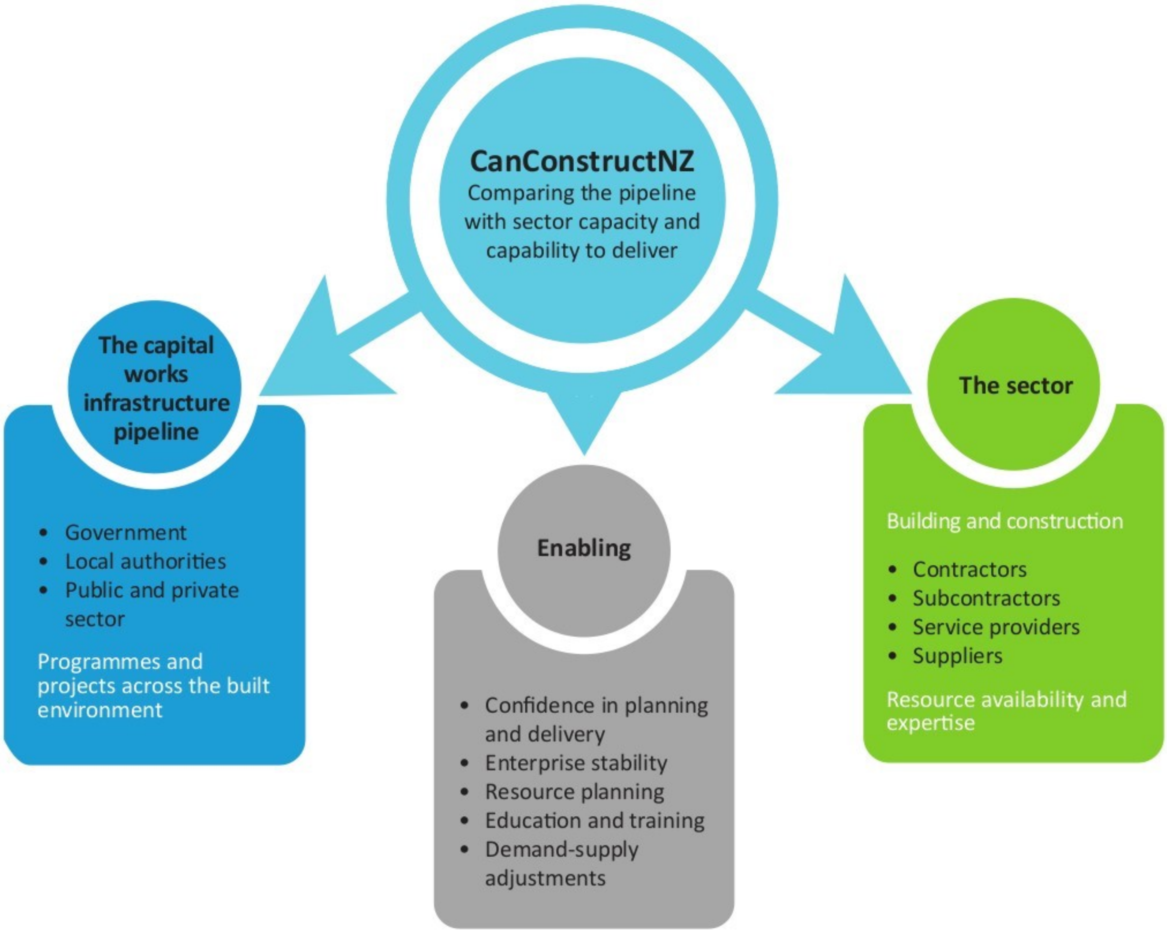

Figure 1. Schematic of the CanConstructNZ system.

It has been identified that the New Zealand construction sector faces a challenge delivering its proposed pipeline of work emerging since 2020 onwards and the situation is further exacerbated by the post-COVID-19 recovery funding initiatives. To tackle the challenge, we develop a smart system called CanConstructNZ – a partnership between New Zealand Universities and BRANZ, that will enable a shared understanding of horizontal and vertical infrastructure planning and the sector's ability to deliver (Figure 1). The significance of the study here is reflected by the fact that CanConstructNZ is the first in-depth evaluation and mapping of the entire New Zealand construction sector against the whole country's pipeline projects. This paper signifies the first steps taken in the research project to explore the potentials of using a particular modelling approach known as the System Dynamics (SD) modelling to develop a conceptual model to relate and compare information from both pipeline and sector sides.

2 System Dynamics Modelling

System Dynamics (SD) is a simulation-based modelling approach based on feedback systems theory that complements systems thinking approaches. It applies to dynamic problems arising in complex social, managerial, economic, ecological and physiological systems. It is a well-established and valid approach for analyzing the management of complex environmental systems. Examples include water resource management (Simonovic, 2002, Stave, 2003), agriculatural development (Saysel et al., 2002) and global climate change (Sterman, 2011).

Community-based systems dynamics (CBSD) extended Group model building (GMB) to focus explicitly on the inclusion of community members throughout the modelling process. “CBSD is about building the public constituency to support the policy reversals that can address the root causes of dynamic problems from a feedback perspective. It is about engaging communities, helping communities cocreate the models that lead to system insights and recommendations, empowerment, and mobilizing communities to advocate for and implement changes based on these insights” (Hovmand, 2014, p. 6). The dynamics of innovation system within the project system is demonstrated using causal loop diagrams (Jelodar et al. 2018). Project management often encounters problems such as cost overrun, schedule overrun, delay in material supply, and loss of productivity. A systems dynamic model of the construction material supply chain (CMSC) in Engineering, Procurement and Construction has been presented capturing the attributes relevant to the foregoing problems and the policies that are expected to overcome these problems (Bajomo et al., 2022). A causal loop diagram (CLD) was established using the ST technique following the investigations on causative influencing factors affecting construction profitability through a comprehensive literature review and the integrated effect was quantified using SD modelling. This study ultimately is helpful to field professionals with profitability-influencing factors, diagnosing issues, and integrating impacts regarding decision-making and policy formulation (Shah Jahan et al., 2022).

Existing literature has demonstrated that SD modelling is applicable to workforce planning, however, most works restrict their focus to a single organization. Parker and Caine (1996) focused predominantly on modelling staff promotion within a single organization which initiated the application of SD to Workforce Planning (WP). Expanding upon this work, Hafeez and Abdelmeguid (2003) developed a model illustrating the relationship between recruitment, training, skills, and knowledge in a causal loop form. Mutingi and Mbohwa (2012) developed training strategies for a single organization by combining fuzzy SD and optimization techniques. Alvanchi et al. (2012) also applied SD modelling to study the dynamics of construction workforce skill evolution and understand how a company’s human resource policy affects the project’s performance and cost.

Sing et al. (2016) developed a SD model for WP across the entire construction industry as opposed to a single organization. The model was tested and resulted in formulating training policies thus ensuring workforce equilibrium and nurturing sustainable infrastructure development. Social and business systems are by their nature unpredictable in the absolute sense (Meadows 2008). So, while all models are wrong (Box 1976), as they cannot generate precise point-predictions of future events in social systems, the challenge is to create models that are useful through extensive testing, benchmarking against available data and continually iterating (Sterman, 2002).

The system dynamics modelling is a five-stage iterative process (Duggan 2016). The five stages involve articulation of the problem, proposing dynamic hypothesis, building simulation model, testing simulation model and designing and evaluating policies. The first stage involves defining the problem which includes selection of variables. In the next stage, a dynamic hypothesis is proposed which is best expressed using visual representative tools. With the variables and feedback loops identified, the next stage results in formulating a simulation model. The fourth stage involves testing where the behaviour of the model is tested against reference models. In the last stage, a scenario analysis is performed to observe the potential impact of policies. Following this, consultation with concerned parties can take place to agree upon action points and implementing the same to effect in the real world.

Causal Loop Diagrams (CLDs) and Stock and Flow Diagrams (SFDs) are the two commonly used approaches of illustration for systems dynamics. CLDs are qualitative in nature whilst SFDs are quantitative. CLDs are visual representations of dynamic influences with inter-relationships amongst a collection of variables. In this paper, a simplified CLD is presented for the model development in the next section. They are used to qualitatively capture structures and interactions of some key variables identified and the associated feedback loops. However, they lack detail and are not easy to conceptualize.

3 Model development

The system consists of pipeline submodel and sector submodel. SD model developed in this study is restricted in scope to pipeline sub-model with Figure 1 illustrating a simplified causal loop diagram (CLD) of the proposed sub-model. CLD is used to represent the feedback loop systems diagrammatically. It is a communication tool describing the basic causal mechanisms hypothesized thus generating the dynamic behaviour of the system over time. A feedback loop consists of cause and effect variables with arrows connecting them. A polarity is assigned, either positive (+) or negative (-), thus indicating the relationship between cause and effect. In addition, a delay can be added to the loop to incorporate delays within the system. As an example, this could account for the delays when assessing labour shortage and implementing training policies for the supply of new labourers. The balancing loop represents the workforce demand condition of construction workers. If the workforce gap increases this leads to a reduction in construction works thus reducing the demand for construction workers.

Ministry of Education (MoE) is chosen as a case study example to demonstrate the pipeline submodel. The MoE is the Government's lead advisor on the New Zealand education system, shaping the direction for sector agencies and providers. Projects in the pipeline within MoE are either at the tender or contracting stages. Whilst the collected datasets span across the entire country with readily available pipeline and sector information with wide ranging projects, the MoE data used in this paper was focused on the subsets that have been verified, which was the pipeline projects in Auckland and Northland region of New Zealand, as the data indicates that the majority of the projects are focused in the Auckland region at 89% (Figure 1). This particular subset includes projects in the pipeline from 2021 until 2024.

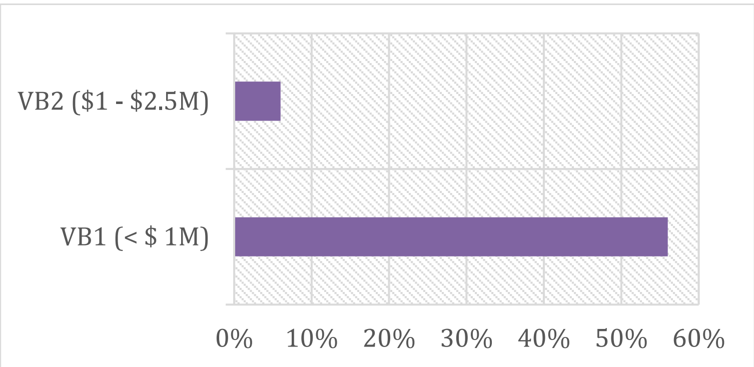

Figure 2. Pipeline projects in Auckland and Northland regions from 2021 until 2024.

MoE uses a value band system to categorize the value of pipeline projects as shown in Figure 2. For instance, VB1 (< $1m), VB2 ($1m - $2.5m), VB3 ($2.5m - $5m), VB4 ($5m - $10m), VB5 ($10m - $15m), VB6 ($15m - $25m) and VB7 (> $25m). The pipeline dataset encompassing Auckland and Northland region indicates that the total cost of the project from 2021 until 2024 ranges from 344,500,000 NZD to 789,000,000 NZD based on the value band system listed above. The majority of the project costs (56 %) in the Auckland region fall within VB1, whereas only 1% falls under VB7 with 13% of the project costs not available as indicated in Figure 3.

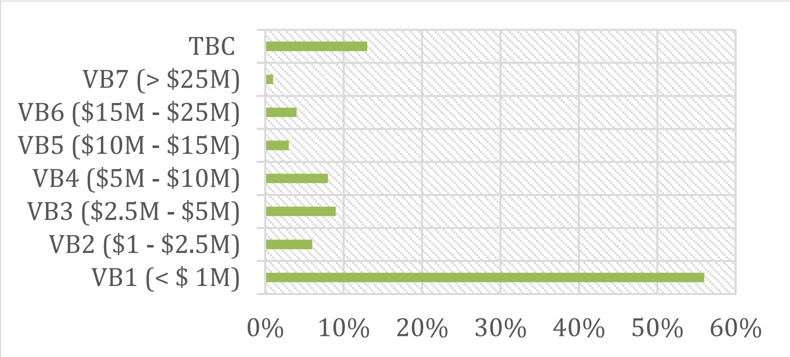

Figure 3. Classification of project costs into value bands in Auckland.

The primary variables for the pipeline submodel have been identified as workforce demand, workforce gap, delays and value of work performed. The loop loosely represents the workforce need in the construction industry. The overall construction demand value (in NZD) informs the workforce demand whereas project type, location, status and duration impact the workforce gap.

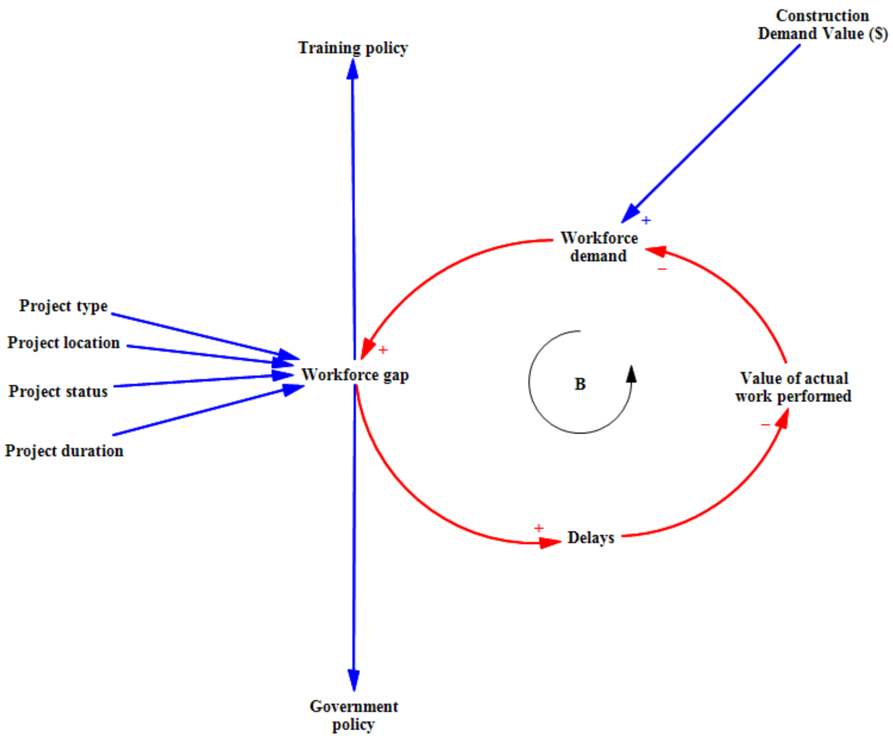

Figure 4. Causal loop diagram of the pipeline submodel.

Further, secondary variables can be classified as training levels, immigration policies and the different factors that could cause delays, i.e. COVID, border closures and supply chain disruption. The details are listed in Figure 5 below.

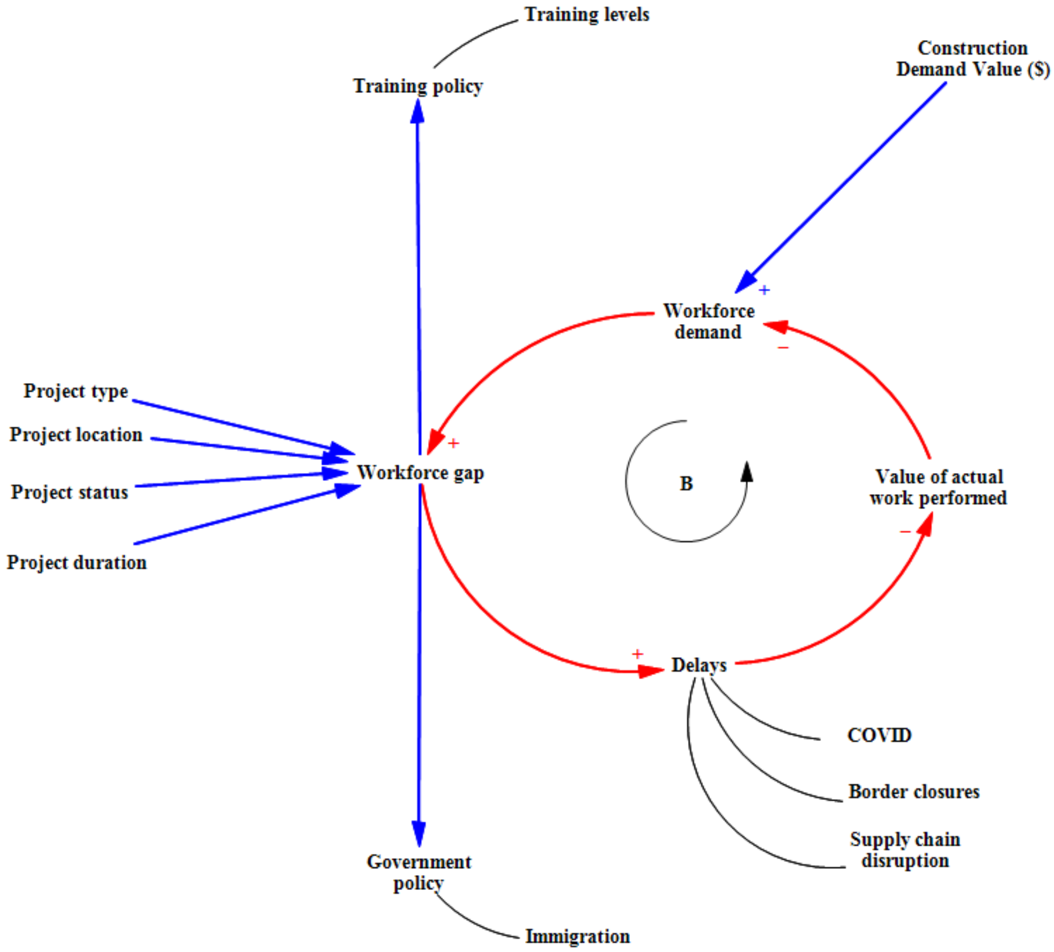

Figure 5. CLD with secondary variables.

4 Discussion

Existing literature has shown that if the workforce gap increases, new construction projects will be suspended due to shortage of workers. This leads to reduction in construction work which in turn reduces demand for construction workers (Sing et al., 2016). A simplified sub model of the pipeline is the focus of this study with initial variable in the literature and further variables incorporated in the system. From Figure 4, it is observed that as the demand for labourers increases, the workforce gap widens resulting in delays in construction projects. With increasing delay there is a reduction in the value of work performed (proportional to the amount of construction work performed). Given the number of negative cause-effect relationships in the loop indicated by red, it results in a balancing loop in the counter-clockwise direction denoted by "B". The loop in turn informs the appropriate training and government policies.

Golden and Skibniewski (2010) analysed the impacts of immigration on construction project costs in the United States. COVID-19 pandemic has had a standout impact on the construction sector resulting in increased cost of material due to supply shortages. It has also created greater uncertainty in forward work pipeline. Also, not having accessing to international skilled labourers impacted the industry by 30% (Rethinking Construction, 2021).

In Figure 5, the list is expanded to include secondary variables, i.e. training levels impacting training policies and immigration impacting government policies. A linear relationship between workforce demand and gap is not always true as there could be multiple factors impacting the workforce gap. For instance, if the workforce demand is impacted by COVID, then an added factor will not result in a linear relationship between workforce demand and workforce gap.

Also, delays could be due to various shocks and stresses (secondary variables), for instance, supply chain issues, immigration (border closures), COVID etc. and each of these needs an in-depth investigation on how it impacts delays. Such shocks and stresses should be quantified via a survey method involving a core questionnaire adjusted to suit each distinct sample group. Shocks and stresses could be varied in nature, i.e. organisational, technological, political, socio-economics and external hazards. A more detailed list could include supply chain issues, skills shortage, boom-bust cycles, climate change, work onsite, remote working, policies at various lockdown levels, decreased/increased economic activity. External events/hazards could be weather related events, flooding, wild fire, elections, failed infrastructure, demographic changes, urbanisation and contractual issues. Since the majority of the works are focused in the Auckland and Northland regions saturation of labourers in a location (location saturation) could have a significant impact on the workforce gap.

5 Conclusion and Further Research

In this work, the Ministry of Education is used as a case study example to demonstrate the pipeline submodel. A systems dynamic modelling approach is used listing the primary, secondary and tertiary variables. The impact shocks and stresses, i.e. delays for instance could have on the system can be noticed from the CLD. The novel contribution of this work is to demonstrate the potentials of developing a systems dynamic model specific to New Zealand construction industry using specific dataset available (i.e. the MoE dataset) with specific attributes/factors identified as essentials to the development of the CLD. This has allowed the research team to move forward with expanding the datasets to cover other types of projects with the view to cover all project types across New Zealand.

However, a more comprehensive and holistic view of the major causal loop dependencies that exist within the pipeline submodel is required as part of further research investigations. Also, CLDs are ambiguous, lacking in detail and are not easy to conceptualize. Systems dynamic simulation will be also developed in the form of stock and flow variables with respect to the supply sub model. Stock variable describes the system’s state and the flow variable represents the rate of change.

As a next step, model validation is required to build confidence in model predictions and to gain a deeper understanding of the system. Then, scenario analysis can be performed to explore how each of the variables listed impacts the system. As an example, the base pipeline value can be held constant to see its effect on the system and other variables in the system can be altered to see their impact on the base pipeline value. Further, a supply submodel should be developed that will then allow a comparison between the pipeline and sector information.

6 Acknowledgement

The paper acknowledges the funding from the New Zealand Ministry of Business, Innovation and Employment (MBIE), Endeavour Programme Research Grant. Contract Number: MAUX2005

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Opportunities for Innovation Competitions for the Australian Construction Industry

Christopher A. Jensen[1*]

[1]Melbourne School of Design, Faculty of Architecture Building and Planning University of Melbourne

cjensen@unimelb.edu.au

*Corresponding author

Abstract:

A large body of knowledge exists relating to the theory of innovation as well as its practical implications. In recent years large scale global technology innovation prizes have become common as a strategy to develop and test innovations, with the rise in success of the format being attributed to the use of the internet, allowing a greater global participation. These large-scale competitions have attracted the attention of many different industries, to the point that U.S. government agencies now use innovation prizes as a procurement strategy. In contrast, construction industry competitions are relatively limited and concentrated at the design stage such as architectural design competitions. This study uses conceptual analysis to understand the relationship between established strengths and weaknesses of the Construction industry, and the essential criteria for industry competitions defined by the Staged Competition Innovation theory, which presents three key principles that lead to a successful industry competition, including 1) a new mechanism for innovation, 2) A unique competition environment, and 3) A pathway for industry adoption. The analysis presented shows that a successful construction competition must be closely aligned with the regulation and practices of the industry to be adopted, and favours organisations with an innovative culture and top management support. Attributes from a construction competition to be avoided would include onerous upfront financial commitments, risk to intellectual property rights and omission of the suppliers and subcontractors in the tasks.

Keywords:

Construction Industry, Construction Innovation, Innovation Competition

1 Introduction

Despite many successful technological innovations to address industry needs, innovations are not always diffused well through industry. The construction industry is repeatedly found to have lower overall rates of adoption of innovation than other industries (Dibner & Lemer, 1992; Johnson & Tatum, 1993; Slaughter, 1993). So despite being described as “a lively source of new ideas”, a general conclusion is that “the rate of innovation lags behind most other sectors, and appears to be falling further and further behind” (Winch, 1998).This lack of adoption leads to reduced productivity and other external considerations such as climate change. Geopolymer concrete is just one example of a construction related radical innovation available to reduce emissions in the construction industry but blocked by seemingly insurmountable barriers. Geopolymer concrete provides an estimated 26-45% reduction in CO_2-e compared with ordinary Portland cement (OPC) (Turner & Collins, 2013), and concrete is the most widely used construction material in the world, with current consumption of 1 m^3 or more per person per year (Gartner, 2004), suggesting that geopolymer concrete should be adopted quickly in order to address these environmental issues. Within the construction industry, widespread adoption of such materials has not occurred due to a combination of financial, technical and institutional barriers inherent to the industry (Berndt *et al.*, 2013), suggesting that other pathways to adoption are required, potentially including innovation competitions.

2 Literature Review

2.1 Construction Innovation

Extensive historical research (Tatum 1986) has comprehensively summarised construction industry innovation into strengths and weaknesses. With regards to strengths, Tatum highlights project organization, necessity and challenge, engineering and construction integration, low capital investment, capability and experience of personnel, process emphasis, and variation in methods. Highlighted weaknesses include investment reluctance, competitive conditions, institutional framework, seasonal and economic cycles, and role of suppliers. This summary shows clearly the static nature of the construction industry, which is a result of reluctance to innovate due to lack of incentive, institutional barriers, competitive conditions and reliance on small suppliers within an inflexible environment.

In the Australian construction industry context, Blayse and Manley (2004) describe a structure of six main factors that influence innovation: clients and manufacturers, structure of production, relationships between individuals and firms within the industry and between the industry and external parties, procurement systems, regulations/standards and the nature and quality of organisational resources. Also Australian specific, Loosemore (2014) cites: leadership, competition, projects, fragmentation, governance and regulation, attitudes, and people as important factors. Winch (1998) claims a highly relevant driver of innovation within the construction industry to be clients, described as “one of the most striking themes running through the literature”. Despite being hard to measure and highly variable between industries, innovation is critical to the advancement of an industry and this is most evident by the focus put on the topic by Government, industry and researchers. Although hard to target, higher risk radical innovation is the most likely source of dramatic change within an industry.

A more detailed study by Manley (2006) reports on a survey that showed obstacles in the Australian construction industry to be: cost of initiative (33%), insufficient time (29%), lack of skilled staff (9%), conservative stakeholders / clients (8%), insufficient benefits (6%), inadequate government support (5%), low volume of available work (3%) and poor staff attitudes (1%), indicating not surprisingly that cost and time are the major obstacles (Figure 1). The uniqueness of the industry has resulted in some variations from the more common innovation types (Slaughter, 1998), notably modular, architectural (component based) and complex products and systems (CoPS) (Hobday, 1998), but none are inducive of significant change.

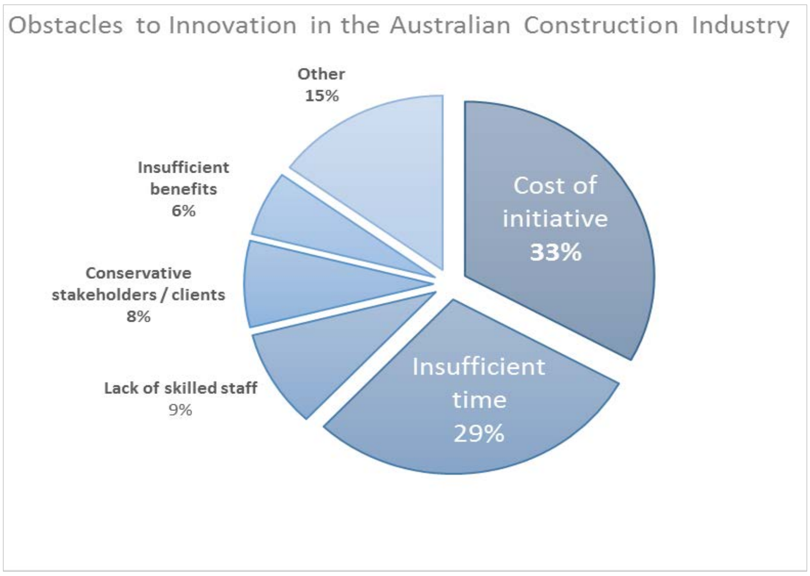

Figure 1. Obstacle to innovation in the Australian Construction Industry adapted from Manley (2006)

2.2 Innovation Competitions

In the last two decades large scale global technology innovation prizes have become more common, with the rise in success of the format being attributed to the use of the internet, allowing a greater global participation. Such contests have large prize money attached, over 20 million dollars (US). These large-scale competitions have attracted the attention of policy makers to the point that U.S. government agencies now use prizes more commonly (Stine, 2009). Kay (2012) comprehensively analysed of the prize incentive category and the research findings show that there is a wide range of motivation and benefits for an entrant to participate and notes the importance of entrants from outside the field, with non-monetary incentives shown to have the greatest incentive power, and that the effect on innovation of the prizes is determined by the prize incentive, the gaps in technology, the definition of the challenge, and the openness of the rules. A key finding of this extensive research on prize incentivised challenges is that they can induce innovation over and above what would have occurred anyway, suggesting that competitions as an innovation pathway are a viable option for industry to pursue. Despite the rise, innovation derived from such competitions does not always get adopted by the parent industry, thus questioning the value of competitions as a valid pathway for innovation. Globally, and within Australia, the most notable construction industry competitions are architectural design competitions (ADC) which can generate a broad range and high level of innovation in design solutions (AIA, 2016). ADC’s are focussed at the early stages of innovation, with successful competition winners following a typical construction procurement process through to completion, and are therefore of limited relevance to this research of innovation adoption.

The Staged Competition Innovation (SCI) Theory (Jensen, 2021) was specifically developed to explain the beneficial pathway and opportunities for innovation provided by a competition platform within an existing industry. The theory is divided into 3 core principles that explain how an innovation competition can; 1) create a new mechanism for innovation, 2) provide a unique competition environment that can increase innovation development, and 3) create a return pathway for innovation back to the parent industry. The principles are defined by the associated factors derived from the Technology-Organisational-Environment (TOE)

Framework which define the Factors affecting the success of an innovation in an industry (Tornatzky, Fleischer, and Chakrabarti, 1990).

Table 1. The Staged Competition Innovation (SCI) Theory

	Principle 1: Incentive to Innovate	Principle 2: The Competition Environment				Principle 3: Adoption Pathway
Factor	**1. Agile Regulations**	**2a. Co-Dependence**	**2b. Relative Advantage**	**2c. Dynamic Rules**	**2d. Competition Frequency**	**3. Adoption**
Technology	Opportunity Technological readiness Compatibility	-	Relative advantage	-	Observability Trialability	Relevance
Organisational	Leadership Top management support Size	Collaboration	-	Prior experience Innovativeness	-	Financial resources
Environmental	Industry structure Innovation opportunity Dynamic regulatory environment	-	Competitive pressure	Large solution space	Repetition	Market pressure * Supplier support *

* Factors are a feature of the parent industry environment.

The combination of a relatively low innovation rate in the constrained Australian construction industry provides a strong opportunity to utilise the innovation competition format in order to determine the opportunities for innovation competitions within the Australian construction industry, the strengths and weaknesses are compared against the relevant TOE factors identified in the SCI theory.

3 Methodology

Conceptual analysis is used to explore concepts and relationships identified in historical text; in this case key literature that address the topic of construction innovation competitions, including 1) the Construction industry strengths defined by Tatum (1986), 2) relevant TOE factors (Baker, 2012) and recent theories about innovation competitions (Jensen, 2021). The goal of concept analysis as an exploratory method of enquiry into a given field of interest is to improve the understanding of the ways in which particular concepts are connected and communicate ideas about the field (Jackson, 1998). Relational analysis of concepts is used to establish if a correlation exists and if so to what extent.

4 Results

The following table presents the strengths and weaknesses of the construction industry identified by Tatum (1986) aligned to the SCI theory principles (Jensen, 2021) and relevant TOE competition factors that describe the requirement of the industry (E), firm (O), or technology (T) for innovation to occur (Baker 2012).

Table 2: Construction Industry strengths and weaknesses with TOE Factors and SCI theory Principles

Industry Strengths (Tatum 1986)	Relevant TOE Factor (Baker 2012)	SCI Theory solution (Jensen 2021)	
Project organization	Top Management Support (O)	Principle 1 - Incentive to Innovate	Industry leadership by the organiser and motivated firms result in a willing engagement into an innovation intensive environment for both parties
Necessity and challenge	Innovation Opportunity (E)		
Low capital investment	Technological Readiness (T)		
Engineering and construction integration	Collaboration (O)	Principle 2 – Competition Environment	Competition design can exploit the solution space size to achieve certain targets with the rules of the competition The frequency of events is closely linked to the rate of innovation development
Capability and experience of personnel	Prior Experience (O)		
Process emphasis	Repetition (E)		
Variation in methods	Innovativeness (O)		

Industry Weaknesses (Tatum 1986)	Relevant TOE Factor (Baker 2012)	SCI Theory solution (Jensen 2021)	
Institutional framework	Industry Structure (E)	Principle 1 - Incentive to Innovate	Reduced barriers to innovate through independent agile regulations enable continual and more radical innovation by teams competing
Seasonal and economic cycles	Industry Structure (E)		
Competitive market conditions	Pre-existing Competitive Pressure (E)	Principle 2 – Competition Environment	The organiser must balance competitive pressure with individual potential for relative advantage
Investment reluctance	Low Financial Resources (O)	Principle 3 – Pathway to Adoption	Relevance is critical for the innovation to be adopted by the parent industry
Role of suppliers	Lack of Supplier Support (O)		

Table 2 demonstrates how the strengths and weaknesses of the parent industry environment identified from the literature can be aligned to the principles of the SCI theory, citing competition innovation relevant TOE factors. Industry strengths align well with Principle 1 and 2 of the SCI theory, which highlights the importance of a competition to industry and firms as a new innovation mechanism, and for the application of a competition environment to increase innovation. This alignment is most associated with the organisational innovation readiness in construction firms combined with opportunity. This alignment between industry strengths and innovation competition suggests a strong opportunity for an increased use of innovation competition that that aligns the competition outcomes with the needs of the organisations. For example, the competition should be designed to be closely aligned with current industry regulation and practices. Industry weaknesses are relevant to all three of the SCI principles but most closely associated with the industry environment context, specifically financial resources, time and industry barriers including regulation. This alignment highlights an opportunity to utilise a custom designed competition environment that avoids the barriers of the parent industry, specifically, financial constraints, pre-existing competition pressure, supplier support, static regulations and industry structure. Opportunities for adoption from a competition are particularly impacted by the industry weaknesses, and this needs to be addressed by either closely aligning the competition with the technical constraints of the industry (such as regulation) or ensuring the innovation that results from the competition can be modified to suit the industry needs very easily.

The practical application of this is achieved by providing firms the opportunity to develop innovations in the way they already know how to do but with the freedom of a competition environment that is not held back by inherent barriers, involves the suppliers, and has financial value. Financial value is less likely to be from marketing benefits in the short term and instead will be derived from the R&D nature of prototypes resulting from the competition, however as the competition reputation develops the monetary and non-monetary value assigned to participating and winning the competition will shift in value. Attributes to be avoided in a construction competition would include onerous upfront financial commitments, and omission of the suppliers and subcontractors in the tasks. The competition must address the negative aspect of the institutional framework in the parent industry and economic conditions that might prevent an entrant from participating in the competition. Such issues could be addressed by minimising the financial and resource commitment by creating a multistage competition that allowed ‘opt-out’ opportunities to avoid any requirement for firms to commit to a long timeframe.

5 Discussion

5.1 The case for competitions in the construction industry

Both safety and environmental concerns are good examples of industry challenges that require co-ordination across projects, governments, policies and firms, and are unlikely to be comprehensively addressed at the firm level in the absence of an incentive or regulation. The current industry response to such challenges is to cautiously implement regulation to address such issues without harming the financial viability of the firms within the industry, resulting very slow progress. As construction competitions for innovation outcomes are still in their infancy, advocacy is required for the beneficial use of competition in industry to drive Government or industry bodies to act as organisers and champion these issues. Such leadership to acknowledge the potential of the competition mechanism as a valuable pathway for innovation in the Australian construction industry will establish a co-dependence and result in a greater uptake of the mechanism to drive innovation. A structured approach to the design and implementation of a series of competitions will assist in improving this perception, leading to competitions that will create a demand for innovation that does not otherwise exist in the parent industry. This approach is suited to public good innovations such as environmental or safety initiatives that will demonstrate the value of the competition environment that can operate independently of the parent industry to achieve innovation goals. This outcome represents the desired outcome for the Australian construction industry that innovation goals can be targeted and achieved independently of the needs and barriers of the parent industry and firms. This extends to new radical innovations that would likely not be otherwise pursued.

This is how the competition environment encourages innovation with a rate and radicalness of innovation beyond what is possible in the parent industry. Competition to achieve such innovation is only possible if the competition rules are structured to bypass the same barriers that originally prevented the innovation. Although the key barriers to innovation within the Australian construction industry of time and cost (Manley, 2006) are not avoided completely in a competition environment, the competition environment can be designed to work around these barriers. The right competition environment can provide the incentive for unique teams and can encourage the provision of time and financial resources to the competition. In the case of Geopolymer concrete, a competition design that addresses the industry concerns of time and cost will potentially result in increased adoption by the firms. A competition that is highly valued by firms within industry is one that has significant industry support where the parent industry recognises the value of the original need or challenge identified by the organiser, demonstrating the importance of leadership by the government and industry bodies.

Based on the strong case that can be made for industry-based competitions, at the surface it is unclear why they are not in more widespread use in construction. However, when considered at a closer resolution, the lack of knowledge of the industry of the competition environment as an innovation mechanism is a clear issue. The construction industry instead favours industry-based awards programs which retrospectively award projects at competition. The benefits to firms of awards programs includes the lack of a modified competition environment - the entry criteria is same as the parent industry project criteria and the normal rules apply. There is minimal additional time or cost involved outside of compiling the submission in an awards program but the potential for marketing benefits exists even without much challenge. Awards programs are not easily able to address the more challenging industry needs, and there is no collaboration for innovation outcomes required between teams and the organiser. Consequently, awards programs are beneficial to teams but provide minimal motivation for innovation development or advancement of industry needs. The popular use of awards rather than competitions in the construction industry indicates that there is a lack of leadership in addressing industry wide challenges, and therefore limited supported from an overarching body that is taking the lead role of innovation co-ordinator and organiser of construction competitions.

5.2 Perceived value of competitions by teams

The existing literature of prize competitions is primarily focussed on the issues related to the teams in a competition. Although the focus of this present research is on the industry level issues and benefits, it is widespread involvement of teams in the competition that is critical for success. In contrast to grants or funding programs which represent comparative certainty, participants in competitions are cautious about the relative unpredictability of when and to who prizes will be awarded (Leonhardt, 2007). Another significant barrier to competition entry is the potential for a negative outcome for the team. This can occur in two ways, firstly by the inadvertent sharing of the intellectual property (IP) to the other competitors - this of course is most relevant when the competition is within the parent industry and the teams are firms from the industry although the construction industry is noted to be a less patent intensive industry (Terzis, 2022) . Secondly, the potential negative outcome of poor performance or losing the competition. The first barrier, which is best defined as the loss of IP, is addressed in the parent industry through the use of the patent system, which protects inventions by firms and is intended to stimulate R&D, although this belief is under scrutiny (Davis, 2002). From an industry perspective in pursuit of widespread use of an innovation, the patent system is a barrier to diffusion and adoption, due to the restrictions it creates for use by other firms, thus the strength of this system is the commercial protection to firms that innovate, rather than to industry goals. This suggests that the benefits of the patent system are primarily for the commercial protection of a firm, and not in the best interests of the industry and widespread adoption of innovation. Innovation from competition cannot be easily protected using the patent system as the competition process specifically results in the sharing of the design or idea through the competition display, if not judging criteria. Competitions are often deliberately an open-source format of innovation (Kay, 2012), therefore, alternate IP protection strategies are required to maintain the commercial relevance of the competition. In some innovation competition examples, the IP is owned by the organiser. Under this arrangement, it is the competition prize that forms the ‘payment’ for the IP, and the organiser takes the risk as to what will be received. This arrangement favours competitions that address ideas generation, where teams are less likely to have well resolved design that could be commercialised but can still benefit from financial compensation through the prize money for their effort. In the case of competitions that address the later stages of innovation from which teams have greater potential to commercialise, the competition organiser can choose to allow IP to be retained by the teams, as is common with architectural design competitions. This approach means that the competition is a platform for innovation development, testing and publicity, with potential future commercial benefits. This approach requires the teams to accept the risk of the potential for sharing of IP during the competition as a result of the inherent observability. The second barrier to participation by teams is the negative impact from poor performance can be addressed by awarding the top three entries, and not ranking the remaining entries. Under this arrangement, poor performing teams are not individually highlighted, they are simply one of the entries that did not win, as is the case in architectural design competitions.

Despite the opportunities and solutions proposed, adoption to the parent construction industry is likely to remain a key challenge for innovation competitions to demonstrate their value. The construction industry is potentially one of the most difficult industries to address the barriers of adoption from competition given the scale and cost of a building project which limits repetition, and inherent parent industry barriers that reduce industry leadership and support of the competition series. For these reasons simpler competitions that demonstrate relevant outcomes are better suited to the construction industry in the short term until the value of the competition platform is demonstrated. Even so, architectural design competitions have also already found a valuable place in the parent industry for pursuing design innovation with a competition structure that is consistent between competitions locally and globally for a range of building types. This successful, interesting, ideas generation structure could easily be refocussed on technological innovation outcomes with modification only to the judging criteria.

5.3 Issues related to Innovation Adoption

As explained in the SCI theory (Jensen, 2021), adoption is the final step of the innovation competition process, representing the key decision point that represents the success or otherwise of the innovation. A competition that does not result in adoption by the parent industry has only limited benefit if the intention is to increase innovation to address needs, challenges, or goals in the parent industry, and this is particularly problematic in a construction context due to the scale, demanding regulations other constraints. This research suggests the process of innovation adoption into industry from competition is the single most challenging aspect of achieving increased innovation outcomes from a competition, with the most important factors that determine the successful adoption of innovation by industry from competition being the importance of industry commitment to the competition and its pursuit of innovation goals, and the relevance of the innovation goals to team’s commercial values. Identification of these two factors through this research represents a significant advancement in the understanding of the motivation for industry adoption, and potential advancement of innovations beyond existing research.

6 Conclusion and Further Research

The Construction industry is notably absent with regard the use of competitions to advance innovation to the detriment of the construction industry. This is in contrast to other similar industries that include competitions for innovation development. It has been demonstrated that competition is well suited to public good innovation that would otherwise not have occurred due to well understood industry constraints, such as onerous cost, time constraints and IP restrictions. Attention to a suitable competition design targeting existing innovations such as geopolymer concrete have the potential to increase industry adoption. Future research is required into the detailed pathways of innovation in the Australian construction industry. This should include both case studies of successful innovation and those blocked at the adoption phase. Additional research into the mechanisms used in other industries to use competition to advance innovation is also required.

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Construction Industry Capacity and Capability Evaluation; Application of Modelling Techniques for Resource Allocation in Multi-Project Portfolios

Jaleh Sadeghi[1*], Mostafa Babaeian Jelodar[1] and Monty Sutrisna[1]

[1]School of Built Environment, Massey University,
Auckland, New Zealand

j.sadeghi@massey.ac.nz; m.b.jelodar@massey.ac.nz; and M.Sutrisna@massey.ac.nz
* Corresponding author

Abstract:
Multiple projects that consume shared resources are handled in a multi-project portfolio (MPP) and can be subject to portfolio management for budget allocation, prioritisation and timing. An MPP owner may face many challenges finding the best scheduling and resource allocation programs for its in-progress and pipeline projects. In construction project management, complexity and uncertainty problems raise the need for proper construction-related MPP (C-MPP) planning techniques. In a C-MPP, several projects with shared and limited resources shall be executed in a certain period and must be modelled and well-understood. Mathematical and computational modelling techniques have been developed to be compatible with environments with diverse construction projects. These models usually targeted cost balancing, optimal budget allocation and efficient timing programs, to name a few. This paper explores the current theories on C-MPP management and identifies fit-for-purpose modelling techniques. As the outcome, a proposed computational model of the projects and their interdependencies in a portfolio contributes to MPP and C-MPP management area. This conceptual model offers a method for evaluating the capacity and capability of construction enterprises and introduces a significant application for agent-based modelling, i.e. portfolio-level visualisation and resource allocation.

Keywords:
Agent-based modelling, Construction industry, Multi-project portfolio management, Resource allocation, Capacity, Capability

1 Introduction

There is no holistic view of project portfolio management in construction, and the dynamism of construction-related multi-project portfolios (C-MPP) is less investigated. However, multi-project portfolio (MPP) management is a critical subject in general management theories. Evaluation of the projects, when placed in a diversified environment, takes a different process from evaluating them in isolation (Ravanshadnia *et al.*, 2010). MPPs include multiple projects consuming a single source of funds, facilities, etc. The projects in an individual enterprise portfolio should be executed in a limited period, and in most cases, conflicts are expected in MPPs (Kao *et al.*, 2006). Portfolio management is introduced as a matter of multi-criteria optimisation where risk, returns and sustainability factors participate (Dobrovolskienė and Tamošiūnienė, 2016, Siew, 2016). The main goal of portfolio optimisation is mostly to maximise overall portfolio value by balancing the cost-budget dyad and meeting the organisational and enterprises' capacity (Ravanshadnia *et al.*, 2010, Vacík *et al.*, 2018). The construction sector, as a mega-enterprise, also requires C-MPP optimisation from the project selection stage to prioritise and manage interdependencies (Khalifa Mohammed *et al.*, 2020, Bathallath *et al.*, 2022). However, inherent dynamism in construction projects and inevitable uncertainties lead to many complexities that challenge the process of C-MPP management (Hans *et al.*, 2007).

So far, modelling techniques have been developed for MPP management, and a few articles contribute to revealing and reviewing the state of the art in this regard. For example, Saiz *et al.* (2022) introduced the clusters of project portfolio optimisation methods with a bibliometric analysis approach. Moreover, Bathallath *et al.* (2022) and Micán *et al.* (2020) reviewed the literature on risk management in project portfolios and interdependencies. Also, literature on portfolio management in more specific areas, like renewable technology (Davoudpour *et al.*, 2012) and information technology (Kumar *et al.*, 2008, Verhoef, 2002, Gellweiler, 2020), is so far reviewed and discussed. However, despite some valuable arguments on C-MPP management, no review paper has contributed to this realm.

Some theories have been developed to solve resource allocation, timing and cost management difficulties in construction portfolios either with computational modelling approaches, e.g. (Farshchian and Heravi, 2018, Farshchian *et al.*, 2017, Lee, 2011) or with mathematical methods, e.g. (Ghasemi *et al.*, 2018, Touran, 2010). This review paper significantly explores the modelling/optimisation techniques for C-MPPs. The objectives of this review paper are 1) finding the trends in MPP modelling, 2) skimming the articles focusing on modelling C-MPP management, and 3) conducting a comparative discussion and outlining a fit-for-purpose model for C-MPPs.

2 Review Method

This review is based on "two" data-sets, including 1) articles on MPP modelling and 2) on C-MPP modelling. The primary purpose of collecting "two" data-set is to conduct a comparator mechanism and distinguish the less explored techniques in C-MPP modelling. After early-stage data-set collection, the four primary steps are taken:

1) bibliometric analysis of the first data-set and finding the trends in modelling techniques and approaches;
2) skimming the models developed and included in the second data-set; this step is inspired by the initial understanding of the trends in the first data-set;
3) discussing the trends and contributions in C-MPP modelling;
4) proposing a new C-MPP conceptual model fit for visualising and estimating at the portfolio level.

2.1 Dataset collection

For article-set collection, a comprehensive search keyword that contains key criteria in MPP and C-MPP is obtainable through an early-stage ontological review. In this process, some vocabularies are found to be related to MPP management, like project selection, decision-making, prioritising, capability, and value. Khalifa Mohammed *et al.* (2020) denoted that the steps in a portfolio project selection model are categorising, prioritising, authorising and revising the projects while managerial capabilities are engaged in all stages. Besides, de Souza *et al.* (2021) and Hauc *et al.* (2010) mentioned the key concept of multi-criteria decision-making for project selection. The methods of portfolio optimisation and maximising the value of the portfolio are mentioned in the literature as well (Beasley, 2013, Doering *et al.*, 2019). Among all, risk management integrates with MPP modelling in many articles (Ahmadi-Javid and Fallah-Tafti, 2019, Doering *et al.*, 2019). Accordingly, the prementioned keywords help produce a proper search phrase in the databases, the web of science (WoS). WoS is selected since it contains high-quality sources and helps skip the articles' quality and genuineness control step.

Figure 1 is the graphical representation of the data-set collection. First, a search phrase including all the keywords is used to browse the web of science (WoS) indexed papers to find article-set 1. The result is again refined to include just the "journal papers". The article publications period is not specified and limited, and the step 3 search result contains the articles published between 1996 and 2022. In the next stage, an extra phrase, including "construction", is combined with the prementioned search phrase. The result showed that the second article contains papers published between 2010 and 2022. Due to this finding, one can conclude that C-MPP modelling is a new specification in general MPP modelling since the date range of article-set 2 represents a more limited period than article-set 1. Therefore, data-set 1 is cut and limited to 2010 to 2022 to make the comparator mechanism more feasible. Finally, after scanning the abstracts, 240 and 10 articles, including article-sets 1 and 2, are passed to the next data-set quantitative/qualitative analysis stage.

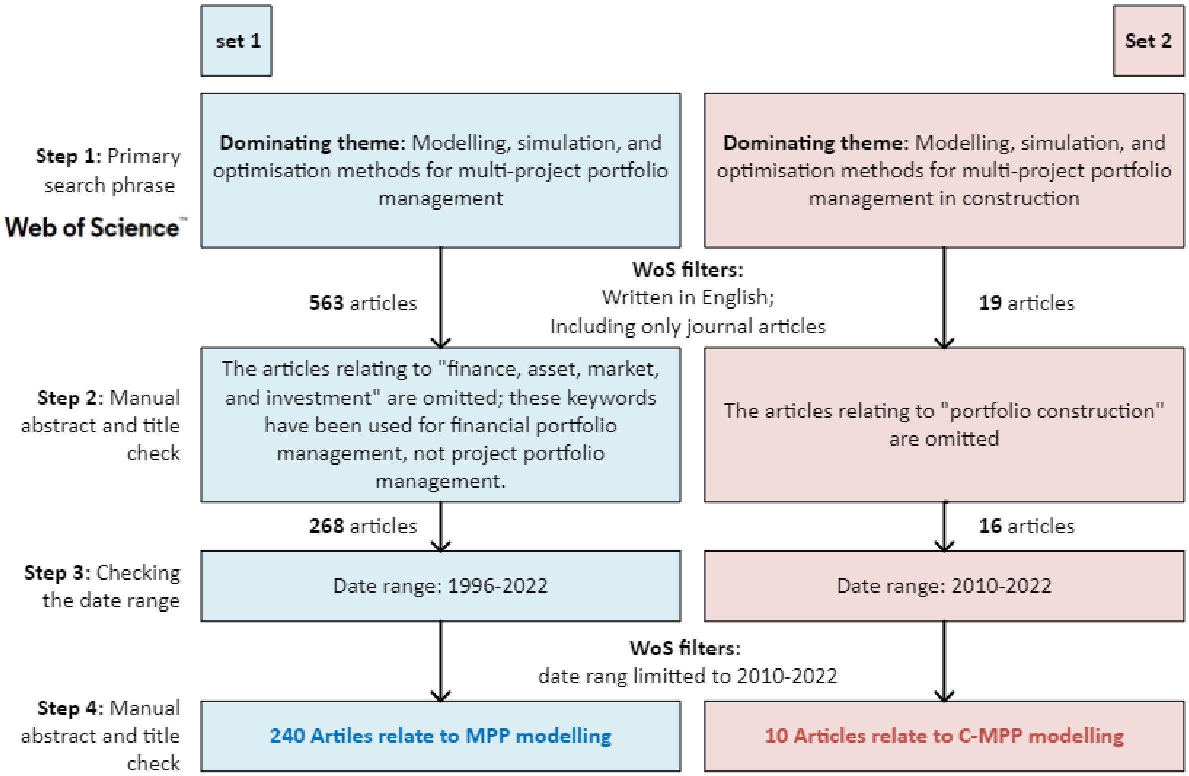

Figure 1. Graphical representation of the data collection process

2.2 Data screening: Quantitative approach

In this stage, a quantitative bibliometric review of the general MPP modelling reveals the status quo of MPP modelling, i.e., data-set 1. Initial quantitative screening of the first data-set shows that the interest in the subject has increased, and more than 30% of the papers (out of 240 papers) are published in the current decade. The milestone and most productive years are also 2021 and 2020. On the other hand, bibliometric maps help obtain a big picture of the data-sets and explore the trends through networks. VOSviewer software (Van Eck and Waltman, 2010) is employed to produce the bibliometric network of the source journals (Figure 2). Each journal (with more than two articles) is represented as a node, while the edges describe the co-citation relationship between the sources. "International journal of project management", "sustainability", "expert systems with applications", and "European journal of operational research" are the most productive journal in this area, respectively, with 16, 11, 11, and 10 articles within article-set 1.

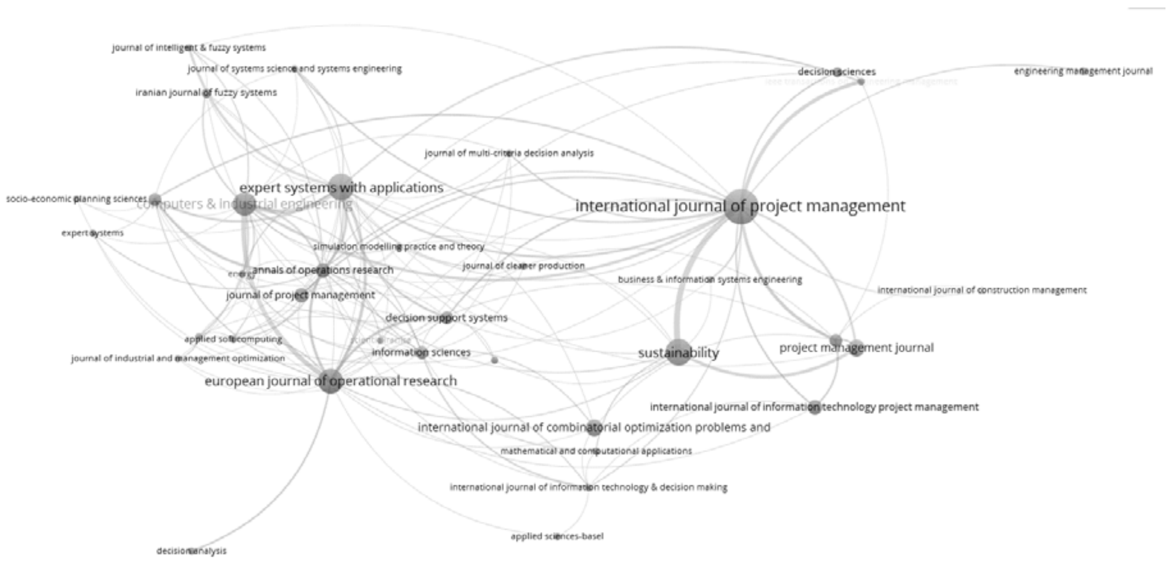

Figure 2. Bibliometric network of the journal sources of the article-set 1

VoSviewer is also used for author keyword and keyword-plus analysis of the 240 articles. The terms that are denoted in Table 1 are the selective modelling/optimisation trends in the article-set 1. Note that these terms are selected based on the authors' opinion according to the main rule: select the term if it refers to a specified model/optimisation method in which there are some input (row data), output (processed data and solutions), and a determined process (equation, algorithms, etc.). In the second column, the times of occurrences of each keyword are mentioned.

Table 1. Trend keywords in article-set 1: modelling in MPP

Term	Times of occurrences
Fuzzy model	23
Genetic Algorithm	19
Ant colony optimisation (ACO)	7
Evolutionary algorithm	7

Note that general keywords referring to the meta-categories of modelling techniques are not included in Table 1. Among all, "Mathematical modelling/programming (10 times)", "stochastic modelling/optimisation (7 times)", "robust optimisation", and "(meta)heuristics (7 times) are considered as the global terms and the words noting the categories of modelling. For instance, Lee (2011) referred to ant colony optimisation as a "heuristic" and "computing mechanism". In another study, Ghasemi *et al.* (2018) propose a Bayesian network and set up equations, thus a "mathematical approach". And, the Second Oder moment method is a part of "robust optimisation" proposed by Saiz *et al.* (2022) that works with variance statistics and probabilities. On the other hand, except for fuzzy modelling, the three other methods mentioned in Table 1 are "computational techniques". Also, two of the important journals in Figure 2, i.e., "expert systems with applications", and "European journal of operational research", are the Q1 sources in computer science and artificial intelligence. Therefore, two main categories of MPP modelligs are identified as "mathematical" and "computational". What follows is inspired by the identified categories and results from a closer review of the articles in data-set 2.

3 Results

3.1 Mathematical modelling in C-MPP

Mathematical models work based on either randomness (probabilistic) or determined variables. They operate based on pre-set functions to understand the relationship among variables (Hunt *et al.*, 2008). Referring to the trends, they are shown to have the upper hand in C-MPP. Table 2 contains the articles that have applied mathematical models on C-MPP management, the adopted modelling approach and the taxonomies in C-MPP problem-solving.

Among mathematical models, Fuzzy models play a key role in MPP management. This approach is the most repetitive term within the realm of MPP management and is followed by researchers in C-MPP as well. A fuzzy arithmetic method is employed by Ravanshadnia *et al.* (2010) to facilitate the decision-making process at a portfolio level. Applying the expert domain idea, the ontology behind the multi-criteria decision-making is developed, e.g., the company's workload (supply and demand), the similarity between prospective and existing projects, etc. Each criterion is weighted using an analytical hierarchy process. The score of the projects is shown to be calculatable by applying some equations and helps decide for bidding. The fuzzy model is also used by other researchers such as Abbasianjahromi and Rajaie (2013), Banihashemi and Khalilzadeh (2022) for, respectively, helping project selection and risk assessment. Moreover, the former article integrates fuzzy case-based reasoning with linear goal programming for identifying risk factors and project selection.

System dynamic (SD) is another approach to mapping and understanding the mathematical relationships among system components (cause and effect). It is employed in research conducted by Haghighi Rad and Rowzan (2018) to facilitate a multi-criteria decision-making process for project selection. In short, this SD model works on the technology, innovation, pace and complexity criteria. It implements the variables like schedule pressure, productivity, etc. The authors hybridised the SD with an optimisation method called TOPSIS or "Technique for Order of Preference by Similarity to Ideal Solution".

Except for SD, the solutions for project portfolio selection are proposed using another mathematical framework called network mapping. In the realm of C-MPP management, Delouyi *et al.* (2021) focused on easing multi-criteria decision-making according to sustainability, project interdependency and ongoing-projects adjustment based on network mapping. The interdependencies among projects are illustrated, while categorical-based evaluation analysis helps find the best decision in project selection. Another example is the framework proposed by Hofman *et al.* (2017). It depicts some theoretical relationship models of portfolio risks and verifies them empirically. In other papers, "portfolio risk" management as a sustainability impact factor is argued by Ghasemi *et al.* (2018). They developed a bayesian network (BN). In BN, like SD and network mapping, any interdependencies among the system variables (nodes) are revealed by connector edges. In the compiled BN, some parent nodes are raised out of probability calculation, e.g. risks based on managerial decisions and portfolio project types imbalance. Then based on conditional probability tables, a set of connected nodes is mapped, and the total portfolio risk is shown as the final output.

Siew (2016) developed a model for optimal project selection in which sustainability comes before financial benefits. The owner is demanded to assign a score to each sustainability criterion (1-to-10-point interval scale). The criteria are categorised into the social, environmental and economic sub-areas. Applying the second-order moment method, a set of equations (based on portfolio variance) produces the weighted sum of the scored criteria. A mathematical model is then developed to estimate the efficient frontier (Pareto optimality). Selecting the high-turnover projects in a given risk level or low-risk projects in a given turnover are the criteria defining Pareto-optimal portfolio in this model.

However, apart from the pre-mentioned multidimensional perspectives and integrated view of the portfolios, some researchers divided the portfolio into individual subjects and then assessed the effects of any changes on the portfolio level. For example, Touran (2010) proposed a thoroughly mathematical model for assessing the individual projects' "actual cost" Vs. "allocated budget". This model estimates the probability of the scenarios where the costs are overrun and underrun.

Table 2. C-MMP management; mathematical models

Reference	Source journal	Title	Proposed model	MPP management taxonomy
(Ghasemi *et al.*, 2018)	Sustainability	Project Portfolio Risk Identification and Analysis, Considering Project Risk Interactions and Using Bayesian Networks	Bayesian network	Assessing portfolio level risk
(Ravanshadnia *et al.*, 2010)	Canadian Journal of Civil Engineering	Hybrid fuzzy MADM project-selection model for diversified construction companies	Fuzzy arithmetic method	Project selection (for offering tender)
(Siew, 2016)	KSCE Journal of Civil Engineering	Integrating sustainability into construction project portfolio management	Second order moment method	Screening and Optimal project selection
(Haghighi Rad and Rowzan, 2018)	Simulation Modelling Practice and Theory	Designing a hybrid system dynamic model for analysing the impact of strategic alignment on project portfolio selection	System dynamic and TOPSIS technique	Project selection
(Touran, 2010)	Journal of Construction Engineering & Management	Probabilistic Approach for Budgeting in Portfolio of Projects	Mathematical model	Budget allocation and portfolio risk assessment
(Delouyi *et al.*, 2021)	Sustainability	Dynamic Portfolio Selection in Gas Transmission Projects Considering Sustainable Strategic Alignment and Project Interdependencies through Value Analysis	Network mapping	Project selection
(Hofman *et al.*, 2017)	Sustainability	Shedding New Light on Project Portfolio Risk Management	Network mapping	Portfolio level risk
(Abbasianjahromi and Rajaie, 2013)	Iranian Journal of Science and Technology	Application Of Fuzzy CBR And Modem Approaches In The Project Portfolio Selection In Construction Companies	Fuzzy model and linear programming	Portfolio-level risk and project selection

3.2 Computational modelling in C-MPP

Experience-based approaches use algorithms for studying complex systems and are called computational models (CM). These are fit-for-purpose techniques where analytic solutions are unavailable, and the relationships among variables are not deterministic. These models help understand the interactions of the components based on experiments (Hunt *et al.*, 2008). The artificial particle swarm intelligence (PSI) modelling is the most popular CM and works with progressive trial and error. Ant colony optimisation (ACO), agent-based modellings (ABM), Bee algorithm, and bird flocking are the models working based on PSI (Kennedy and Eberhart, 1995, Suarez, 2018). These models experiment with the solution space and look for candidate solution improvement based on evolutionary optimisation principles (Zhang *et al.*, 2015). Table 3 denotes the computational approaches adopted so far for modelling C-MPPs and are developed in the articles in article-set 2.

It has been understood that a few researchers have come up with computational models for C-MPPs. Among all, ACO and ABM are so far applied for scheduling and resource allocation in C-MPP. ACO is considered by Lee (2011) for portfolio-level optimisation. This method is a biomimicry model and is adopted from the natural behaviour of insects (Kothari *et al.*, 2011). In such models, the agents (i.e. ants), as model components, seek the source of food (objectives) and experience the various path ending to that goal. Pre-determined environment and set of rules limit the components' exploration, while their awareness of neighbouring directs them in the self-organisation process (Van Dam *et al.*, 2012). In the model proposed by Lee (2011), the ants' trails help rank the resource priority. In a diversified project environment, the duration of each project is determined, and the development level (based on size, land condition, etc.) is expressed. Then, the ants take the miscellaneous path to finish all the projects and produce a pool of solutions for prioritisation.

On the other hand, Farshchian *et al.* (2017) contributed to expanding ABM application into C-MPP modelling. ABM is useful in understanding the collective behaviour of a set of individuals. It can explain how individuals' changes affect emerging outputs. In the proposed model by Farshchian *et al.* (2017), the portfolio projects are considered as the system components (agents) acting and reacting in a multi-agent environment. The environment is constrained due to budget limitations and project prioritisation scenarios. The portfolio's overall outcome is then produced as an indicator for choosing a proper budget allocation (prioritisation) plan.

Table 3. C-MMP management; computational models

Reference	Title	Proposed model	MPP management taxonomy
(Lee, 2011)	An integrated model for planning development projects using ACO and construction simulation	Ant colony optimisation	Scheduling and prioritisation
(Farshchian *et al.*, 2017)	Optimising the Owner's Scenarios for Budget allocation in a Portfolio of Projects Using Agent-Based Simulation	Agent-based modelling	Budget allocation and prioritisation

4 Discussion

Due to the inherent dynamism of a portfolio, in which the projects inevitably get cancelled, changed and replaced, proposing dynamic solutions for recurrent reallocation and re-prioritisation is of great importance. For example, in the case of covid-19 outspread, the need for building/redeveloping the medical centres increased while the construction supply chain got interrupted due to countries' lockdowns. This scenario includes both capacity shortage and changes in enterprises' project portfolio prioritisation. In the C-MPP literature, project prioritisation is the crucial purpose of modelling. It is not far-fetched to see that poor MPP management gives rise to the ultimate failure when the project's prioritisation is changed (PMI, 2013, Siew, 2016). Moreover, the concept of efficient frontiers is brought to the argument (Siew, 2016) where the portfolio is in an optimal and balanced stage, i.e., in a neuter risk-turnover trad-off status. On the other hand, Ravanshadnia *et al.* (2010) showed that owners' supply and market demands are the key indexes in portfolio-level decision-making models. Therefore, the efficient frontier is a valid concept at a higher level, where the enterprise supply (capacity) and demands (capability) shall be balanced,

Moreover, despite the diversities and the imbalance of project types, the projects in a portfolio are usually interdependent (Ghasemi *et al.*, 2018). The prementioned index is revealed through network mapping models, e.g., (Delouyi *et al.*, 2021) and (Ghasemi *et al.*, 2018). Projects may be interdependent regarding 1) sharing resources (technology, workers, etc.); and/or 2) outcome (Project A's accomplishment affects the capability to accomplish the project B (Ghasemi *et al.*, 2018, Gear and Cowie, 1980, Killen and Kjaer, 2012). On the other hand, except for assessing collective projects' impact on the portfolio level, each project is also recognised as an independent entity, and its impact on the portfolio level can be analysed (Farshchian *et al.*, 2017, Touran, 2010). Accordingly, the following indexes are recognised as the most significant C-MPP modelling factors: capacity, capability, project independency (individual level), project interdependency (portfolio level), and risk and interruptions (like in the case of inevitable re-prioritisation).

On the other hand, it has been discussed that, due to inherent uncertainties, C-MPP optimisation problems are more compatible with heuristic methods (Abdzadeh *et al.*, 2022, Kao *et al.*, 2006). ABM is one of the popular heuristics that is proven to be compatible with the dynamism of C-MPP, however, few articles expanded its applicability in this regard; Table 3 shows that ABM fits resource management and project (re-)prioritisation. On the other hand, ABM, as a method helping explain complex systems from the micro-level substitutes' interactions to collective behaviour and macro-system levels (Stieler *et al.*, 2022), is a fit-for-purpose method for representing the projects from the individual level (independency index) to portfolio level (interdependency index).

C-MPP is dynamic and fits dynamic modelling (Hans *et al.*, 2007). However, the proper visualisation of the model dynamism is still required to understand the complexity better and produce the ready-to-use portfolio information. Indeed, visualisation helps identify the main causes of an emergence driven by a complex system like enterprise capability evaluation in a multi-project portfolio (Ghasemi *et al.*, 2018). On the other hand, expert domain evaluation on variables selection and model validation in practical C-MPP development (Ravanshadnia *et al.*, 2010). Therefore, the model's explainability to the construction practitioner is essential; this aspect is less considered in the literature. This section develops an early-stage conceptual ABM for visualising and modelling the C-MPP dynamism. The optimisation method is also discussed at the end to help estimate the construction capacity-capability indexes.

4.1 Conceptual model development

Considering the construction sector as a mega-enterprise with a portfolio of miscellaneous projects, mapping the pipeline projects is the main objective of this conceptual model. Each pipeline project is determinable in terms of type, duration (start and end date), and value. Therefore, developing an exploratory model of portfolio-level collaborations based on individual projects is considered. Then, based on historical data and the amount of work done (actual enterprise capacity), the main goal is to find whether pipeline projects are executable and understand the time at which capacity is over or under-loaded.

The collective impacts of the projects on the portfolio status are to be estimated. Thus, visualising the projects in parallel is helpful. The main indicators of individual projects are time and cost. These indexes refer to the construction key performance indicators, known as the iron triangle: "[on]Time, "[on]budget", and "[according to] specifications or quality" (Mellado *et al.*, 2019, Toor and Ogunlana, 2010). The cost also roughly reflects other indicators such as machinery, technology, labour, engineers, etc., and is worth considering. Note that the construction industry portfolio is regarded as a poor-data environment, and the model should be compatible with the minimum data available.

Figure 3 is a sketch of the model's graphical visualisation. In brief, the projects are considered as the components with bodies (spatial agents), in which the body size reflects the project value. The surrounding environments reflect the enterprise resources (actual capacity), and each iteration in the model corresponds to the equally divided time frames (quarterly or annually). In each iteration, the agents; status and locations change based on pipeline data,

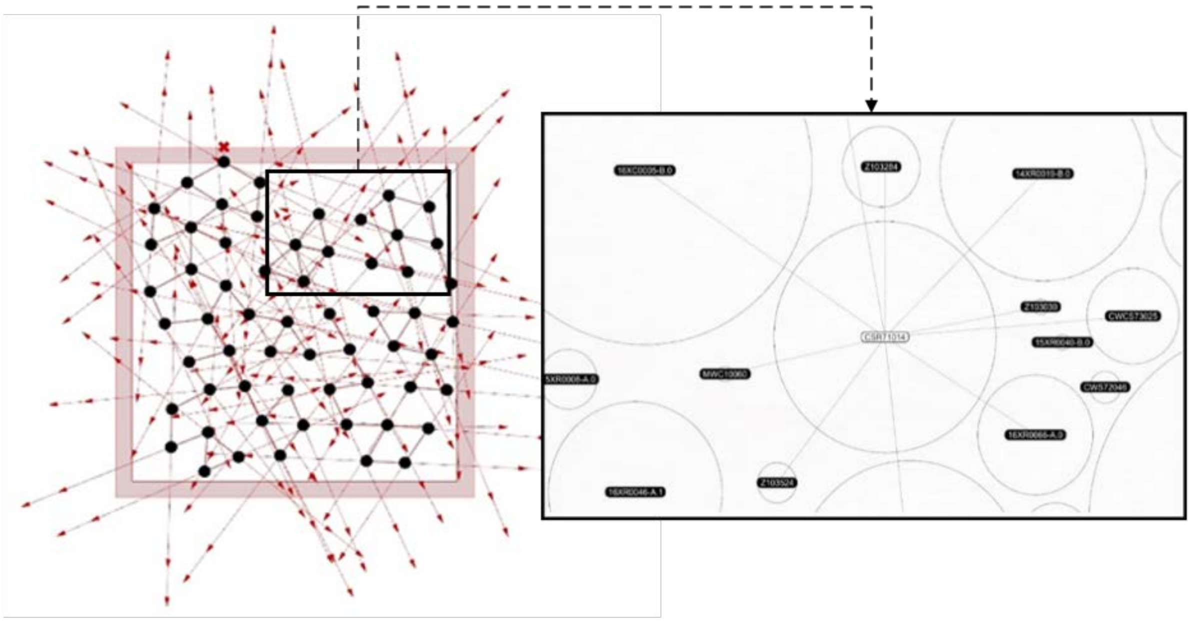

Figure 3. Agents act in a multi-project environment; right) an agent scanning the surrounding; left) the cumulative behaviour and moving vectors

After understandably mapping the portfolio, the next step will be finding the answer to the question: What are the critical points (conflicts) in either scheduling or resource consumption pressures? Is the capacity under/overloaded at that critical point? Is there any other possible portfolio configuration (in terms of project value distribution or timing) where the capacity is satisfied? What is the potential optimisation solution for balancing the capacity-capability dyad?

Seemingly, allocating awareness attributes to the projects as the agents of an Agent-based (AB) model, helps this agent to 1) know the other agents (projects), 2) perceive their limited environment (limited capacity to explore), and 3) perceive their goal, i.e. exploring until removing all conflicts with surrounding (other agents and the environment). The prementioned attributes depict the interdependency index and are visualised in Figure 3. The goal is to find the optimal solution(s) in which the capacity-capability is zero-sum while most of the projects are done. The value distribution and the scheduling in the optimisation process are the independent variables and can be changed till reaching Pareto-front optimality. The challenge in the process of optimisation shall be fitting to the constraint capacity and limitations at the time of (re-)prioritisation (e.g. in case of interrupted resilience factors).

5 Conclusion and Further Research

This paper contributes to the body of knowledge on construction management, portfolio management and applied computational modelling. It is a significant review paper considering the application of popular modelling techniques in C-MPP management. Moreover, a novel application for a popular complex system modelling technique, ABM, is conceptually proposed to help C-MPP optimisation.

The trends in MPP modelling are identified to be categorisable under two main headings: computational and mathematical. It has been understood that most of the modelling applied to solve the risk, budget, time management, and decision-making in construction are mathematical. It is found that although the computational models are more compatible with the dynamic nature of diversified project environments, they are less explored in the construction research area. Note that this review paper is restricted by the employed search keyword. The data-sets for the final review are refined to include the journal articles. However, some conference papers might address novel models and initiate some techniques in this regard. Also, the vocabulary mentioned in table 2 is chosen based on the authors' opinions with expert consultation, and some other terms related to modelling, simulation and optimisation may be missed.

In the end, the idea of capacity-capability mapping is brought into the argument, and an AB model as a heuristic to solve C-MPP problems is conceptually proposed. Consequently, Future research can target the following objectives:

- The AB model is to be justified through another review paper to investigate the history and feasibility of AB models.
- The conceptual model needs to be implemented and verified.
- The local capacity and the region-based optimisation remains to be plugged into the model and verified.

6 Acknowledgement

This study is part of the "Creating Capacity and Capability for the New Zealand Construction" research programme funded by the New Zealand Ministry of Business, Innovation and Employment (MBIE) under the MBIE Endeavour grant.

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Realising United Nations Sustainable Development Goals through Offsite Construction

Buddhini Ginigaddara[1*] Marcus Jefferies[1] and William Sher[1]

[1]School of Architecture and Built Environment, University of Newcastle, Callaghan, NSW 2308, AUSTRALIA

Buddhini.GinigaddaraAppuhamilage@newcastle.edu.au, marcus.jefferies@newcastle.edu.au, willy.sher@newcastle.edu.au

* Corresponding author

Abstract:

Amalgamating construction and manufacturing processes is referred to as offsite construction (OSC). These deliver buildings that are produced in factories and then transported and erected onsite. In line with the UN's Sustainable Development Goals (SDGs), OSC moves traditional onsite construction methods to potentially more efficient, safe, and sustainable factories with advanced robotics and assembly lines. This paper reviews how OSC assists realisation of the SDGs by achieving targets specified in the SDGs. A systematic literature review (SLR) was conducted, identifying 24 publications in the Scopus database. The SLR was guided by the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) protocol. As only six publications directly referred to 'OSC and SDGs', those on 'construction and SDGs', 'manufacturing and SDGs' and 'prefabrication and SDGs' were also reviewed. The investigation identified five SDGs directly related to OSC. Factory-based manufacturing processes and improved working conditions promoted through OSC help to achieve SDG 8: decent work, and economic growth, SDG 9: industry, innovation, and infrastructure and SDG 12: responsible consumption, and production. Additionally, the use of sustainable materials, renewable energy sources and being cautious about ecology through design for sustainability practices adopted in OSC are in line with SDG 11: sustainable cities and communities, and SDG 13: climate action. This study provides insights into how modern methods of construction, such as OSC, can assist in delivering SDGs. Further, it contributes to knowledge by recognising potential steps to be followed to realise SDGs through OSC in line with current technological advancements.

Keywords:
Offsite construction, Systematic literature review, UN sustainable development goals

1 Introduction

The construction industry has been a consistent contributor to global warming and climate change accounting for 40% of the world's annual greenhouse gas emissions (Gholipour *et al.*, 2022). As one of the least digitalised and least industrialised sectors, the industry is also known for high wastage, poor working conditions, gender disparity, inefficient processes and exposure to health and safety risks (Wang *et al.*, 2020, Fei *et al.*, 2021). In contrast, offsite construction (OSC) is acknowledged as a sustainable alternative that resolves many issues in the construction industry. It accommodates digitalised, sustainable and industrialised processes and takes place in controlled environments (Goulding and Pour Rahimian, 2019). Compared to traditional construction methods, OSC promotes construction waste minimisation and the use of sustainable materials resulting in many studies that focus on the sustainable aspects of OSC (Goulding and Pour Rahimian, 2019, Wuni *et al.*, 2020). However, the relationship between OSC and the Sustainable Development Goals (SDGs) introduced by United Nations (UN) is not well documented as no recent scientometric reviews on OSC provide any indication of studies that explore the significance of OSC to achieve the SDGs (Wang *et al.*, 2020, López-

Guerrero *et al.*, 2022). This gap is the focus of this study - to establish how OSC can assist in achieving the SDGs.

Following the Millennium Development Goals, the SDGs were introduced in 2015. They consist of 17 goals and 169 targets to be achieved by 2030 (UN, 2022). The SDGs are based on the five P's: planet, people, peace, prosperity, partnership and the goals can be considered under three categories of social, economic, and environmental sustainability (Ye *et al.*, 2022). The increasing number of worldwide natural disasters and catastrophes related to climate change have generated much research focusing on achieving the SDGs in various sectors including construction (Fei *et al.*, 2021) and manufacturing (Beekaroo *et al.*, 2019). OSC represents both these sectors. The first step in realising the SDGs through OSC is to understand the existing body of knowledge. Although there is a plethora of research on various aspects of OSC (Hosseini *et al.*, 2018, Wang *et al.*, 2020), only a few research publications directly refer to SDGs. Hence, this research aims to review how OSC assists in achieving the SDGs and identify the SDGs that are applicable to OSC. It addresses this aim via a systematic literature review (SLR) of high-quality journal papers (Scimago ranking Q1 and Q2) published since 2015 on the said topic. Content analysis of 24 eligible research articles on both the construction and manufacturing sectors enabled the identification of OSC-related SDGs.

2 Literature Review

2.1 Review of Previous Studies on OSC

OSC is commonly known as prefabrication when used in connection with buildings or functional elements of buildings made in factories. OSC types include components, panels, pods, modules, complete buildings and foldable structures (Ginigaddara *et al.*, 2021). Several other terms such as modular construction, offsite manufacturing, offsite production, and volumetric construction are also interchangeably used to refer to OSC (Luo *et al.*, 2017). OSC is a modern method of construction that helps to move traditional construction activities from site to factory-based production and assembly processes (Masood *et al.*, 2021). This results in the adoption of Industry 4.0 driven technological advancements such as advanced robotics, cyber physical integration, artificial intelligence, virtual reality, augmented reality, cloud computing, internet of things, digital twins, and the like (Goulding and Pour Rahimian, 2019, Wang *et al.*, 2020). OSC represents digitalised and industrialised production processes that also create a safer, more sustainable, and productive construction sector.

Several researchers have conducted critical literature reviews on OSC—including scientometric and bibliographic analyses—and these help to understand the common themes, trends, and research areas in OSC (Hosseini *et al.*, 2018, Jin *et al.*, 2018, Wuni and Shen, 2019, Hou *et al.*, 2020, Wang *et al.*, 2020, Saad *et al.*, 2021, López-Guerrero *et al.*, 2022). Luo *et al.* (2021) conducted a comparative study on OSC and manufacturing approaches while López-Guerrero *et al.* (2022) explored the sustainability of OSC products. Hou *et al.* (2020) and Wang *et al.* (2020) investigated the applications of technologies in OSC. Hosseini *et al.* (2018) and Jin *et al.* (2018) summarised the OSC-related research conducted over the past two decades. The themes generated in these studies vary and encompass areas such as OSC products, production planning, scheduling, and performance evaluation. Interestingly, these reviews do not provide any direct reference to OSC research on SDGs.

2.2 United Nations Sustainable Development Goals (SDGs)

The SDGs present a powerful and a holistic aspiration that envisions sustainable growth for everyone (Hoosain *et al.*, 2020). A summary of the SDGs is presented in Table 1.

Table 1. SDGs and their research agenda
Adapted from: (Hoosain *et al.*, 2020, Fei *et al.*, 2021, UN, 2022)

No.	SDGs	Category	Description
1.	No poverty	Economic	End poverty in all its forms everywhere
2.	Zero hunger	Economic	End hunger, achieve food security and improved nutrition and promote sustainable agriculture
3.	Good health and wellbeing	Economic	Ensure healthy lives and promote well-being for all at all ages
4.	Quality education	Social	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
5.	Gender equality	Social	Achieve gender equality and empower all women and girls
6.	Clean water and sanitation	Economic	Ensure availability and sustainable management of water and sanitation for all
7.	Affordable and clean energy	Economic	Ensure access to affordable, reliable, sustainable, and modern energy for all
8.	Decent work and economic growth	Economic	Promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all
9.	Industry, innovation, and infrastructure	Economic	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation
10.	Reduced inequalities	Social	Reduce inequality within and among countries
11.	Sustainable cities and communities	Environmental	Make cities and human settlements inclusive, safe, resilient, and sustainable
12.	Responsible consumption and production	Environmental	Ensure sustainable consumption and production patterns
13.	Climate action	Environmental	Take urgent action to combat climate change and its impacts
14.	Life below water	Environmental	Conserve and sustainably use the oceans, seas, and marine resources for sustainable development
15.	Life on land	Environmental	Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
16.	Peace, justice, and strong institutions	Social	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable, and inclusive institutions at all levels
17.	Partnerships for the goals	Social	Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development

Overall, it can be assumed that all 17 SDGs are related to OSC as they revolve around environmental, economic, and social sustainability aspects. SDGs help to balance built environment and ecological needs of lands (Beekaroo *et al.*, 2019). However, in the current context of construction activities, protecting biodiversity and ecology does not seem to be a priority (Fei *et al.*, 2021). SDGs also refer to sustainable energy sources, use of green and eco-friendly materials, sustainable needs of contracts and the potential of offsite passive houses (Wuni *et al.*, 2020). Although the relationship between SDGs and OSC is apparent, it is important to identify the most applicable SDGs that can be achieved through OSC. This research focusses attention on OSC as a means of achieving the SDGs. Consequently, this should promote OSC. The next section describes the research methodology adopted to achieve this target by conducting a SLR.

3 Research Methodology

The research methodology follows the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) protocol. Previous research on SLRs also used similar research methods to identify relevant publications for analysis (Wang *et al.*, 2020, Wieser *et al.*, 2021). According to the article selection process presented in Figure 1, initial search identified 1,051 articles from the Scopus database. At the screening stage, 556 articles were excluded as they were duplicates (30), published in languages other than English (30), published before 2015 (17), conference papers (183), book chapters (76) and not belonging to Scimago ranking Q1 or Q2 journals (166). Only the Scopus database was reviewed as only peer-reviewed journal papers in the highest ranked journals under Scimago ranking (Q1 and Q2) were selected for analysis. As SDGs were introduced in 2015 (UN, 2022), it was necessary to only focus on articles published after 2015.

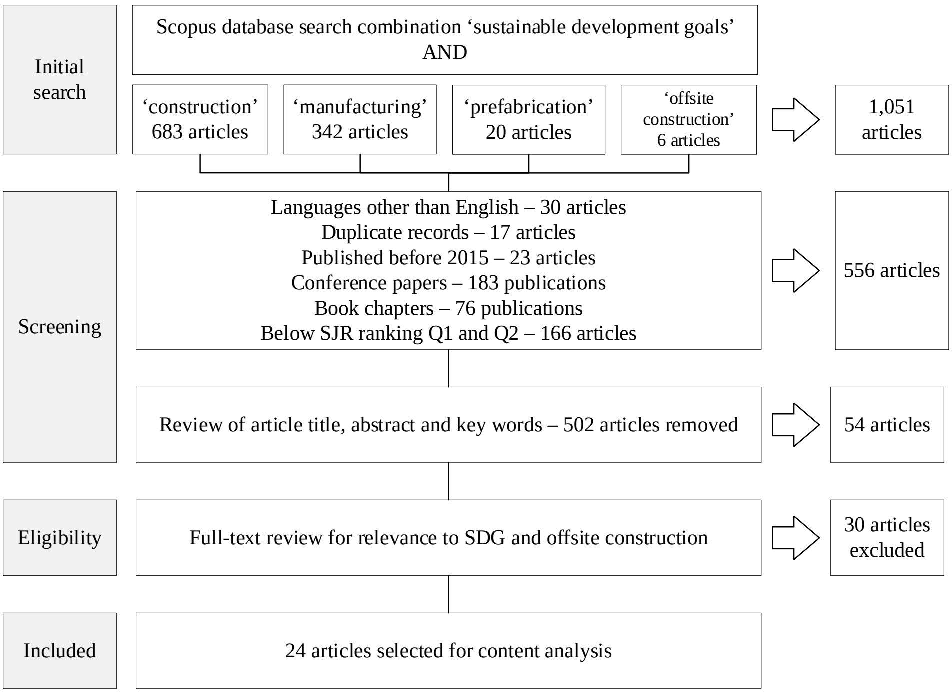


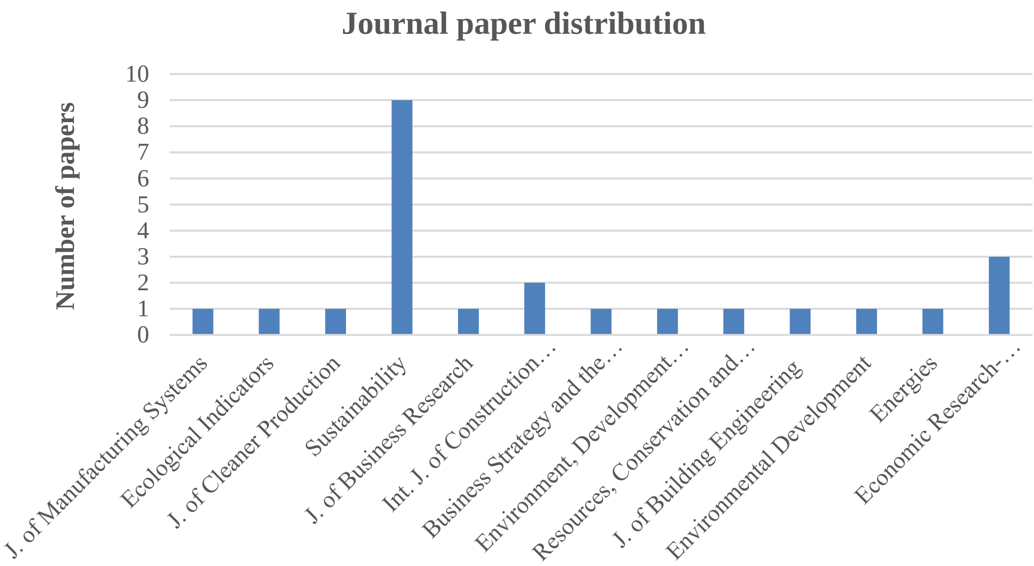
Figure 1. Methodology for conducting the systematic literature review

The inclusion criteria were directly related to SDGs in construction or manufacturing. The review of titles, abstracts and keywords resulted in the removal of 502 articles. Fifty-four articles were selected as eligible for full-text review, out of which 30 were excluded as they did not relate to either OSC or SDG. Finally, 24 articles were selected for content analysis.

4 Findings and Discussion

4.1 Summary of Selected Articles

The systematic process resulted in identifying 24 articles for content analysis and their details are included in Table 2. Although journal articles from 2015 to August 2022 were included in the initial screening process, all selected articles were published from 2019 to 2022. These articles were published in 13 different journals, and nine of the 24 articles (37.5%) were from the journal Sustainability. The research methods incorporated in these articles varied from SLRs, case studies, interview surveys, questionnaire surveys, analytical hierarchy processes, action research to mathematical model development. Interview surveys were found to be the most popular followed by literature reviews and questionnaire surveys. The distribution of journal papers and research methods in the articles is presented in Figure 2.



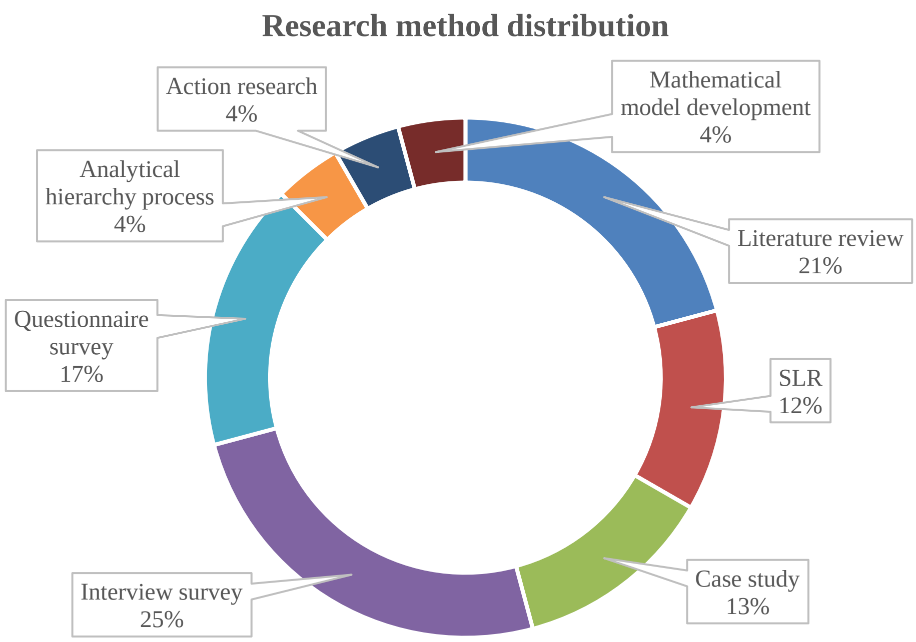


Figure 2: Distribution of journal papers and research methods

Table 2. Summary of selected articles

No.	Title	Journal	Journal ranking	Research method	Research contribution	Relevant SDG	Citation
1.	A holistic approach to corporate sustainability assessment: Incorporating sustainable development goals into sustainable manufacturing performance evaluation	Journal of Manufacturing Systems	Q1	Case study	Proposes a new corporate sustainability assessment method for manufacturing companies to report their contribution to SDGs	All 17 SDGs	(Moldavska and Welo, 2019)
2.	Developing a sustainability index for Mauritian manufacturing companies	Ecological Indicators	Q1	Questionnaire survey	Develop a sustainability index to quantify the impact of manufacturing companies	All 17 SDGs	(Beekaroo *et al.*, 2019)
3.	Sustainable manufacturing. Bibliometrics and content analysis	Journal of Cleaner Production	Q1	SLR	Identify how existing literature focus on green and lean practices rather than the role and criticality of sustainable manufacturing	All 17 SDGs	(Bhatt *et al.*, 2020)
4.	New business models from prescriptive maintenance strategies aligned with sustainable development goals	Sustainability	Q1	Action research	Formalise new opportunities enabling advanced servitisation business transformations	SDG 8, 9, 11	(Grijalvo Martín *et al.*, 2020)
5.	The impact of 4ir digital technologies and circular thinking on the United Nations sustainable development goals	Sustainability	Q1	Case study	Evaluate how technological advancements of Industry 4.0 helps to achieve SDGs	All 17 SDGs	(Hoosain *et al.*, 2020)
6.	The smart circular economy: A digital-enabled circular strategies framework for manufacturing companies	Journal of Business Research	Q1	SLR	Proposes a digitally enabled framework that can influence digital technology adoption in circular economy	SDG 12	(Kristofferse n *et al.*, 2020)
7.	Disruptive technological innovations in construction field and fourth industrial revolution intervention in the achievement of the sustainable development goal 9	International Journal of Construction Management	Q2	Questionnaire survey	Establish strategies that can achieve disruptive innovation and subsequently, SDG 9	SDG 9	(Lekan *et al.*, 2020)
8.	Construction industry post-COVID-19 recovery: Stakeholders perspective on achieving sustainable development goals	International Journal of Construction Management	Q2	Interview and questionnaire survey	Investigate challenges in the construction sector and propose feasible solutions for SDGs achievement through stakeholder management and modern technologies	All 17 SDGs	(Ebekozien *et al.*, 2021)

No.	Title	Journal	Journal ranking	Research method	Research contribution	Relevant SDG	Citation
9.	The critical role of the construction industry in achieving the sustainable development goals (SDGs): Delivering projects for the common good	Sustainability	Q1	Interview and questionnaire survey	Explores how construction industry can act as a driver to realise SDGs	SDG 3, 5, 6, 7, 8, 9, 11, 12, 13, 15	(Fei *et al.*, 2021)
10.	A review of corporate purpose: An approach to actioning the sustainable development goals (SDGs)	Sustainability	Q1	Literature review	Explore whether and how corporate level strategies facilitate the operationalisation of SDGs	All 17 SDGs	(Jimenez *et al.*, 2021)
11.	Leveraging STARA competencies and green creativity to boost green organisational innovative evidence: A praxis for sustainable development	Business Strategy and the Environment	Q1	Questionnaire survey	Investigate how green creativity boost green organisational innovation	All 17 SDGs	(Ogbeibu *et al.*, 2021)
12.	Multi-objective mixed-integer linear optimization model for sustainable closed-loop supply chain network: a case study on remanufacturing steering column	Environment, Development and Sustainability	Q2	Mathematical model development	Investigate whether organisations can make profits by adopting remanufacturing principles	All 17 SDGs	(Rajak *et al.*, 2021)
13.	Shaping digital ecosystems for sustainable production: Assessing the policy impact of the 2030 vision for Industrie 4.0	Sustainability	Q1	Literature review	Assess the policy impact on shaping digital ecosystems for sustainable production	SDG 8, 9, 12, 13	(Sautter, 2021)
14.	Environmental impact of construction transport and the effects of building certification schemes	Resources, Conservation and Recycling	Q1	Case study	Investigate the environmental impact of transportation that is paramount for the effective adoption of OSC	SDG 9, 11, 13	(Sezer and Fredriksson, 2021)
15.	A hybrid MCDM model combining DAMP and PROMETHEE II methods for the assessment of cybersecurity in Industry 4.0	Sustainability	Q1	Literature review	Propose a cyber security scheme to achieve SDGs and carbon reduction in manufacturing companies	SDG 7	(Torbacki, 2021)
16.	Challenges of a healthy built environment: Air pollution in construction industry	Sustainability	Q1	SLR	Provides an overview about the air pollution in construction by focussing on building life cycle, building materials, processes, and components	SDG 3, 7, 11, 13	(Wieser *et al.*, 2021)
17.	New execution process of a panel-based façade system that reduces project duration and improves workers' working conditions	Journal of Building Engineering	Q1	Theoretical study	Design a new procedure for prefabricated panel installation to improve workers' working conditions	SDG 3 and 8	(Cruz Astorqui *et al.*, 2022)

No.	Title	Journal	Journal ranking	Research method	Research contribution	Relevant SDG	Citation
18.	Industry-related sustainable development Goal-9 progress and performance indices and policies for Sub-Saharan African countries	Environmental Development	Q1	Literature review	Evaluate industrial aspects of SDG 9, based on cross country performance indices and policies	SDG 9	(Luken *et al.*, 2022)
19.	Role of Standards as an Enabler in a Digital Remanufacturing Industry	Sustainability	Q1	Analytical hierarchy process	Explore how standards help to achieve remanufacturing challenges by enabling the adoption of digital technologies	SDG 12	(Pratapa *et al.*, 2022)
20.	Impact and Potential of Sustainable Development Goals in Dimension of the Technological Revolution Industry 4.0 within the Analysis of Industrial Enterprises	Energies	Q2	Questionnaire survey	Analyse the potential of sustainable technologies emerged through Industry 4.0 innovations and renewable energy initiatives in manufacturing and logistics	All 17 SDGs	(Richnák and Fidlerová, 2022)
21.	Responsible Leadership and Sustainable Development in East Asia Economic Group: Application of Social Exchange Theory	Sustainability	Q1	Questionnaire survey	Investigate the integrated relationship of responsible leadership, knowledge sharing, and sustainable performance	All 17 SDGs	(Xuecheng *et al.*, 2022)
22.	The role of sustainable development goals, financial knowledge, and investment strategies on the organizational profitability: Moderating impact of government support	Economic Research-Ekonomska Istrazivanja	Q2	Questionnaire survey	Examine the impact of SDGs on organisational profitability	All 17 SDGs	(Yang and Liu, 2022)
23.	Investment on environmental social and governance activities and its impact on achieving sustainable development goals: evidence from Chinese manufacturing firms	Economic Research-Ekonomska Istrazivanja	Q2	Questionnaire survey	Investigates the how investing on environment, social, and governance activities assists the achievement of SDGs	All 17 SDGs	(Ye *et al.*, 2022)
24.	Does quality management system help organizations in achieving environmental innovation and sustainability goals? A structural analysis	Economic Research-Ekonomska Istrazivanja	Q2	Questionnaire survey	Investigates whether organisational quality management systems help to achieve environmental innovations and SDGs	All 17 SDGs	(Zhao *et al.*, 2022)

4.2 SDGs related to OSC

Content analysis of the articles identified ten SDGs directly related to construction and manufacturing practices used in OSC. Out of the these, the most frequently cited SDGs are *SDG 9: industry, innovation, and infrastructure* (19 articles), *SDG 8: decent work, and economic growth* (17 articles), *SDG 11: sustainable cities and communities* (17 articles), *SDG 12: responsible consumption and production* (17 articles) and *SDG 13: climate action* (17 articles). A summary of these findings is presented in Figure 3.

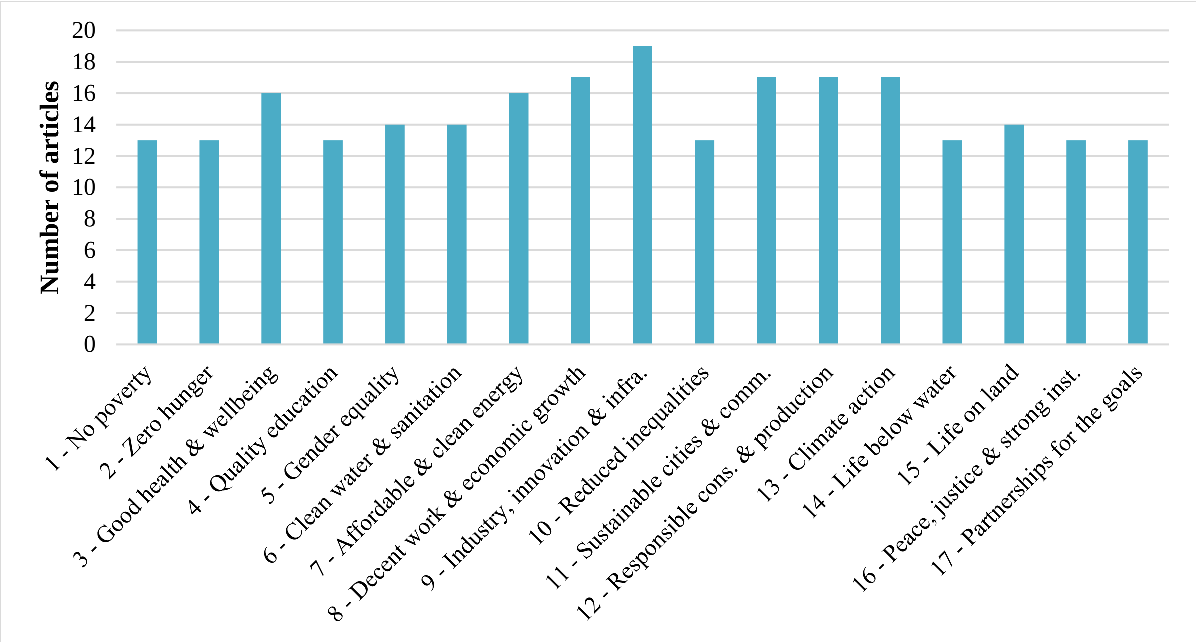


Figure 3. Number of articles with different SDGs references

This section explains how SDGs can be incorporated into OSC-related research as well as OSC practices. OSC projects need to be delivered with a focus on ecology (Fei *et al.*, 2021) and this is in line with *SDG 6: clean water and sanitation* and *SDG 15: life on land*. As built environment activities directly impact on natural environments, it is vital that design, manufacture and assembly principles benefit ecology and the environment. According to *SDG 8: decent work, and economic growth*, business models in manufacturing companies create safer and improved working conditions which in turn deliver economic growth (Grijalvo Martín *et al.*, 2020). For example, the working conditions promoted in OSC are comparatively better than traditional construction methods which are more prone to health and safety risks as well as external weather conditions. Similarly, as opposed to construction (Fei *et al.*, 2021), the factory-based safe work environments in manufacturing processes promote *SDG 3: good health and wellbeing* (Cruz Astorqui *et al.*, 2022). Compared to traditional onsite construction with stereotypical masculine jobs suited for men (Fei *et al.*, 2021), OSC promotes technology driven jobs and skills that do not require substantial physical strength. For example, OSC has the potential to adopt advanced technologies such as exoskeletons and robotic arms (Wang *et al.*, 2020). These tasks are accessible to women and hence OSC is in line with *SDG 5: gender equality*. OSC is perceived as a female-friendly alternative (Smith and Quale, 2017) which promotes technical skills such as operating machines that are rarely found in traditional construction practices.

Many researchers have highlighted the relevance of *SDG 9: industry, innovation, and infrastructure* for both construction and manufacturing activities. Digitalisation and data-driven approaches were heightened by Industry 4.0 which also results in innovative processes in manufacturing (Grijalvo Martín *et al.*, 2020). It is paramount to understand how disruptive technologies affect the built environment and use Industry 4.0-driven technical advances for better stakeholder management, and the management of innovative procurement routes (Lekan *et al.*, 2020).

In line with *SDG11: sustainable cities and communities*, introducing technology-driven business models assists both internal and external stakeholders and this is recognised as creating sustainable communities (Grijalvo Martín *et al.*, 2020). As the construction sector is responsible for providing shelter to the rapidly increasing global population, achieving green and sustainable cities in turn results in generating sustainable communities (Fei *et al.*, 2021). One of the methods of achieving this is to follow environmentally friendly alternative construction methods such as OSC.

SDG 12: responsible consumption and production is one of the SDGs prominent in manufacturing processes that relates to the circular economy. Kristoffersen *et al.* (2020) proposed a matrix of how digital technologies can leverage the adoption of the circular economy and benefit manufacturing companies. This matrix assists by generating roadmaps and facilitating strategic decisions to achieve SDG 12. Further, Pratapa *et al.* (2022) explored how enabling digital technologies in remanufacturing processes help to achieve SDGs.

SDG 13: climate action is an urgent need of the planet. It is important to restrict carbon emissions throughout construction and manufacturing processes from inception to demolition (Fei *et al.*, 2021). This includes sustainable transportation (Sezer and Fredriksson, 2021) of OSC structures. For example, passive houses are an OSC-driven building technique that reduces the ecological footprint of these structures through ultra-low-energy consumption for heating and cooling (Smith and Quale, 2017). In addition, *SDG 7: affordable and clean energy* also relates to OSC where renewable energy sources are used in manufacturing and transportation of OSC elements. These can be achieved by reducing the carbon footprint with zero carbon targets in design, manufacturing, and assembly processes. A similar approach is promoted through 'design for excellence' principles in manufacturing which recognises 'design for sustainability'.

Moldavska and Welo (2019) developed a corporate sustainability assessment tool for adoption by OSC manufacturers. The model assists in establishing a sustainability strategy to pursue SDGs through progress measurement. Similarly, a sustainability matrix developed by Beekaroo *et al.* (2019) incorporates quantitative indices for environmental, economic, and social sustainability aspects.

According to Bhatt *et al.* (2020), bibliometric analysis of published articles on sustainable manufacturing reveals how existing literature does not focus on SDGs-related empirical studies. All SDGs can be related to Industry 4.0-driven technological advancements as well as circular economy principles which deviate from the 'take, make and dispose' mindset (Hoosain *et al.*, 2020). Additionally, leadership from policy makers is necessary to realise policies based on SDGs (Ebekozien *et al.*, 2021, Sautter, 2021). Furthermore, knowledge and skills on green thinking (Ogbeibu *et al.*, 2021) and the efforts of construction-related manufacturing stakeholders (Ebekozien *et al.*, 2021) are also required to realise SDGs through OSC. An action oriented 'business-as-usual' approach with the appointment of 'SDG action managers' can provide a long-term impact via SDGs (Jimenez *et al.*, 2021).

5 Conclusion and Further Research

This study has explored how OSC can lead to achieving specific SDGs. It included a SLR of high-quality journal papers (Scimago ranking Q1 and Q2) published between 2015 and 2022, identifying 24 articles that refer to several SDGs. The article selection procedure was conducted using the PRISMA protocol and a limited number of publications that refer to 'OSC and SDG' led to the selection of articles that relate to prefabrication, construction, and manufacturing. As OSC is a combination of both construction and manufacturing activities, the findings highlight how all SDGs relate to OSC. We found that OSC relates to five specific SDGs and focusing on them will help to realise their targets expeditiously. These SDGs are *SDG 8: decent work and economic growth*, *SDG 9: industry, innovation, and infrastructure*, *SDG 11: sustainable cities and communities*, *SDG 12: responsible consumption and production* and *SDG 13: climate action*.

This research contributes to knowledge by identifying the most relevant SDGs for OSC activities. It is one of the first studies that directly connects OSC to SDGs. The study provides theoretical implications for future OSC research on specific SDGs. This SLR has consolidated the existing body of knowledge on OSC and SDG and can contribute to improving OSC-related policies and practices that support decent work, better working conditions, innovative processes and responsible production that results in economic growth and sustainable communities. The study has the inherent limitations of a literature review, being based on research findings. Empirical research needs to be conducted to confirm how SDGs can be achieved through OSC. Future research may also include comparative studies of construction and manufacturing sectors and their progression to achieving SDGs, potentially using case studies from construction organisations, OSC projects and government initiatives.

6 Acknowledgement

Authors acknowledge the funding and support received from the School of Architecture and Built Environment, College of Engineering Science and Environment, University of Newcastle, Australia.

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Inconsistent Workloads Hamper the Transportation Construction Sector in New Zealand

Nicola West[1*], Jacobus Daniel van der Walt[1] and Eric Scheepbouwer[1]

[1]Department of Civil and Natural Resources Engineering, University of Canterbury, Private Bag 4800 Christchurch 8140, NEW ZEALAND

nicola.winter@pg.canterbury.ac.nz; eric.scheepbouwer@canterbury.ac.nz; daniel.vanderwalt@canterbury.ac.nz
* Corresponding author

Abstract:
The New Zealand Transport Agency spends billions of dollars on infrastructure projects annually and plans to increase the quantity of work in the next 25 years. However, there is a question about the capacity of the construction sector to deliver this quantity of work. The objective of this paper is to present an initial assessment of contract tender data for Government transportation works to provide an overview of resource allocation requirements. Project data gained from the Waka Kotahi NZ Transport Agency (NZTA) through a request under the Official Information Act (OIA) in combination with award notice data published by the NZTA on the Government Electronic Tender Service (GETS) has been used to investigate the amount of transportation work that has been awarded from January 2001 to June 2021. Analysis of contract award dates and amounts showed that the level of resources required to deliver physical works transportation contracts was inconsistent throughout the period. Findings show fluctuation in the number of projects awarded, the percentage of advertised projects awarded, the value of projects awarded, and consequently, the number of labour hours required per year. In other words, the release of government-funded transportation physical works projects is inconsistent. Companies increase their capacity based on expectations of future work. Inconsistencies in actual workloads may not offer the security that companies need. Consequently, it could be unlikely that companies will increase their capacities and cope with an increase in work over the following years. Governmental agencies may find themselves competing for limited construction resources. A strategic release of physical works and transportation projects could level out the demand for construction resources and create continuity for contracting companies. This would help increase the capacity of the construction sector.

Keywords:
Capability, Contractors, Transportation work, Construction, Resource levelling

1 Introduction

High levels of investment in infrastructure projects are being made in New Zealand (Infrastructure Commission, 2020). The value of infrastructure activity in New Zealand is expected to increase gradually to $11.2 billion per year by the year 2026, with 40% of that value attributed to transport infrastructure construction (MBIE, 2021). There is a question of whether the current New Zealand civil infrastructure sector can meet the demand of public development needs in the coming years (Infrastructure Commission, 2020; Construction Strategy Group, 2019). This is a compelling question to ask when faced with the substantial programmes of planned construction projects required to be delivered to meet public development needs (MBIE, 2021; Infrastructure Commission, 2020). There is concern that the construction sector's capacity will not be sufficient to deliver such large programmes of work as planned by clients. This concern is not unique to New Zealand. Other countries, including the United Kingdom, Malaysia, and the United States, have asked the same question (Mackenzie *et al.,* 2012, Kim *et al.,* 2020).

2 Aim and Objective

This paper aims to provide an overview assessment of available government contract awards and tendering data for transportation projects to understand the construction industry's resource allocation requirements from year to year in New Zealand. Specifically, this study will focus on the transportation works contracts published on the Government Electronic Tender Service (GETS). This is a national government service provided for purchasers and suppliers to advertise and respond to tenders in competition. The award notice data from central and local governments in New Zealand, and purchase and procurement data from New Zealand's national road controlling authority – Waka Kotahi, The New Zealand Transportation Agency (NZTA) will be analysed to answer the research question. The analysis will provide an understanding of when government tenders are advertised and how much work is being put into the construction market year to year. This information will help build a picture of the transportation construction pipeline that must be matched with the resources.

3 Literature Review

To investigate whether the current resources of the New Zealand civil infrastructure sector can meet the demand of public development needs in the coming years, it is important to first understand the definition of capacity, construction procurement implications, and the role of the client.

3.1 Capacity

Research into the civil infrastructure sector's capacity must first define this term to provide context. Once the definition is clarified, methods for measuring capacity can be explored. General dictionary definitions state capacity is the maximum amount something can contain or produce. Literature is largely consistent with this definition, where capacity refers to quantity.

In terms of the construction sector, capacity has been defined by Arneson et al. (2016) as "the maximum building volume a regional construction industry can supply with available resources", where the available quantity of material resources, such as material manufacturers, suppliers, and distributors, and the available quantity of labour resource, to include contractor and subcontractor labour, determines the supply of construction. Similarly, Kauffman (2001) describes the capacity to include the number, size, experience, and equipment of contracting firms based on interviews and surveys of local contractors in Lake County, Oregon. Gill (2015) goes on to include a time component suggesting capacity in the construction sector is "the number of available resources or the output achievable to meet the operational challenges over a specified period of time". In this case, the time component encourages assessing capacity from short, intermediate, and long-range perspectives.

In the health sector, Potter and Brough (2004) present a definition of capacity building that needs to include a capacity hierarchy. The hierarchy includes performance capacity, personal capacity, workload capacity, supervisory capacity, facility capacity, support service capacity, systems capacity, structural capacity, and role capacity (Potter and Brough, 2004). This approach recognises that one definition of capacity does not articulate all the factors contributing to a lack of capacity, which also applies to the construction sector.

In some literature, capacity and capability are discussed together. Chang-Richards et al. (2016) provide a study of factors affecting the capacity and capability development of subcontractors in Christchurch, New Zealand, following the 2010 and 2011 Canterbury earthquakes. Here capacity and capability development refer to resourcing approaches influenced by the subcontractors' unique characteristics, changing circumstances in an uncertain recovery process, and internal company factors for goals and employees' needs (Chang-Richards *et al.*, 2016). Like Potter and Brough (2004), Chang-Richards et al. (2016) recognise that capacity and capability encompass many factors, including skills, finances, staff, and systems.

Literature links capacity and capability to public procurement and government responsibility, which is worth mentioning as it is relevant to this research. Latham (1994) explains that government directly affects the workload of the construction sector by financing public projects and influencing the level of demand in the economy. This may be an issue if the demand from the government exceeds the market capacity (Sykes, 2007). Multiple studies agree that capacity management is a challenge in public procurement with consequences for both government and suppliers. When government demand exceeds construction sector capacity contracting firms may reduce their staff, tender bids from consultants and contractors may be uneconomically low, training and education may suffer, and less money will be available for research and development or enhancing the industry's image (Latham, 1994). Procurement in the public sector needs to be better planned (Sykes, 2007) and better at communicating needs to the industry (OGC, 2003). Suppliers need advanced warning of expected workload to be able to meet demand and maintain confidence in the government's ability to provide steady demand (Sykes, 2007). These conclusions are echoed by Allan et al. (2008) in a study that states much of the uncertainty and volatility in the New Zealand construction industry is caused by internal system factors and manipulation of policymakers attempting to influence the domestic economy. In this paper, the focus will be on the capacity of the horizontal construction industry, specifically relating to transportation infrastructure.

The literature review identified papers to define capacity and explore the link between government clients and the workload of the construction sector. However, there is a gap in existing literature because there is no mention of how clients decide when to advertise and award a tender. As a result, this research focuses on government contract awards and tendering data to begin to gain insight.

4 Research Methodology

The research methodology follows a mixed methods approach. Statistical information from tendering data and information from semi-structured interviews was collected. GETS data was reviewed from 1197 transportation projects from July 2015 to June 2021. Projects were awarded by either NZTA or one of 37 local councils across New Zealand. Additionally, information requested via an OIA request revealed more detailed information on transportation purchases by the New Zealand central transportation agency. This data contained information from 2002 to 2017. Industry-verified estimations were used to assess project resource requirements. The estimations were verified by receiving email responses from five leading industry professionals from three different-sized contracting companies in New Zealand. The professionals were all in senior project management or tender roles within their company. Semi-structured questions focused on answering the research question were asked over the phone when professionals opted to discuss the topic further. This provided the researchers with additional details describing nuances and systematic and holistic understanding that complement the numerical analysis.

4.1 The Collection of Data

Historic tender award information was downloaded via the GETS website. The raw data was reviewed to produce a dataset of tender information relating only to transportation projects from local councils and from NZTA. GETS is an online tender service used to facilitate fair competition for contract tenders advertised by New Zealand Government agencies. Government organisations use the service to advertise tenders in various sectors to include transportation, health, social development, education, justice, defence, energy, and business. The resultant dataset contained civil transportation physical works focused tenders, excluding for example, building construction services. The OIA requested data was produced in Excel format and covers a breadth of over 3000 contracts awarded by the agency.

4.2 Review of Data

The datasets were initially analysed by reviewing the number of projects awarded each financial year for both the GETS and OIA data. This was done to understand the spread of transportation works contracts released each year. In the GETS data the percentage of tenders awarded and not awarded also became apparent.

Further analysis used descriptive statistics to assess the contract award amounts. Of the tenders listed 31% included a contract award amount. These award amounts were used to assign indicative values to the total number of tenders awarded and were used to understand and estimate potential labour hours required per year.

4.3 Assessment of Construction Resources

To assess the relative labour requirement from year to year, commonly accepted construction estimations were applied. The labour cost of a transportation construction project can be estimated as being one third of the project value, as the cost of labour is roughly 30–50% of the total construction costs (Shan *et al.*, 2015; Ghodrati *et al.*, 2018). The labour requirement portion of the tender award amount was determined using this estimation.

Table 1. Project composition and hourly rates

	Number of employees per project		
	Small project	Medium project	Large project
Number of employees at $64.00/hr	3	50	200
Number of employees at $103.00/hr	1	3	5
Average hourly rate for project	$73.75	$66.21	$64.95
Average hourly rate across all project sizes	$68.30		

Additionally, an overall average hourly rate was derived for a current labour rate across small, medium, and large projects. Table 1 displays the derived average labour rate. The rate was produced by assessing the labour requirements for different-sized New Zealand transportation projects. During the semi-structured interviews industry professionals were consulted to ensure that the values in Table 1 were up to date at the time of writing.

5 Results and Discussion

The OIA dataset for the number of transportation related projects awarded shows that the number of tenders awarded per year fluctuates greatly from year to year. Figure 1 below indicates the fluctuation can be up to 107% compared to the previous year.

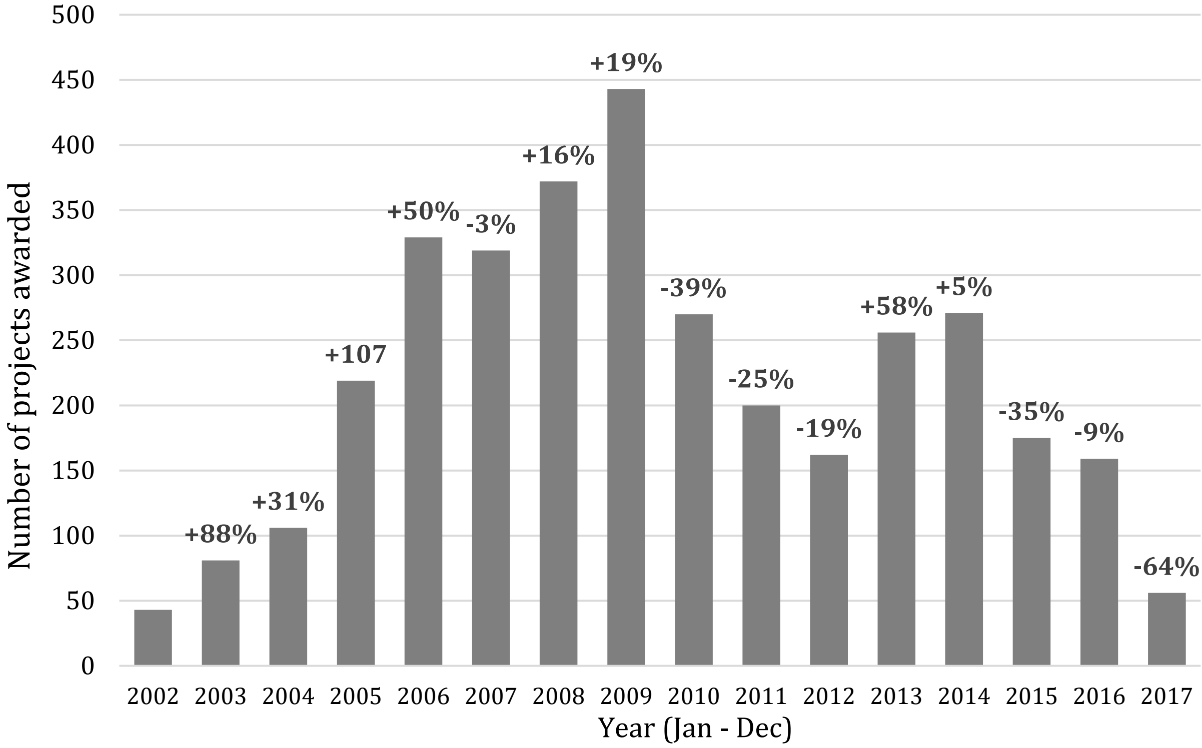

Figure 1. Estimated number of contracts awarded per year where the average change year on year is 38% (based on the OIA data)

Figure 2 shows the proportions of delivery methods used in the OIA data for contracts awarded that were greater than $40 million in value. Results show that maintenance related contracts, that is, Maintenance, Performance Specified Maintenance Contracts (PSMC, Gransberg et al. 2010), and Network Outcome Contracts (NOC) make up ~45% of the total number of awarded contracts. While delivery methods typically associated with capital works, for example Alliance (Scheepbouwer and Gransberg, 2014), Design and Construct (D&C), and Early Contractor Involvement (ECI, Scheepbouwer and Humphries, 2011) make up ~ 28% of projects over $40 million. The remaining delivery methods for projects, Measure and Value (M&V), Lump Sum (LS), Professional Services, Physical Works/Construct only, and Not Defined make up 27% of projects over $40 million.

This information shows that maintenance related work makes up a significant amount of investment in New Zealand and is immensely important when assessing the capacity of the horizontal construction sector.

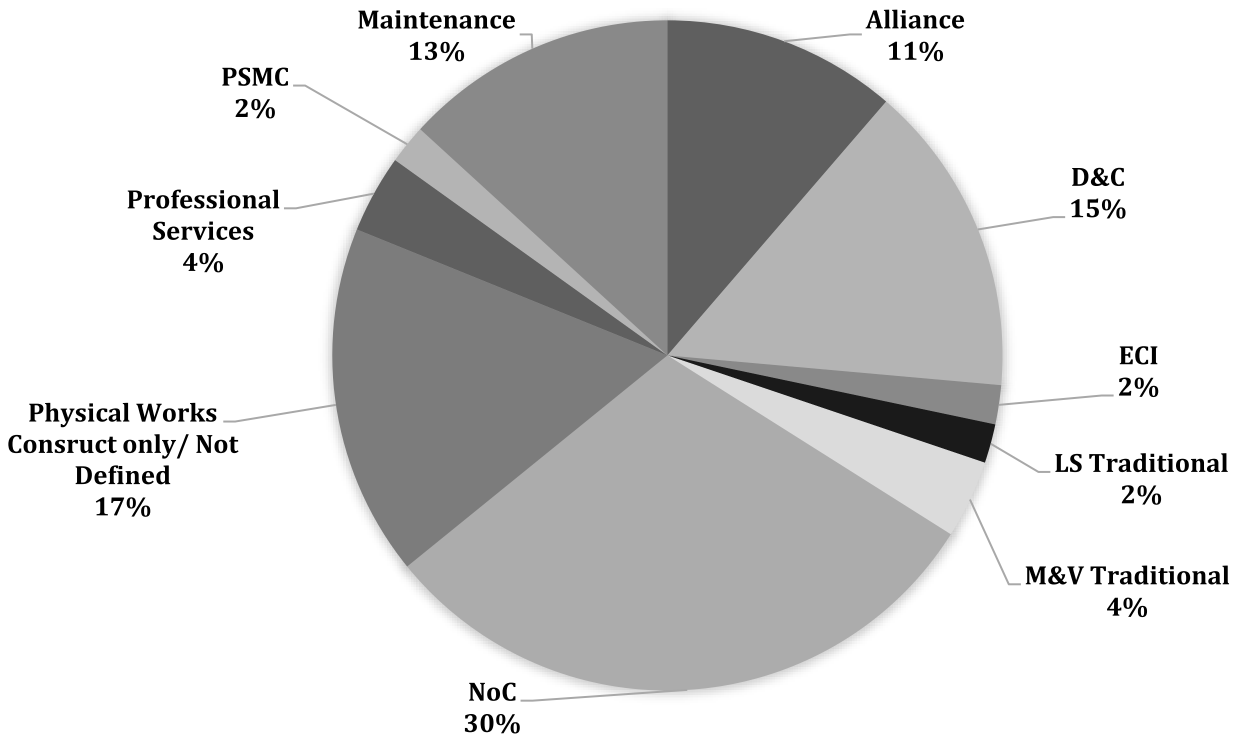

Figure 2. The break-up of delivery methods used for contracts over $40M awarded from 2002 to 2017 (OIA data)

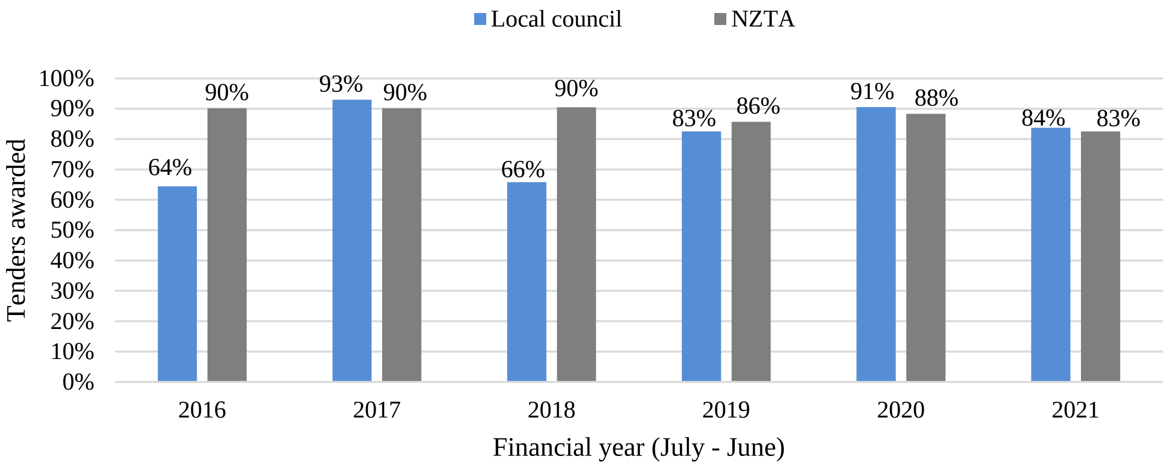

Figure 3. An estimate of the tenders awarded per financial year, as a percentage of tenders advertised (GETS data)

The GETS data shown in Figure 3 indicates that tenders advertised by NZTA are awarded 88% of the time on average. Similarly, tenders advertised by local councils are awarded 80% of the time on average over the six financial years shown in Figure 3. As a result, there is more variability year to year in local council tender award rates than in NZTA tender award rates. Of those advertised, the percentage of tenders that end up being awarded is inconsistent from year to year. This means that even if the industry is seeing plenty of work advertised to the market, there is still no guarantee of the quantity of work.

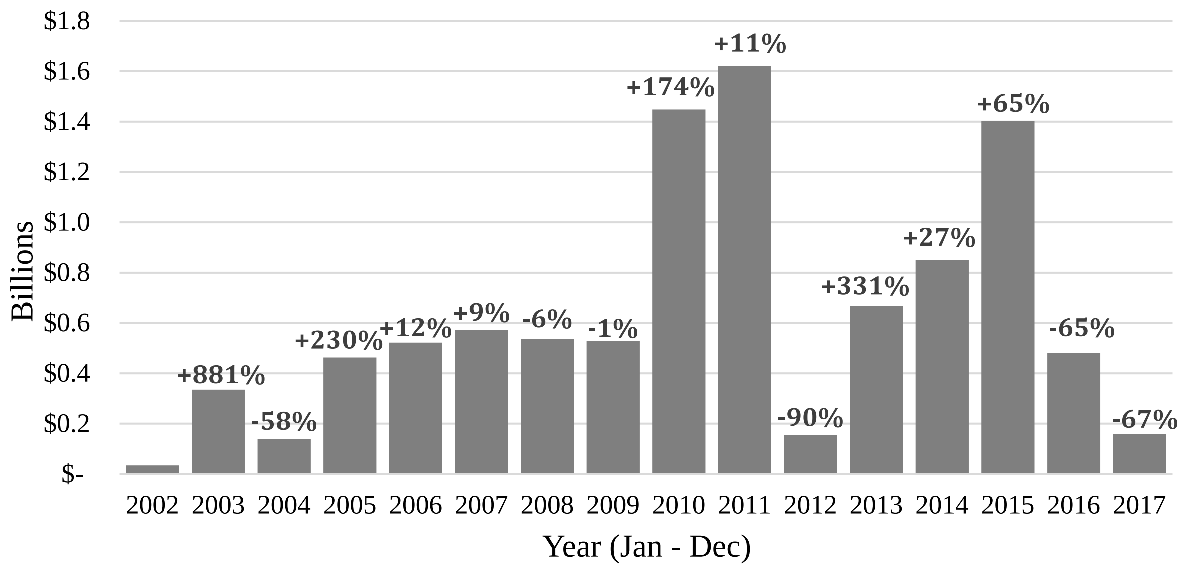

Figure 4. An estimate of year-to-year value invested in transportation (excluding inflation) based on accepted contract award amounts reported from 2002 – 2017* (OIA data)

Figure 4 shows an inconsistent but slow growth of spending between the periods of 2002 – 2009. In 2010 and 2011, spending increased dramatically. This increase can be attributed to a list of major infrastructure projects, one of which was above $1 billion. In the 2015 period spending increased significantly again, this largely attributed to multiple large projects and the release of multiple maintenance contracts. While Figure 4 shows the accepted contract value, it does not show the actual cost, or how the amount is allocated and over what time period.

The fluctuation in the number of projects awarded, the percentage of advertised projects awarded, and notably the value of projects awarded can be used to estimate the fluctuation in the number of labour hours required per year. The estimated labour hours required per year for transportation-related contracts awarded were calculated using the estimations described earlier, as displayed in Table 2.

Table 2. Conservative estimate of labour hours and FTE (Full Time Equivalent) using average rate (Table 1) and OIA data (excluding inflation)

Financial Year	OIA Data (Hours)	FTE (2000hr per year)	Financial Year	OIA Data (Hours)	FTE (2000hr per year)
2002	199,826*	111*	2010	8,483,881	4,242
2003	1,961,990	981	2011	9,498,590	4,749
2004	820,394	410	2012	904,617	452
2005	2,708,760	1,354	2013	3,907,180	1,954
2006	3,055,364	1,528	2014	4,979,693	2,490
2007	3,348,207	1,674	2015	8,219,282	4,110
2008	3,142,309	1,571	2016	2,815,838	1,408
2009	3,090,348	1,545	2017	927,284*	464*

6 Discussion, Conclusion and Further Research

The presented result supports the concern of the New Zealand construction industry around the inconsistency of the number and value of tenders awarded each year. Government clients provide little uniformity in planning resource allocation to deliver the projects. This greatly impacts small construction companies, requiring certainty of future work to allocate resources to stay afloat. Efficiently planning to ensure continuity of work and productive use of assets is of the utmost importance for construction companies' bottom line, especially if running on low margins, which is common in the construction sector. A lack of certainty of future work disrupts the ability to plan efficiently and potentially provide better value for the client. Inadvertently Government agencies may be competing for construction resources by releasing tenders during a similar period. This often happened due to a lack of communication between client organisations, limiting prior knowledge of other agencies' release of tenders. Additional research should be conducted to understand the level of certainty necessary to alleviate the negative impacts of poor resource planning and fluctuating demand for resources.

This paper provided a preliminary assessment of tender data for transportation projects to answer the research question. The results showed that the number of transportation project tenders awarded was inconsistent from year to year. The number of projects awarded in a year fluctuated dramatically compared to the previous year. Additional research would be necessary to understand the impact of fluctuating resource requirements and the level of certainty required by the construction industry to improve resource allocation planning.

The yearly demand for construction resources, including labour, material, and equipment, would be more consistent if transportation projects were released strategically and coordinated. This would lead to positive outcomes such as less uncertainty for contracting companies, more continuity of work, and more effective utilisation of resources, enabling more work to be delivered.

Understanding the characteristics that define tender award timing for public sector civil infrastructure projects is pertinent. These characteristics may affect contractor responses to tenders and, ultimately, the alignment of development needs and project delivery. In other words, it is important to understand how and why contractors bid for work. It is arguably as important to understand New Zealand public sector tender award factors and the effect they can have on shaping the competitive construction market, which will deliver the work. However, despite numerous papers outlining procurement methodologies and guidelines, existing literature does not mention how clients decide when to advertise and award a tender.

The following factors limit this preliminary research:

- The impact of natural disasters, such as earthquakes and flooding, on recourse allocation needs to be further investigated. This is particularly important in the context of New Zealand.
- The accepted contract cost is not equal to the actual project cost, so the estimated values in Table 1 are most likely conservative.
- Figure 1 shows fluctuation in the number of projects awarded rather than the value of projects awarded. This does not account for possible variation in the total value awarded each year and duration. For example, fewer high-value projects may be awarded one year,

while a larger number of low-value projects may be awarded the next year with different durations.
- The analysis does not account for the duration of projects. NOC projects can often last five-plus years and spread the value of the contract over multiple years. Additional money is paid in some circumstances also.
- Much of the earlier data from the OIA data request seemed to be missing or incomplete. This may significantly impact on the accuracy of the results presented here.
- The GETS data is input by a wide variety of people. Such diversity increases the possibility of incorrect data and missing information, which was witnessed in the dataset.
- Tender award amount information was missing from the GETS data. Award amounts were reported for approximately 30% of the projects.
- Nearly one-third of the GETS tenders were for one region in New Zealand. This dataset may not be representative of the construction market in New Zealand.

7 Acknowledgement

This paper acknowledges the funding of the New Zealand Ministry of Business, Innovation and Employment, Endeavour Programme Research Grant. Contract Number: MAUX2005.

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Challenges in Measuring the Construction Sector Capacity: Lessons for New Zealand

An Thi Hoai Le[1*], Niluka Domingo[1] and Monty Sutrisna [1]

[1]School of Built Environment, Massey University, Auckland 0632, NEW ZEALAND

A.lethihoai@massey.ac.nz; N.D.Domingo@massey.ac.nz, M.Sutrisna@massey.ac.nz
* Corresponding author

Abstract:
The construction sector plays a large role in New Zealand's economic development. It has a significant impact on other industries and the nation's wealth and well-being as well. Over the next 25 years, the construction sector is forecasted to deliver over 90 billion in infrastructure, residential and non-residential pipeline projects in New Zealand. However, concerns about the ability of the industry to deliver expected demands have been raised due to capacity limitations urging the demand to understand the current sector capacity. This study conducted a narrative literature review to investigate different aspects of measuring the construction sector capacity, including examining existing measuring models. Findings from the literature review found various challenges in measuring the sector capacity, including complexities of definitions, levels, components, and methods to measure capacity and limited access to required data. The findings provide a fundamental step for future research to identify indicators and methods to help measure New Zealand's construction sector capacity.

Keywords:
Capacity development, Construction industry, Measuring capacity, New Zealand

1 Introduction

The ability to deliver projects of the construction sector is affected by economic fluctuations (Ercan, 2019). For example, in high-demand periods, the construction sector usually suffers from lacking resources and expertise. However, in downturns, it witnessed significant job losses in the construction sector more so than in other sectors (PwC, 2016). Therefore, understanding the "ability" to deliver is vital to maintain stability and certainty in the construction sector. Meanwhile, capacity is an important economic measure to identify potential output in consideration of the capital stock, existing regulations, and the state of technology (Shaikh and Moudud, 2004, Kirkley and Squires, 2003). Therefore, measuring capacity help identify whether the sector is over/under-investment in stock resources and taking advantage of market changes (Kirkley et al., 2002, Squires and Segerson, 2020).

The question of how to measure the sector capacity is still challenging. The typical measuring approach is known as the technological approach, which is defined as "the maximum sustainable level of output that can be reached under normal input conditions" and "fully employing" the variable inputs (Klein et al., 1973). In either approach, economic capacity defines the firm's benchmark level of output based on optimising economic behaviour (Squires and Segerson, 2020). The term "capacity utilisation" also refers to the economic capacity which is defined by actual output divided by capacity (Morrison, 1985) and to identify whether the industry is over/under capacity and how efficient it is. Other researchers and organisations established sets of indicators to measure different aspects of capacity, such as organisational capacity (IFC, 2017), and regional capacity (Arneson, 2018). Unfortunately, the current capacity measurement approaches seem not to be able to assess all these aspects of the construction sector capacity.

Hence, this study aims to investigate the dimensions of the construction capacity for the future development of a capacity measurement model for the construction sector. The paper conducts a critical literature review of different aspects of capacity, existing models for measuring the construction capacity and different types of data used for the measurement.

2 Literature Review

2.1 Defining the scope of the construction sector

It is necessary to set boundaries for the construction sector to determine where it begins and ends to measure its capacity. Figure 1 illustrates the construction sector's input-output process and its key players that help us to understand the inputs required to produce potential outputs in the construction sector. The key inputs are divided into "primary" inputs, including workforce, capital and land, and "intermediate" inputs such as materials, equipment, transport, storage and professional services. Although the input-output process should be further broken down to the value of each input needed to produce a set amount of output, it is possible to check different output scenarios for construction based on the availability of the key inputs (Lowe, 2009). The intermediate outputs in the construction sector are maintenance and repair of the existing stock, including both public and private sectors and residential and non-residential buildings. The outputs can be categorised into different project types for the public and private sectors in terms of new buildings and facilities.

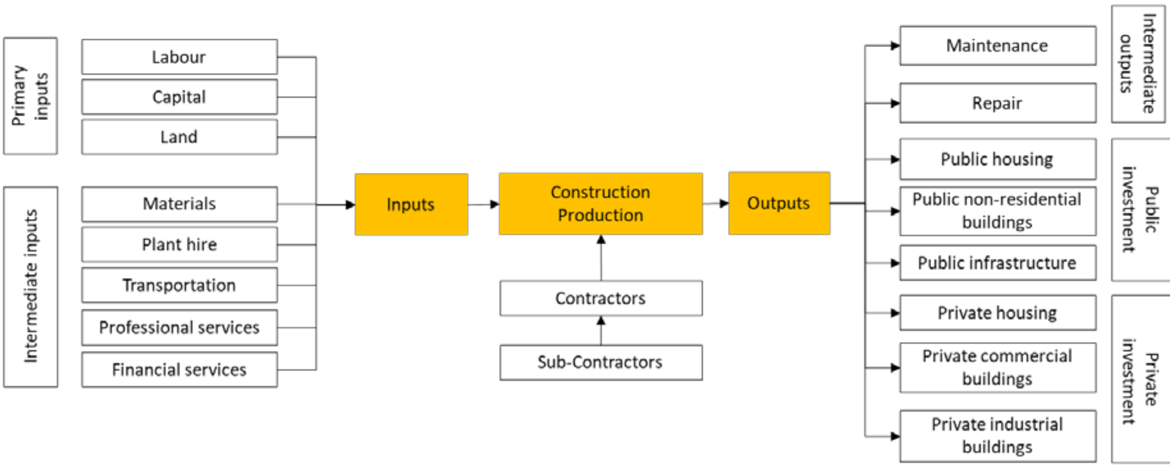

Figure 1. Construction input-output process. Adapted from Lowe (2009)

The construction sector boundary typically consists of on-site assembly, including the construction of buildings and infrastructure, specialised construction activities such as site preparation, building installation and building completion (Lewis, 2009). On the other hand, Foulkes and Ruddock (2007) suggested that analysing "the construction" should include the construction production, operation of the constructed assets, professional services and the supply-chain for construction-related products such as mining and manufacturing to capture the true scope of the construction activities. For example, Carassus (2004) created new boundaries for the construction sector, which is made of three groups of activities as below:

- Group 1: construction related services: management of the existing stock of structures, including asset management, property management and facilities management
- Group 2: core construction: project management, implementation, and assembly activities to create a new structure or facility

- Group 3: construction related services: material manufacturing and distribution, implementation and assembly activities of equipment and plant on worksites

2.2 Defining capacity

There are many definitions of capacity and no broadly accepted definition. Capacity is defined as the ability to carry out stated objectives and capacity exists to perform a certain action or enable performance (Brown, Lafond, & Macintyre, 2001). Somarriba-chang, Nacional, & Una (2014) described “organisation’s capacity is its potential to perform—its ability to successfully apply its skills and resources to accomplish its goals and satisfy its stakeholders’ expectations”. UNDP (2010) offer a more detailed definition of capacity as “the ability of individuals, institutions, and societies to perform functions, solve problems, and set and achieve objectives in a sustainable manner”. Some practitioners and analysts see capacity as a humane resource issue dealing with skill development and training at the individual level (Alsop and Kurey, 2005). Many other analysts accept the broader scope of capacity, which includes the ability to deliver and general management problem-solving to implement better at the organisational level (Backer, 2000). Despite the lack of clarity in the literature about the definition of capacity, Morgan (2006) suggests there are five central characteristics of the concepts of capacity:

- Capacity is about empowerment and identity that makes people act together and allow an organisation or system to survive, grow, diversify, and become more complex
- Capacity has to do with collective capabilities that enable a system to perform, deliver value, establish relationships and renew itself
- Capacity as a state or condition is inherently a systems phenomenon. It comes out of the dynamics involving a complex combination of attitudes, resources, strategies and skills, both tangible and intangible
- Capacity is a potential state that may require different approaches to its development, management, assessment, and monitoring
- Capacity is about the ability of a group or system to make a positive contribution to public life

In the construction field, O’Brien and Fischer (2000) distinguished two definitions of capacity. The first capacity definition is for manufacturing concept so the capacity can be defined as the maximum productive output of a firm’s resources, which usually refers to suppliers’ capacity. The second definition is about contractors’ capacity which is determined by their labour and equipment resources. Arneson (2018) introduced the concept of construction capacity as the maximum building volume that a construction industry can supply due to the supply chain availability of labour and materials. Tucker et al. (2015) defined capacity is ability to innovate, having adequate human resource (staff size), technical and managerial skills, technical ability, financial capital and experience. Although the capacity definition varies in different sectors, it can be understood as the ability and resources of the sector/organisations to deliver their projected plans and achieve their development goals.

3 Research Methodology

This study used the narrative review approach to identify the challenges facing measuring capacity in the construction sector. This review used the “SCOPUS” database for the search because SCOPUS has a large array of the indexed journal in the construction field (Hong and Chan, 2014). The search was conducted using the keywords “construction” and “capacity” in the title. The initial search on the SCOPUS database returned a total of 609 papers. Then, the search was limited to articles published in the English language; published in journals; since 2000; and engineering field resulting in a selection of 94 papers. These papers' full titles and abstracts have been read to remove irrelevant papers. Also, duplicate articles were removed. In the end, nine relevant articles were used for the study; of which only five papers discussed the capacity measurement of the construction sector. The sources of the relevant articles are summarised in Table 1.

Table 1: Source of the selected articles (sorted by published-years)

References	Title	Published by
O'Brien and Fischer (2000)	Importance of capacity constraints to construction cost and schedule.	Journal of Construction Engineering and Management
Lowe (2009)	Capacity of the UK construction sector	The Construction and Building Research Conference of the Royal Institution of Chartered Surveyors
Tucker et al. (2015)	Exploring the use of financial capacity as a predictor of construction company corporate performance	Journal of Engineering, Design and Technology
Chang-Richards et al. (2016)	Capacity and capability development of Canterbury subcontracting business: Features, motivating factors and obstacles	Building Research Association of New Zealand
Arneson et al. (2018)	How construction capacity affects housing reconstruction in Tornado Valley	Construction Research Congress 2018
Mishra (2018)	Assessment of Human Resource Capacity of Construction Companies in Nepal	Journal of Advanced Research in HR & Organizational Management
Ercan (2019)	Building the link between technological capacity strategies and innovation in construction companies	Sustainable Management Practice
Offei et al. (2019)	Factors Affecting the Capacity of Small to Medium Enterprises (SME) Building Construction Firms in Ghana	Journal of Construction in Developing Countries
Kamal et al. (2021)	Absorptive capacity of Malaysian SME construction organisations	Architectural Engineering and Design Management

4 Findings and Discussion

4.1 Different dimensions of the construction sector capacity

With thin the construction management research, few studies have been done to capture capacity in certain aspects of the construction sector as summarised in Table 2. The previous work usually investigated on foundational components or elements of the construction capacity, such as financial capacity (Tucker et al., 2015), human resource capacity (Mishra, 2018), technological capacity (Ercan, 2019), absorptive capacity (Kamal et al., 2021), supply chain capacity (Arneson, 2018), contractors' capacity (Asante et al., 2018, Offei et al., 2019), the sector's capacity (Lowe, 2009). Other studies identified factors affecting subcontractors' capacity, including internal factors (company's vision/strategic goal, employee's needs and skills structure), external factor (industry structure, procurement environment) (Chang-Richards et al., 2016).

Table 2: Aspects of the construction sector capacity

Terms of capacity	What it measures	References
Financial capacity	Financial Capital Structure and Net Assets can be used to predict the company's financial performance (turnover).	Tucker et al. (2015)
Human resource capacity	Human resource capacity is about ensuring that an organisation has enough people with the necessary skills to achieve its objectives.	Mishra (2018)
Technological capacity	Is the ability to find and use technology to maintain and achieve competitive advantage, to enhance and modernise the company's productivity and performance	Ercan (2019)
Absorptive capacity	Is the ability to be able to absorb and leverage from new technologies, and knowledge.	Kamal et al. (2021)
Organisational capacity	Organisational capacities include both its resources (such as human, financial, technology, information, infrastructure resources) and its management capacities (such as strategic leadership, program and process management, and networking)	Offei et al. (2019); O'Brien and Fischer (2000)
Construction capacity	The construction sector's capacity to identify whether the sector is under/excess capacity.	Arneson (2018); Lowe (2009); Chang-Richards et al. (2016)

4.2 Existing models in measuring the construction capacity

Only five studies in the search developed a model to measure one or more aspects of the construction capacity. Different kinds of data have been used to measure the sector capacity. The data collection methods can be categorised and presented in Table 3 as follows:

- "hard" data, such as the construction resource cost indices, tender price indices (Lowe, 2009), data for wholesale material and labour cost (Arneson, 2018);

- subjective assessments, e.g. interviews with knowledgeable people or selected case studies (Mishra, 2018, Ercan, 2019, Tucker et al., 2015);

- survey results, similar to the subjective assessment, require large numbers of participants, thus reducing the risk of individual bias (Ercan, 2019).

Lowe (2009) and Arneson (2018) developed their models using "hard" data. Lowe (2009) analysed the construction sector capacity status (under/excess capacity) based on the change in construction resource cost indices (RCI) (Equation 1) and tender price indices (TPI) (Equation 2). RCI measures prices change for the key inputs used by the construction sector, such as materials, components, and labour.

$$\Delta RCI\ t = (RCI\ t - RCI\ t\text{-}1)/RCI\ t\text{-}1 \times 100\% \quad (1)$$

Where RCIt = Resource cost index for quarter t; RCI t-1 = Resource cost index for quarter t-1 ΔRCIt = Change in resource cost index from quarter t-1 to quarter t

$$\Delta TPI\ t = (TPI\ t - TPI\ t\text{-}1)/\ TPI\ t\text{-}1 \times 100\% \quad (2)$$

Where TPI t = Tender price index for quarter t; TPI t-1 = Tender price index for quarter t-1; ∆TPI t = Change in tender price index from quarter t-1 to quarter t

The industry is assumed to be below economic capacity if the change of RCI runs ahead of the the change of TPI and vice versa. The results can inform the decision makers in terms of the level of capacity working for the construction sector so they will issue suitable policy strategies for the sustainable development of the sector.

Table 3: Aspects of the construction sector capacity

Model	Indicators	Data sources
Lowe (2009)	Construction sector capacity: Construction resource cost indices (RCI) and tender price indices (TPI)	UK, hard data, BCIS General Building Cost Index; BCIS All in Tender Price Index; Building Cost Indices
Mishra (2018)	Human resource capacity	Nepal, questionnaire survey, 40 valid responses from contractors
Ercan (2019)	Technological capacity	Turkey, questionnaire survey, 91 contractors responded
Tucker et al. (2015)	Financial capacity	South Africa, questionnaire survey, 65 valid responses of building and civil engineering contractors.
Arneson (2018)	Regional supply chain capacity: unit labour cost, material capacity utilisation (roofing)	US, hard data, the U.S. Bureau of Labor Statistics (BLS) and the U.S. Census Bureau, based on NAICS codes.

Using similar hard data, Arneson (2018) measured regional construction capacity using regional unit labour cost and capacity utilisation. The regional unit labour costs in the study reflect the cost of labour required to generate output, as shown in Equation 3 (Pancotto and Pericoli, 2014), which “indicates the economic value of roofing construction work generated within a region for every $1 of annual wages paid to roofers”. Therefore, the results can tell which regions are more efficient at mobilising labour resources in the roofing sector in the US.

$$\text{Regional unit labour cost} = \frac{1}{\frac{Regional\ annual\ average\ wage}{Regional\ net\ value\ of\ construction\ installed}} \quad (3)$$

On the other direction, the regional material capacity utilisation indicates the available material stock inventories within a regional construction supply chain (Mulligan, 2017). For the residential roofing sector, capacity utilisation was calculated as the ratio of demand over supply for roofing materials, as shown in Equation 4.

$$\text{Regional capacity utilisation} = \frac{Cost\ of\ material, components\ and\ suppliers}{Whole\ trade\ sale} \quad (4)$$

The regional capacity utilisation can be over or under 100%. If the regional capacity utilisation is over 100%, the wholesale establishments within the region do not maintain an adequate material inventory and could not meet customer demand for roofing materials. This view is supported by Walsh et al. (2004), who stated the high capacity utilisation rates often reflect high demand for construction services.

Regarding “soft” data, Tucker et al. (2015) explored the use of financial capacity as a predictor of construction company performance with 12 indicators of financial capacity, including the value of annual contract works (turnover), the value of annual loans obtained, the growth rate of organisational profit status, organisational asset status, organisational profit status, effective communication with financial institutions, knowledge about financial policy, the growth rate of organisational total asset, payment to sub-contractors/suppliers on time, the capability of loan repayment, and organisation debt status. Mishra (2018) assessed the human resource capacity of construction companies in Nepal. The human resource capacity (HRC) was found to ensure that the organisation has enough people with the necessary skills to achieve its objectives. The HRC also referred to the system of recruitment, training, team development, boarding program, benefits, health and safety and performance appraisal. Different indicators for measuring the technological capacity of the contractors were found, such as staff technological skills, on-job training scheme, investment in R&D, and top management’s supports (Ercan, 2019). The “soft” data usually is obtained by collecting knowledge and experience of experts or knowledgeable people using either nominal measurement scales (yes/no, active-non active) or ordinal measurement scales (Likert scale).

4.3 Challenges in measuring construction sector capacity

Previous studies revealed that there are limited attempts to measure the construction sector capacity. Only one study tried to measure the whole sector capacity; one research discovered the regional capacity, and few studies measured different dimensions of the construction capacity. However, no research measures the organisational capacity, which reflects the organisation’s resources and management capacity. Some reasons behind this can be explained as follow:

Various aspects of the construction sector capacity

As discussed above, typical construction projects often involve several organisations joining the project to perform specific and short-term tasks/missions. The sector capacity should be developed in conjunction with Figure 1 and cover the “wider” scope of the construction sector (core construction and construction-related services). Furthermore, the players that influence the sector capacity are clients, contractors/sub-contractors and consultants, manufacturers and distributors, institutional actors and regulators, and associations. Although some aspects of the construction sector have been explored, measuring the sector capacity considering all aspects (i.e., financial, technological, human, and equipment resources) and relationships between organisations involved in the sector (i.e., communication and collaboration capacity) is still challenging and needs to be explored in greater detail in future work. This challenge should be addressed by develop a holistic construction sector capacity framework which helps mapping all aspects of the sector capacity and their interrelationships. As the result, stakeholders can understand where to start measuring capacity and how.

Limited access to “hard” data

Ideally, a construction sector capacity index would be constructed entirely from hard data (Polidano, 2000). However, there is insufficient hard data to capture the sector capacity, especially to measure various intangible aspects of the construction sector capacity. As discussed in Section 3, the "hard" data, such as building cost index, or tender price index, was provided by Government departments and organisations or national data centre services. Therefore, more cooperation between research institutions and Government agencies should be established to understand which data needs to be generated from the data centres for measuring the construction sector capacity and how should structure the data collection system. Furthermore, as construction is made up of a core construction industry and construction-related services, it has not always been able to separate the core and construction-related services if the construction statistic data does not permit it. For example, in the Australia and New Zealand Classification system, the construction-related service includes Professional, scientific and technical services, but it cannot be isolated from broader industry data (Author, 2021). This challenge can be addressed by clearly defining the boundaries of the construction sector in conjunction with the reliability of collecting the related data for the measuring system.

The complexity of measuring methods and indices

Due to the various dimensions of the construction sector capacity, the indices are feasible, provided it is considered acceptable to rely on subjective ratings and hard statistical data (Polidano, 2000). Traditionally, hard statistic follows standards of the national classification system and sometimes it does not allow capturing certain aspects of the construction sector capacity. For example, Statistic New Zealand publishes the number of businesses and employees working in the core construction nationally, but the information is not available regionally, so it cannot capture the regional capacity utilisation. This issue can be solved if we can identify information needed and how to collect the information before the data collection phase. On the other hand, "soft" data is often collected using different techniques and rating systems. Consequently, the measuring system might be inconsistent. Therefore, there is a need to develop a set of indicators for "soft" data which should be validated by some case studies. Hence, companies and organisations can commonly use the set of indicators to measure their "soft" capacity.

5 Conclusion and Further Research

This review presents foundational elements of the construction sector capacity, which allows to development of a novel model to measure the construction sector capacity. The findings of this study contribute to the body knowledge by providing a review of different dimensions of the sector capacity, which can aid policymakers and organisation managers in measuring their capacity against the identified indicators. The findings serve as a starting point for future research to establish a holistic measuring system which can capture all the dimensions of the sector capacity. The study also addressed three major challenges in measuring the sector capacity. Future research should find solutions to collect both "hard" and "soft" data systematically or develop indicator systems which can take advantage of the available "hard" statistic. Despite this study's contributions, it still has a limitation. Due to the limited resources, this study concentrated on publications on the Scopus database only; thus, our future research will examine publications in other academic sources and Government or industry reports as well.

6 Acknowledgement

The paper acknowledges the funding of the New Zealand Ministry of Business, Innovation and Employment, Endeavour Programme Research Grant. Contract Number: MAUX2005.

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Capacity Modeling for the Construction Industry; An Initial Framework

Azam Zavvari[1*], Mostafa Babaeian Jelodar[1], Monty Sutrisna[1], Teo Susnjak[2], Arun Kumar Manickavasagam[3]

[1]School of Built Environment, Massey University East Precinct Albany Expressway, SH17, Albany, Auckland 0632
[2]School of Mathematical and Computational Sciences, Massey University East Precinct Albany Expressway, SH17, Albany, Auckland 0632
[3]Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch 8041, NEW ZEALAND

a.zavvari@massey.ac.nz; m.b.jelodar@massey.ac.nz; m.sutrisna@massey.ac.nz; t.susnjak@massey.ac.nz; arun.manickavasagam@canterbury.ac.nz

Abstract:
Similar to any other industry and associated sectors it is critical for significant stakeholders involved in construction activities to understand demand and supply and how this determines capacity. Evaluating capacity is essential for meaningful future work planning in any industry. However, at such levels of planning, the construction industry has traditionally faced many uncertainties and issues. This is associated to the project-based and inherently fragmented nature of the industry with poor record keeping and information sharing. This study focuses on construction capacity by evaluating the pipeline of construction work and the sectors associated with the pipeline. The main aim of this study is to create a model for comparing characteristics of the pipeline and sector data to assess and improve capacity in the New Zealand construction sector. The methodological approach used in this study is a mixed methodology based on a literature review and a case study from the New Zealand construction industry. A review of the literature aided the authors in the first stage of addressing supply and demand issues in the construction industry. The construction-related data was then used in a case study approach to develop the conceptual framework to predict the capacity of the market. Accordingly, a model concept is developed based on the properties of the sector associated with the pipeline of projects. The proposed concept enables capacity modelling; a review is provided on the evolution of capacity models for use in construction systems planning and investment and an initial capacity model is proposed and discussed.

Keywords:
Capacity, Complexity, Construction, Modelling, Sector

1 Introduction

The construction sector can be divided to horizontal and vertical. Horizontal sector projects are mostly government-funded, such as railroads, bridges, highways, and airfields and usually have more length and width than height. Vertical sector projects such as apartment/commercial buildings typically have a greater height than the length with projects usually depend on private sources of funding. Both horisontal and vertical sector projects are significant for the society and economy (Lee and Shin, 2017).

In the construction industry, definitions of capacity are inconsistent and typically ambiguous. Capacity can have varying definitions depending on the context, i.e. technological, economic, planning situation and so on (Hillebrandt, 1984). Capacity can also be defined at different granularities such as individual, organisation, or industry. Previous studies have looked into individual capacity based on skills, knowledge, and experience that allow people to perform their roles in an organisation. Another level of capacity usually involves a breakdown into the different parts of an organisation, like finance, service management, and operational capacity. Capacity can also be evaluated at industry-level for greater governance of the industry, effective resource planning and decision-making (Mason et al., 2020, Walters, 2020, Savvidis et al., 2019, Jiao et al., 2019). The inter-relationship of relevant project stakeholders, i.e. contractors, sub-contractors, skilled workers, labour and so on represent the supply side of the industry. Construction works are typically planned in advance and these future projects form the pipeline of work to be done and represent the demand of the industry. Pipelines as an indication of upcoming projects are a common concept used in infrastructure planning and investment discussions (Zhu et al., 2021, Moradi et al., 2019).

This study uses available datasets to investigate the imbalance pattern of supply and demand in the construction industry and then demonstrate the relationship between supply and demand. Therefore, the focus of this study is to evaluate capacity through the assessment of supply and demand in construction. The study proposes a modelling framework to compare supply and demand in New Zealand as part of CanConstructNZ research programme.

2 Literature Review

Supply is the utilisation of resources, such as materials, technology, skills and so on to satisfy demand (Weddikkara and Devapriya, 2001). There is a general concern about the ability of the construction sector to cope with the demands currently being placed on it by the Government and private sectors, and there is an interest in being able to forecast the future capacity of the sector (Wong et al., 2010, Sing et al., 2015, Liu et al., 2015, Squires and Segerson, 2020, Lowe, 2009). Several studies have investigated and tried to model capacities such as workforce, capital cost, workforce, and skills. A model was proposed using construction cost as a predictor indicator for highway project activities in Texas to forecast the workforce (Persad et al., 1995). Based on a computer model, a cost escalation model was proposed in large long-term construction infrastructure projects (Touran and Lopez, 2006). After a sizeable boom in the 1990s followed by an economic downturn, reliable employment planning became critical for the Hong Kong construction industry and a. workforce demand modelling was proposed in the case of Hong Kong (Wong et al., 2010). To improve the performance of transportation infrastructure assets, a case study was then proposed to model the capability of assets. In another study, the Australian's construction demand was modelled to predict the workforce (Liu et al., 2015). Additionally, a model for forecasting construction work was proposed based the basic economic indicators: gross domestic product, vacancy rate, and property price index to get a view of private sector work demand (Sing et al., 2015).

Capacity is a dynamic term, and there are various definitions for capacity in the literature. For example, the United Nations Development Program (UNDP) defines capacity as "the ability of individuals, institutions, and societies to perform functions, solve problems, and set and sustainably achieve objectives". There are different approaches to measuring capacity. In different research, some approaches are listed, such as the input-output approach, time-series approaches, and approaches linking output to resource inputs. Each approach is accompanied by its challenges (Squires and Segerson, 2020, Lowe, 2009). In order to quantify capacity, it is first necessary to identify the main indicators of capacity. Based on the literature, the key indicators for capacity should be identified based on the scope of work, for instance, projects published as part of the client organisation in the pipeline and depending on the projects in the sector side (Biukšāne, 2015, Bakkour et al., 2015). The identified initial capacity indicators for this paper are listed below:

- Human resources (Mishra and Adelung, 2018)
- Financial (Tucker et al., 2015)
- Technology-equipment (Ercan, 2019, Kamal et al., 2021)
- Material (Arneson, 2018, Sen, 1993)

The construction sector is project-based and functions based on temporary organisations, with an embedded and inherent level of complexity (Pauget and Wald, 2013). This directly affects the pipeline and the type of projects performed within the industry. Additionally, the characteristics of the construction sector are difficult to identify as it is demand-driven, dynamic, and constantly in exchange with other sectors, especially at more granular workforce and trades levels (Persad et al., 1995, Sing et al., 2016). Information availability issues and uncertainties around databases make any specific data collection process multifaceted and time-consuming ((Eliwa and El-Morshedy, 2022)). Such evaluation also requires a diagnostic approach that can enable tracking of changes to the pipeline and sector over time.

3 Methodology

This study adopts a longitudinal mixed research approach to the problem of capacity and capability evaluation. It involves a mix method approaches assessing the pipeline of work, construction sector, and recorded databases available over a period of time (Babaeian Jelodar et al., 2022, Shelton et al., 2016). The challenge in evaluating and estimating capacity and capability is that it is multidimensional, and these concepts are unstructured by nature. Therefore, the mixed research approach is popular in construction research, particularly in dealing with unstructured knowledge areas. The methodology section covers the two parts consisting of the conceptual framework and case study.

3.1 Conceptual framework

The proposed modelling framework is comprised of four stages. These high-level stages are depicted in Figure 1. In the first stage, the capacity is quantified by drawing data from the human resources (contractors and suppliers/sub-suppliers), financial, technology-equipment and materials indicators. Likewise, the project pipeline data is quantified by collating data from the following indicators in order to estimate demand. These indicators consist of the total project value, location, and project types.

Once the supply and demand components are quantified, then stage two involves comparing them and calculating the divergence. The following stage in the proposed model extrapolates the capacity and pipeline data using historical trends toward a target forecasting horizon. Once the projection of the supply and demand is estimated, the forecasted discrepancy between capacity and the project pipeline is calculated in the final stage. The proposed model is generic and can therefore be applied to different granularities, such as different regions.

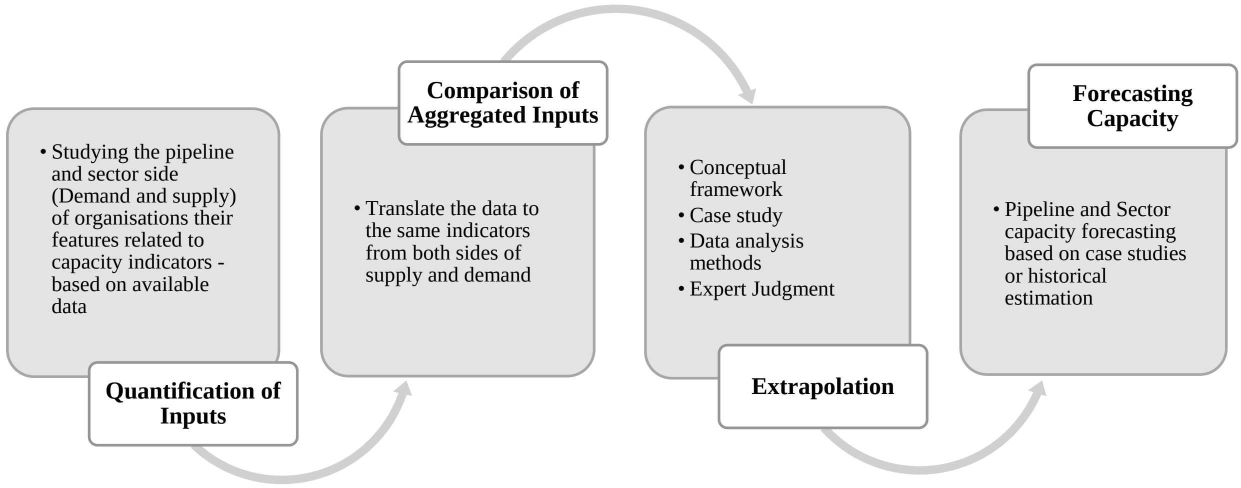

Figure 1. Proposed modelling framework in four stages

3.2 Case Study

The Ministry of Education (MoE) of New Zealand as a major construction client was chosen for a case study to demonstrate the application of the conceptual framework. In this section, a brief description of the case study is provided. MoE was chosen as a case study since it has a nationwide cover and covers New Zealand educational projects with an emphasis on school projects of varying scope. MoE projects and mainly categorised as vertical sector and includes development of new schools, expansions of old schools, redevelopments and others.

The analysis identifies high-level model indicators, relationships, data sources, and moderating effects which serve as inputs to the conceptual framework development. The case study was performed based on assessments, outputs, and strategies developed and guided by the literature review. The MoE was formed in 1989 and is the Government's lead advisor on the New Zealand’s education system. The MoE has numerous functions, such as giving guidance to the Government, providing learning resources, and administering and issuing information to the education sector. Moreover, it provides support and delivers the education providers' findings, specialist services, management, and operation.

3.2.1 Unique features of the construction project in the pipeline

Information on pipeline construction projects is listed as project-based since they have their own unique features. Large companies and local governments conduct their planning based on three and ten-year project plans, which constitute the project pipeline. The key features of each project are an assigned priority level and a phase descriptor. For the case study, we used three main features based on the availability of the data. These features were the project value band, location, and project types. Table 1 list the details of these features.

3.2.2 Unique features of the construction project in the sector

Information on the sector side (supply) of construction is at an organisational level and is thus accompanied by organisation-specific features which may not generalise across all entities. The main challenge in attempting to compare supply and demand to determine the sector's capacity lies in the fact that large companies and local governments do not conduct their annual turnover reporting on a project-level basis.

Table 1. Characteristics of the case study data from pipeline and sector side and data availability

Pipeline side	Sector side	Data availability
Value band • VB1 (<$1M) • VB2 ($1M -$2.5M) • VB3 ($2.5M -$5M) • VB4 ($5M -$10M) • VB5 ($10M -$15M) • VB6 ($15M -$25M) • VB7 ($25M+)	Projects are mainly • vertical	Annual reports • Mostly large-size companies publish their activities as a report
Locations- Whole NZ • Auckland • Bay Of Plenty/Rotorua/Taupo • Canterbury • Nelson/Marlborough/West Coast • Otago/Southland • Tai Tokerau • Taranaki/Whanganui/Manawatu • Waikato • Wellington	Pre-qualification • Pre-qualification system in place based on project type	Government reports • Government-published high-level reports
Project types • Combined • Learning Support -Modification • LSPM • New School • New School Expansion • Redevelopment • Roll Growth	Sector contractor /subcontractor /stakeholder • Quantity Surveyor • Project Manager • Master Planner • Lead Designer • Contractors	Website • There are a few companies that collect sector data. • Individual organisation websites • News websites

As applied to the case study and its specific characteristic, the proposed framework can be seen in Figure 2, where all the pipeline and sector inputs are shown together with the mechanism for comparing them and determining capacity. The figure shows that four quantities are estimated from each set of inputs originating from both sides of the supply/demand equations. These are workforce, machinery, materials, and cash flow. These quantities serve as a means of quantifying sector capacity.

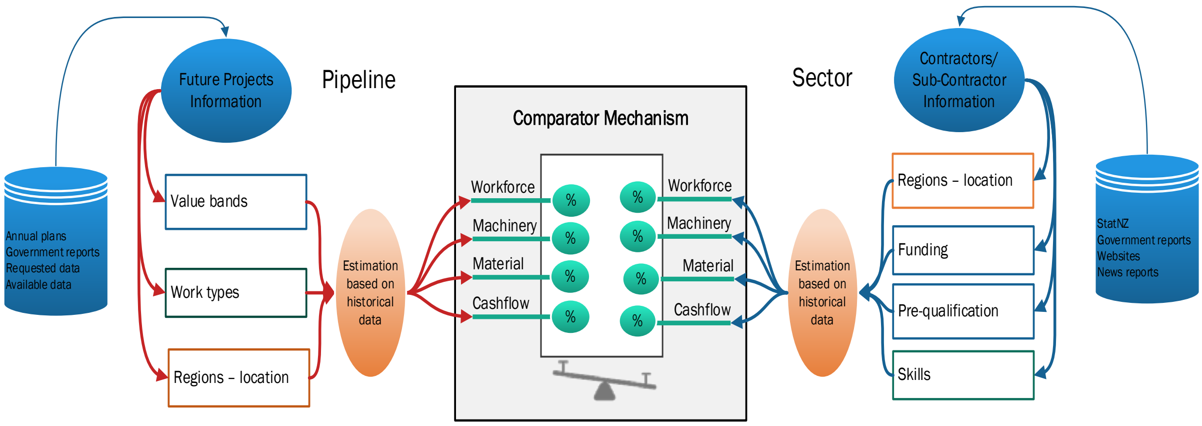

Figure 2. The conceptual capacity framework

4 Results and Discussion

Quantification of Inputs - The pipeline data is derived from various organisations based on the nature of the project. Organisations collect data according to their own standards. They gather the information needed by their organisation, while not all the information is captured. To propose a general framework, there is a need to first identify the key indicators which are to be captured in all datasets. The key indicators used here are value bands of the projects, work types, and regions based on the case study data (see table 2). These key indicators and historical data can be used to estimate capacity indicators. On the sector side, there are a number of contractors, sub-contractors, and suppliers. Their primary key indicators are location (see table 3), pre-qualification, funding, and skills. Based on this information, the capacity indicators can be estimated. Financial information can be obtained from contractor company websites, which some companies—usually large companies—mention in their annual reports. Pre-qualification data are available as general information in the client's side. The skills needed are not mentioned in any available data from the project pipeline. Moreover, workers' current skills are also not mentioned from the contractor side. The StatsNZ website has certain information about skills in the whole construction industry. Most projects in the pipeline database do not have information regarding their contractors which complicates the calculation of the sector side of the equation. However, based on the maximum historical value of the, the size of the company and what tier they belong to. this can be computed. Based on the data assumptions it is possible to make some estimates to divide the contractors based on their value band (see table 4).

Table *2*. Pipeline projects by type and region- based on case study data

Project type	***Combined***	***New School***	***New School Expansion***	***Redevelopment***	***Roll Growth***	***Learning Support Modifications***
Auckland	76	27	14	282	266	0
Bay Of Plenty/Rotorua/Taupo	0	2	2	0	0	0
Canterbury	2	6	0	28	1	0
Nelson/Marlborough/West Coast	4	1	0	13	15	0
Otago/Southland	8	0	3	22	36	1
Tai Tokerau	5	0	1	37	55	1
Taranaki/Whanganui/ Manawatu	1	2	0	25	4	0
Waikato	1	10	2	9	12	0
Wellington	17	0	1	63	18	1

Table *3***.** Sector projects done by stakeholders/contractors and region - based on case study data

	Count of Contractor	***Count of Quantity Surveyors***	***Count of Project Managers***	***Count of Lead Designer***	***Count of Master Planner***
Auckland	52	36	65	28	13
Canterbury	18	18	17	18	18
Nelson/Marlborough/ West Coast	4	12	12	10	12
Otago/Southland	21	31	28	29	29
Tai Tokerau	3	6	5	1	2
Taranaki/Whanganui/ Manawatu	16	17	17	17	2
Waikato	7	5	7	5	4
Wellington	17	32	19	36	13
Not Specified	128	147	140	147	144

Table *4***.** Sector projects done by stakeholders/contractors and value band of the projects - based on case study data

	Count of Contractor	***Count of Quantity Surveyors***	***Count of Lead Designer***	***Count of Master Planner***	***Count of Project Managers***
VB1 (<$1M)	22	26	25	15	22
VB2 ($1M -$2.5M)	47	59	52	41	56
VB3 ($2.5M -$5M)	57	58	58	46	65
VB4 ($5M -$10M)	66	76	72	63	75
VB5 ($10M -$15M)	25	34	32	30	33
VB6 ($15M -$25M)	27	27	27	21	31
VB7 ($25M+)	20	22	23	20	26
Blank	1169	1131	1144	1197	1125

Comparison of Aggregated Inputs - The key indicators translate to capacity index when comparing supply and demand. Adding expanded datasets and indicators will likely improve the prediction's accuracy. The conceptual framework attempts to translate the case study's demand and supply sides to the same capacity indicators. Based on historical case studies, the workforce, machinery, material, and cash flow can be estimated for projects coming from the same regional location with the same work type and value band. On the sector side, construction companies are typically listed in the client’s side information, usually in their pre-qualification system, foundation, and skills information listed on the StatsNZ website yearly.

Extrapolation - In the comparator mechanism, different mechanisms were applied to estimate the capacity indicators percentage based on the pipeline data available in the case study data. But on the other hand, since the data is unavailable, estimation based on the project completion rate from the sector side and available data from StatsNZ was deployed. Since the data has a significant quantity of missing values, the sector estimation for this case study is based on expert judgment and estimation.

Forecasting Capacity - Decision-making is part of the planning, and planning is a set of future actions. Forecasting the market's capacity on both supply and demand sides will help decision-makers with better planning. Because multiple quantities are measured at the same time, vector autoregressive models will be used in the future study. The study's future work will focus on forecasting future construction demand in order to prepare for better planning. Forecasting capacity is based on historical data (The data from previous projects completed in the past) and the translation between the sector and the pipeline of work to keep it balanced and avoid the market becoming renowned for boom and bust.

5 Conclusion

This study aimed to understand the data and develop a conceptual capacity framework, demonstrating a proof of concept for the mechanism. Based on the findings and the common information framework created based on the case study. The framework demonstrated the high-level supply-demand trends for the case study. For the next phase of the analysis and implementation of the projects, a comprehensive data collection strategy is required both from the pipeline and sector side. Moreover, this framework will help the professionals, construction managers and Government with providing a framework for capacity modelling and infrastructure and construction planning decisions.

The generalisability of these results is subject to certain limitations. For instance, historical information is crucial for modelling, especially when it comes to sector modelling. Secondly, sector stockholders' and suppliers' capacity information, such as the number of their skilled workers, equipment, technology in use, and type of project, are either not available or incomplete.

6 Acknowledgment

The paper acknowledges the funding of the New Zealand Ministry of Business, Innovation and Employment, Endeavour Programme Research Grant.

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Student Observations of Technical Innovation in an Australian Construction Company

Alexander Kapruziak[1] and Mary Hardie[1*]

[1]School of Engineering Design & Built Environment, Western Sydney University, Locked Bag 1797 Penrith NSW 2751, AUSTRALIA

m.hardie@westernsydney.edu.au, 18454853@student.westernsydney.edu.au
* Corresponding author

Abstract:
Technical innovations in the construction industry shape both the present and the future development of the industry. Technical innovation can be described as the application of knowledge about tools, materials, processes, and techniques to problem solving. Innovation thus combines the science of discovery and the process of change delivery. Innovation can lead to the creation of social and economic value. It also enables a competitive advantage for the companies who make it their method of operation. A systematic study was undertaken to observe, assess and evaluate technological innovation examples within one construction company. Through the examination of the deployment of specific innovations including Building Information Modelling (BIM) in project delivery, central electronic record keeping and digital construction scheduling, this study examines how various technical changes have impacted project delivery. This observational study provides an evaluation of what makes these practices successful. Innovation is a continuous and ever-changing process. Successful companies constantly make changes to products and processes, collecting new knowledge, which demonstrates the importance of innovation to society. The result is not only a simple numerical improvement in one area, but a geometric progression involving and effecting the outcome of several related areas in a synergistic manner. Clear efficiency gains were observed in the subject company.

Keywords:
Construction companies, innovation delivery, technical innovation

1 Introduction

Technical innovations can be defined as comprising of products or processes which significantly change the environment in which the process or product is delivered, albeit in varying degrees. Technical innovations do not have to be ground-breaking inventions or totally new process insights. They can be incremental changes to current practice or ideas borrowed from other areas of endeavour. At the individual company level, successful incremental innovations can create a competitive advantage in the market (Bessant and Venables 2008). However, the process may also create uncertainty within the firm because the new practice is not fully known and there may be doubt as to whether the new model is superior to previous practice (Rogers 2003). This “unknown factor” tests the adequacy of the innovation and as a result some innovations may diffuse rapidly, while others may take a long time or are never fully integrated into common practice (Mahajan 2014).The progress of technical innovation adoption can provide an enhanced insight into the future direction of the industry. Embley (2015) posits that a focus of attention on technical innovation will improve the reputation of the industry by increasing the performance of the products or models for the customers who are the end users of the buildings. This is significant, as it creates a flow on effect on company viability, as well as profitability. Company life cycle generally involves innovation, implementation, developing a business model and then executing and assessing this business model. Without regular innovation, external factors may result in lost profitability for the company (Blank

2010). This process is influenced by the key sustainability factors of social, economic, and environmental vectors. Therefore, these sustainability factors will identify the key measures which result in successful innovation delivery.

2 Literature Review on Innovation Process Management

Mulgan (2006) explains that innovation is more accessible and easier to develop when the associated risks are contained, where there is a clear failure mode, where the users have choice, where the expectations are carefully managed and where the achievement is an outcome rather than an output. Innovation is an ongoing process of development and change. This process is a continual evolution starting from idea conception, through to idea implementation. Original ideas can also be progressively built on, which allows for further incremental improvements over an extended period. Traditional economic theory describes how this enables continuous change rather than one radical "big-bang" solution which could cause significant impacts to the target market (Bessant 1992). An example of the continual development process is shown in Figure 1 below, as developed from Neese (2017).

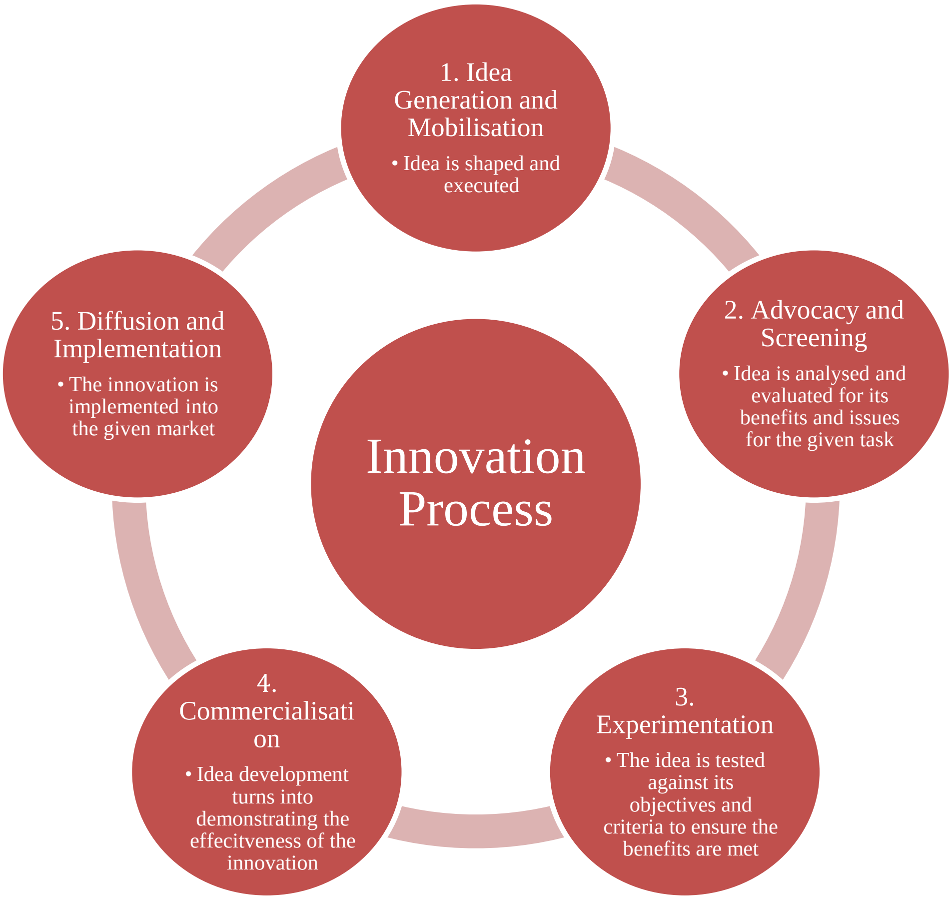

Figure 1. Innovation Process Cycle
Based on: Neese (2017)

The five stages of the innovation process indicate that development needs to be an ongoing, iterative process, starting from idea generation through the stages of development and refinement to the end-product stage, resulting in diffusion and implementation into the market.

Innovation theory has been broadly acknowledged as both a generator and a supporter of industry performance over many years. Encouraging the rate of innovative activity to improve profitability and quality of output has been an axiom of market economics since the work of Schumpeter (Schumpeter 1934). The manufacturing sector in most market-based economies has wholly adopted the theory and process of innovation. The construction industry, however, has had a tendency to resist economic theory generated in other areas and often sees itself as a unique case which cannot be appropriately compared to other sectors (Reichstein *et al.* 2005; Winch 2003). This is partly due to the fragmented, combative, and project-based nature of the industry, but also to a strong innate tendency to avoid unnecessary change. Several authors have addressed the issue of innovation in construction internationally (Gann 1997; Nam and Tatum 1992; Slaughter 1998). In Australia, this work was taken up by several researchers at the Australian Cooperative Research Centre for Construction Innovation (CRCCI) in the early 2000s (Hampson and Tatum 1997; Manley and McFallan 2006; Manley 2008; Sidwell et al. 2001; Walker *et al.* 2003).

The predominant method of measurement of innovation is described in the Oslo Manual, a widely-accepted guideline which interprets and analyses innovation data and can realistically measure the effectiveness and success of the innovation (Organisation for Economic Cooperation and Development OECD/Eurostat 1997). Based on the Oslo Manual, Bloch (2007) describes the key factors that result in a successful innovation as:

- Research and development (R&D)
- Competence building in the labour force
- The formation of new product markets
- End user feedback and interaction
- Innovation support organisations in the form of entrepreneurship, public research, technology transfer, consulting
- Formal/informal support networks
- Institutions (laws and regulations)
- Financial and administrative institutions

Of course, innovation is not an end in itself, but rather a means improving performance at the level of a company, an industry, or a national economy. Performance can be viewed broadly as not just economic performance but also social and environmental performance. Increasingly a Triple Bottom Line (TPL) approach is taken when assessing project performance towards more sustainable construction project performance (Elkington 1997). This paper explores the impact of specific technical innovations on the TPL performance in a sample of construction projects. It is posited that project effectiveness at the company level will be enhanced when technical change involving new practices are embraced. The impact will extend beyond traditional economic accounting to a more wholistic and sustainable performance monitoring schema on projects.

3 Research Methodology

This study is observational and exploratory in nature and is based on a small sample of two real projects worked on by the lead author as a building cadet. The research is primarily qualitative and ethnographic in nature. Qualitative research seeks to provide a reason as to how an event occurred, rather than just providing the outcome (Gelling 2015). The study was intended to encourage thoughtful evaluation of current practice from inside the project team. The qualitative data analysed consisted of the whole project record on Aconex plus the original BIM model and project schedule as amended during the project. This was supplemented by a Balanced Scorecard assessment of the innovation instances studied. An example of the blank scorecard is given in Figure 2 overleaf. The Balanced Scorecard methodology has been in use in the business world since the 1990s as a means of monitoring performance while using largely non-commensurate criteria (Kaplan and Norton 1996). There is a target score under each separate criterion and the scorer judges how close or how far the observed phenomenon is from the ideal target. The methodology enables the observer to make quick judgements about the effectiveness of the phenomenon being studied. It is not claimed to be a strictly rigorous study but rather a snapshot of performance that must, of necessity, be followed up with a more rigorous study of financial and other project data. As the lead author was working on the building projects at the time, he had an opportunity to observe and rate progress from within the company. Although he filled out the scorecards himself, he did so in consultation with more experienced managers who were his professional mentors. The learning experience from doing this study was its primary motivation. In keeping with the long-standing AUBEA goal of sharing teaching practice for the benefit of academics and students.

Three separate technical digital innovations were studied. The level of novelty was ‘New to the firm’. The technologies were: Aconex Document Sharing; Building Information Modelling in Project delivery; and Microsoft Project for Reactive Scheduling Control. The use of these innovations was observed on two building projects in Sydney which were constructed at the same time. Project documentation from the two building projects was collected and studied. The first project was a residential apartment building in the central Sydney CBD at Circular Quay. It contained 104 luxury residences across fifteen levels, with a further three levels of retail tenancies, a substation and six basement levels. The second project was a university building consisting of seventeen-storey tower with key areas including the library, food court, theatres, laboratories, student centres and study rooms. In both cases fully modelled BIM documentation was available from the designer and the builder was required to provide complete as-built documentation for use in facilities management after the project completion. The lead researcher had access to the BIM models as a junior member of the project team and was permitted to use the documents for educational purposes. The project schedule Gantt charts and revisions were also available for study. Aconex was used for Document Control by the Builder as a relatively newly introduced system in the company of the study. It is fully conceded that the judgements made are subjective, albeit based on immersion in the project delivery process. Future studies will seek independent assessment of the scorecards. Close observation of project delivery is recommended as a process improvement strategy that comes under the heading of action research (Nudurupati, Arshad and Turner, 2007). The Balanced Scorecard using Likert scaling introduces a level of rigour to the observation process. There are other ways to measure TBL and general sustainability performance. The scale of more quantitative studies was outside the time frame and scope of this study. Nevertheless, this more limited study can yield useful insights into project delivery for a medium sized construction company which wants to embrace the possibilities of digital technologies for overall performance improvement.

4 Findings and Discussion

All three innovations studied have been evaluated using the nine questions summarised in the blank scorecard in Figure 2. The total possible score for each innovation studied was 45 points. The findings were consistent across the three innovations as can be seen in Table 1.

Detailed discussion of the impacts of each innovation follows, as well as, how judgements were made about the impact of the changes.

Given Innovation Example						
Social Analysis	**1** **Strongly Disagree**	**2** **Disagree**	**3** **Neutral**	**4** **Agree**	**5** **Strongly Agree**	**Total**
Is the given innovation socially responsible?						
	Comments as to why the data value was selected					
Does the innovation improve the company's reputation?						
Is the innovation socially responsible?						
Environmental Analysis						
Provides a reduction in resource consumption and depletion						
Increases Sustainability						
Provides an improved environmental performance						
Economic Analysis						
Creates Competitive Advantage						
Improved value for money						
Provides a reduction in overheads						

Figure 2. Sample Scorecard
Based on Balanced Scorecard Management Group 2018

4.1 Aconex

4.1.1 Social impact

Key to this successful innovation is the social responsibility it enables within the development. It is evident that compared to other document control platforms that Aconex uses software as a service method of function (Devanand 2015). With this only requiring access to the internet from any device (use can be accessed from computers, tablets, iPads, phones, and the like rather than just a dedicated computer and program). This enables access to the given project to be available from anywhere in the world, at any time of the day. All stakeholders can contribute effectively to the construction process, without the time zone and access-based factors causing the project delays (Redwood et al. 2017). Increased communication lines were available enabling a more positive work environment. This social inclusion enhanced the team morale and created a more effective construction process. Aconex was observed to be directly beneficial to this social impact and therefore this aspect was scored at 5.

4.1.2 Environmental impact

Aconex resulted in both direct savings and follow-on savings in terms of resource consumption. This includes the reduction in the resources and also cost savings of items such as printing and stationery that are directly due to Aconex storing all the project specific documents within one central, online location. However, key to the score of 5 out of 5 were the follow-on impacts to the construction delivery that Aconex facilitates. Aconex served to reduce the amount of resource duplication. As well as resource savings, Aconex also has a modelling function. Through the construction phase, Aconex was seen to help provide greater information on materials selection. Greater insight was provided to the builder regarding the material/resource selection and the future implications this resource has, for example its life cycle, effect on the environment and embodied energy content. This long-term analysis was also able to be stored, which can further benefit the end user and construction company through the development of operations manuals and documentation to accompany the development once it has been completed. Aconex was seen to be highly beneficial both with regard to reducing the company's resource consumption and also through improving the company's resource dependency. This justified the score 5 out of a possible 5.

4.1.3 Economic impact

Competitive advantage is a key outcome exhibited by Aconex software and its various modules. This was first evident when using the tender function. The construction company can issue tender invitations and reviews to multiple companies all at once. This was seen to not only provide a fair and equitable tender process for all tenderers, but it also provided a clearer outcome for pricing to the construction company due to all tenderers pricing the same drawings. Using Aconex allowed for all documentation applicable to the given subcontract to be issued, decreasing ambiguity created by using other conventional methods of issuing documentation. Using this system, it was observed that less tenderers raised questions,

Through this analysis of economic advantage, the high score of 5 was given, due to Aconex providing many different functionalities that helped enable improved economic advantage. With the tenderers providing a clearer tender, the company benefited from a reduced commercial risk. This was also identified to further provide a more cost-effective tender process, which was directly connected to an improved competitive advantage. This advantage was also shown by reduced document control staffing. Due to Aconex ensuring that all tenderers were properly notified, all the tenderers invited submitted their pricing for the works within the given time. As a result, this process reduced the staffing resources from following up the tenderers, answered further questions and remarks and addressed further administrative enquiries, thus allowing them to further focus on other project relevant directives.

4.2 Building Information Modelling (BIM)

4.2.1 Social impact

This score was rated 5 due to the innovation being socially responsible in a variety of different ways. There are benefits to construction scheduling, processing and also procurement platforms. In turn, key stakeholders can be easily notified of changes, ensuring less negative impact that construction has on the surrounding neighbourhood. creating more transparency and helping assist with developing a closer relationship between builder and neighbours.

This score was also attributed to the project and site office responsibility. Key to social responsibility is that team ambience and positivity is to be increased. BIM increased efficiency and forecasting within the chosen project and as such enhanced the work environment, thus creating a positive environment for workers, employees, staff, guests and other key project stakeholders (Sacks, Korb & Barak 2017).

4.2.2 Environmental impact

Sustainability within the services design and coordination focussed on functional, long lasting, and environmentally sustainable materials. The building functionality and systems management were also improved with the implementation of BIM. For example, adjusting the lift movement within the building to suit patronage frequency, reduced power consumption and created greater building energy efficiency. Over the course of the building’s life cycle, the savings would be significant. With BIM identifying these key facilities management perspectives, it ensured that once the building was operational there would be less harmful resource consumption due to the data provided in the model. The impact of BIM was also evident within the construction phase of project delivery. With BIM forecasting the stages and rate of construction, only the required materials and resources would be acquired within a staged process. This ensured that there was reduced amounts of wastage, thus reducing the site-specific impact of unnecessary procurement. BIM was scored at 5 out of the possible 5 because the implementation of BIM enhanced construction efficiency. Life cycle analysis and costing, procurement and also scheduling all had a confirmed positive impact to the environmental construction and design process There was a rational benefit to improving and enhancing the construction company’s Triple Bottom Line through including an environmental perspective.

4.2.3 Economic impact

This was ranked a 3 within the overall approach, which was due to the enhanced process which BIM created. Although there are perceived and confirmed cost saving benefits, the initial setup costs of BIM as a model certainly need to be accounted for. For the purposes of the case study, there was an improved value management process, primarily evident with the efficiencies d within the coordination and installation phases of construction. This value was enhanced through engineering solutions prior to them becoming evident onsite. An example was addressing façade detailing prior to all the façade components arriving onsite. Through this analysis, there is an extent to which BIM improves value management; however, the exact beneficial amount was seen to drastically vary upon the holistic factors inclusive of site conditions, building methodology and automation factors. These drastically varied between projects.

4.3 Microsoft Project

4.3.1 Social impact

The potential gains from the implementation of digital project scheduling have been known for a long time without necessarily diffusing throughout the industry at all levels (Dawood & Sriprasert 2006). MS Project was ranked as the highest possible score of 5, due to the savings in time and disruption generated for the neighbourhood. This was due to enhanced value management generated by appropriate time scheduling and planning. With this innovation implementation, there was enhanced scheduling control and as such it provided a clearer forecast of the site-specific timeline. As a result of more efficient time onsite, and better integration between key project stakeholders such as the client and builder and the neighbours. Greater communication integration, advising the neighbours of future project initiatives could circumvent possible issues before they became extreme.

Enhanced social responsibility resulted in improving the company’s reputation. A score of 4 was given due to the company’s reputation being a key outcome. This reputation was identified and enhanced through a clearer and more concise programme being developed. Having a clearer programme allowed for greater analysis and opportunities to be developed, reducing the chances of ambiguity, aiding risk mitigation and issues with onsite coordination and objectives. MS Project implementation provided a clearer, proposed timeline while also enabling a clearer contractual timeframe for the builder and subcontractors. The company’s enhanced reputation through a more concise programme indirectly led to winning further tenders.

4.3.2 Environmental impact

The total score of 11 allocated to Microsoft Project did not tell the full story of its efficacy. There are several impacts that MS Project helps facilitate, whilst there also other key areas to which Microsoft Project’s use does not contribute to the given outcome. With this, it is important to note that further research is to be undertaken to ensure that the given results are employed within the company’s projects and innovations.

On the question of Microsoft Project providing *“a reduction in resource consumption and depletion”* it is clear that there is an indirect impact with its implementation. This scored the innovation 4 out of 5, as the respondent agreed that there is a given link to this reduction, however it is not inextricably and quantitatively linked to reducing the dependency and consumption of resources. With Microsoft Project facilitating scheduling of tools, activities, processes and resources, a more accurate estimate site requirements can be made. This direct site impact allows for and provides information to the given stakeholder to adjust the given quantities as required to meet the site demands and capabilities. This resulted in more efficient site usage, with only the essential resources and tools being available on site. This site basis was evident as Microsoft Project was seen to decrease the extent of activity reactive items such as Concrete and Steel being reduced to only meeting the daily demands and requirements. As a result, less resources were being ordered, used and depleted which also had a benefit to the onsite production of waste. It was also important to note there were two clear score differences between BIM and MS Project. With the implementation of Microsoft Project, adequate resources can be forecast, however BIM within project delivery also allowed the materials required and the primary design of the building and structure to be adjusted, which as a result scored it 5 points. This is in direct contrast, with Microsoft Project being a contributor to reducing the resource with its onsite implementation. This is key as there are known quantities of the given resources displayed and quantitated within Microsoft Project for scheduling, however modelling and resulting outcomes of these resources may not be able to affect the design and outcome of the building.

4.3.3 Economic impact

One of the key aspects of the economical approach is competitive advantage. Key to this impact and for a successful innovation implementation is through improving the company's perception within the market and to the prospective clientele. MS Project was scored at 5 out of a possible 5, because there is a clear advantage to the implementation of this case study. This score was justified through the contract and programming issues being dealt within the one central system. With this innovation, the construction and design processing and activities are moulded into an efficient and productive process whilst ensuring that all the quality standards are safely met. With the successful implementation of a clearer processing and initiatives, various outcomes can be derived. MS Project implementation reduced outcomes such as waiting for crane availabilities, but it also was seen to reduce the wastes and costs associated with these. These cost saving initiatives therefore contributed to further quantifiable costs if it had not been implemented. With this efficiency increase, a cheaper cost for both the builder and client can be achieved, thus obtaining a great benefit to both through a value engineering perspective. This competitive advantage is also generated due to the site safety benefits. Having a well organised site, resulted in fewer incidents occurring compared to that of a disorganised and unsafe site.

This tighter scheduling can also be beneficial in the use of finite resources. Resources chosen can be compared within Microsoft Project with regard to scheduling efficiency. Using Pre-cast Concrete or Prefabricated materials compared to conventional, in-situ concrete, demonstrated a clear time-saving. MS Project enabled selecting and adjusting the construction methodology, materials, process, and procurement objectives of the given project. It is clear that given the score of both the competitive advantage and an increased value management of 5 out of a possible 5 that the intended outcome of the given technical innovation is an increase in value engineering. With the implementation of Microsoft Project for reactive scheduling, it is evident through the extent and organisation of project delivery that a greater value engineering in regard to scheduling is acquired. MS Project allows for a better understanding of the construction process, whilst also introducing and combining the dimension of timing. Introducing this factor allows for an insight into foreseeing many of the aspects of delivery onsite, prior to the implementation. This therefore follows the cycle of further refinement for a lean and efficient process to be developed and tested. As identified by Dewick and Miozzo (2002), a more efficient construction process allows for adequate value to be accentuated.

Table 1. Balanced Scorecard assessments for 3 technical innovations

		Social	Environmental	Economic	Total
Aconex		12	11	13	36
BIM		14	13	14	41
Microsoft Project		12	14	13	39

In summary, the final scores are listed in Table 1 above. This proved to be a quick and simple way of making a first assessment of the innovation impact on the project. Future research is required to draw stronger conclusions.

5 Conclusion and Further Research

It is through the research and development undertaken within this paper that technical innovations have been investigated providing a greater insight into assessing the Triple Bottom Line effects of social, economic, and environmental impacts. Through the research of literature reviews and case studies of Aconex, Building Information Modelling and Microsoft Project a strong insight can be drawn. It is evident within the results that there is a strong and equitable influence amongst the case studies across the Triple Bottom Line. These results are critical as they demonstrate that technical innovations exist in different forms and can all have a fundamental impact regardless of their genre. With the results scoring highly when assessing the respective case studies' Triple Bottom Line, through the successful implementation of technical innovations within construction companies, their respective Triple Bottom Line will be positively influenced. These positive influences however were seen to vary according to the given case study and the given assessment basis. It is recommended that further study be undertaken to establish and assess these notions, which have been commenced in a subjective way here. As a result of this, the Triple Bottom Line, for the whole construction sector, to individuals and companies can be further improved by the successful implementation of technical innovation.

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Theme:

Sustainability in Built Environment

Towards Sustainable Consumption: Enhancing the Use of Reprocessed Construction Materials within the Australian Construction Industry

Gihan Anuradha Tennakoon[1*], Raufdeen Rameezdeen[1] and Nicholas Chileshe[1]

[1]University of South Australia, UniSA STEM, Centre for Sustainable Infrastructure and Resource Management (SIRM), Adelaide, AUSTRALIA

gihan.tennakoon@mymail.unisa.edu.au; rameez.rameezdeen@unisa.edu.au; nicholas.chileshe@unisa.edu.au
* Corresponding author

Abstract:
Despite the ever-growing volumes of demolition waste (DW), extant literature points to a low uptake of reprocessed construction materials (RCMs) derived from DW, thus undermining the success of waste recovery schemes. In an industry driven by economic motives, the lack of demand for RCMs would make resource recovery operations unsustainable in the long run. Moreover, a review of the literature also revealed that there is a narrow focus in existing research on the 'market' aspect of DW recovery operations. Therefore, this study focused on identifying interventions to encourage the uptake of RCMs within the Australian construction industry. Following a qualitative interview-based research approach, interventions for encouraging the use of RCMs were explored from the perspective of construction industry professionals (CIPs) involved in material selection decisions. The thematic analysis technique was used to analyse the interview data. The study findings revealed sixteen informational and structural interventions for enhancing the use of RCMs, and these interventions were mapped against the industry levels at which they should be implemented. RCM suppliers should focus primarily on improving material quality, supply consistency, and marketing while minimizing material costs. The Government should encourage the use of RCMs through supportive legislation and incentive schemes. The importance of awareness building around RCMs and their potential uses was also highlighted, which requires the collective efforts of RCM suppliers, educational institutes, and governmental and non-governmental bodies. Implementing these interventions would create a positive shift in the demand for RCMs, thereby ensuring the long-term viability of resource recovery schemes.

Keywords:
Australian construction industry, Demolition waste, Market, Reprocessed construction materials

1 Introduction

Sustainable management of construction and demolition waste (C&DW) has become a priority, with the ever-increasing rates of waste generation (Purchase et al., 2022). Studies have shown that C&DW accounts for approximately 30% of all waste generated globally, with a notable proportion of this waste ending up in landfills without any value recovery (Oyedele et al., 2014). The National Waste Report 2020 shows that the situation in Australia is similar to the global context, with C&DW accounting for 44% of core waste generation during 2018/19 (Pickin et al., 2020). The report also indicates that C&DW has grown by 61% from 2006/07 to 2018/19, therefore necessitating immediate action to curb the further growth of waste volumes. Compared to construction waste, demolition waste (DW) generated in dismantling end-of-life structures accounts for a more significant proportion of the total C&DW (Chileshe et al., 2019). Therefore, it is prudent to prioritize the management of DW since it can have a greater impact on minimizing the overall volume of C&DW.

With this realisation and driven by concepts such as reverse logistics and circular economy (Hosseini et al., 2015, Wijewansha et al., 2021), the construction industry has now focused on converting DW back into reprocessed construction materials (RCMs) that can be used in new construction applications. This provides a second life for waste materials that would otherwise be disposed of in landfills while also minimizing the demand for virgin resources. However, it is important to note that the success of such resource recovery efforts depends heavily on the market uptake of RCMs (Chick and Micklethwaite, 2004). Unless RCMs are readily accepted and used in new construction applications, the authors argue that waste recovery operations will not be viable in the long run. As asserted by Spoerri et al. (2009), a functioning market with adequate demand for RCMs is the most decisive factor when determining C&DW recovery rates.

Despite the importance attributed to the market uptake of RCMs in driving waste recovery schemes, research shows that the current usage of RCMs is limited. Most construction actors prefer using virgin construction materials whilst maintaining a conservative stance against RCMs (Knoeri et al., 2011). Based on a study in the UK, Oyedele et al. (2014) found that RCMs are under-utilized in construction projects and are not readily accepted as viable alternatives for virgin materials. Similarly, following a survey of the Chinese construction industry, Jin et al. (2017) identified an apparent lack of demand for RCMs. According to Schut et al. (2015), although approximately 95% of C&DW is recovered in the Netherlands, less than 5% of this is used in high-grade applications, while the majority is used in low-grade applications or is disposed of without further use. As noted by Chileshe et al. (2015), the lack of demand for RCMs is also an issue in Australia, where the authors identified this as a significant barrier to the success of reverse logistics practices within the Australian construction industry. Findings from these studies point to a clear lack of demand for RCMs. Moreover, most of the research on DW management has focused on the dismantling and reprocessing stages of the waste recovery process, while the market operations stage has received limited attention. Following on from this background, the current study, therefore, attempts to *identify interventions that can be implemented to encourage the market uptake of RCMs*, thereby ensuring the long-term viability of DW recovery schemes. This study also aligns closely with the United Nations Sustainable Development Goals (SDGs), more specifically Goal 12 which focuses on ensuring sustainable consumption and production.

2 Theoretical Background

Grimmer et al. (2016) identified the purchase and use of environmentally responsible products, which are from firms with a positive environmental image or are manufactured using recycled, biodegradable or carbon-neutral inputs, as a form of pro-environmental behaviour (PEB). Based on this notion, the use of RCMs can also be defined as a form of PEB. According to Stern and Oskamp (cited in Guagnano et al., 1995), such PEBs are the "*outcomes of a series of causally linked external and internal factors, such as physical structures, social institutions, and economic forces (external) and general and specific attitudes and beliefs, information, and behavioural intentions (internal).*" Similarly, theories on PEB such as Attitude-Behaviour-Context (ABC) Theory also emphasize that PEBs are an outcome of both personal factors such as attitudes, personal capabilities, and habits and contextual factors such as pricing regimes, product availability, policy support and other features of the broad economic and socio-political environment (Stern, 2000). Since the use of RCMs is a form of PEB, it can be inferred that the use of RCMs depends upon personal factors such as attitudes and perceptions of construction industry professionals (CIPs) involved in material selection decisions and contextual factors such as material prices, quality, supply and availability of relevant regulations, standards, and specifications (Oyedele et al., 2014). Therefore, interventions to enhance the market uptake of RCMs must address both personal and contextual factors that limit the uptake of RCMs.

Studies on PEBs have classified behaviour change interventions into different categories. Among these categories, the classification of interventions as antecedent and consequence strategies or as informational and structural strategies has been used widely in existing research (Abrahamse et al., 2005, Mair and Bergin-Seers, 2010, Steg and Vlek, 2009). According to the former classification, antecedent strategies are used to influence behaviour ahead of the actual performance of the PEB, while consequence strategies are used to influence behaviour after the occurrence of the PEB by way of providing a consequence that depends upon the outcome of the specific PEB (Abrahamse et al., 2005). For example, antecedent strategies can include providing information on PEBs, setting goals, or modelling expected behaviours, while consequence strategies can include providing feedback or rewards for PEBs adopted (Steg and Vlek, 2009).

Alternatively, the classification of interventions as informational and structural is based on the premise that PEBs are influenced by both personal and contextual factors. Herein, informational interventions are aimed at changing personal factors such as attitudes, knowledge and perceptions that affect behaviour, while structural interventions are aimed at changing the context under which behavioural decisions are made (Steg and Vlek, 2009). For example, information campaigns to improve knowledge among decision-makers on behavioural alternatives falls under informational interventions, while improving the quality and availability of environmental-friendly products falls under structural interventions (Steg and Vlek, 2009). Since it was found that the use of RCMs is influenced by both personal and contextual factors, the classification of interventions as informational and structural was considered the most appropriate classification for this study. As highlighted by Abrahamse et al. (2005), interventions are most effective when they target the underlying factors that drive PEBs.

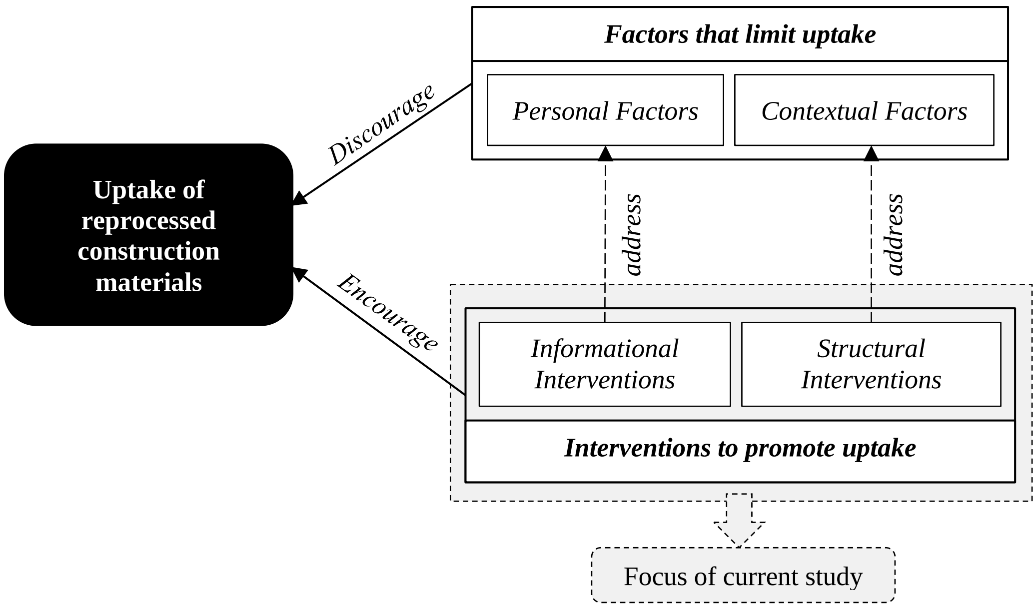

Figure 1. Conceptual framework on the uptake of reprocessed construction materials

This review of studies on PEBs led to the development of the conceptual framework shown in Figure 1. However, the scope of this paper is limited to identifying interventions that can be implemented to encourage the uptake of RCMs (as shown within the shaded area in Figure 1).

The interventions are classified as informational and structural interventions and mapped against the level at which these interventions must be implemented within the construction industry.

3 Research Methodology

Qualitative research is "*an approach for exploring and understanding the meaning individuals or groups ascribe to a social or human problem*" (Creswell and Creswell, 2018). Due to its exploratory nature, qualitative research can be used to garner an in-depth understanding of a topic under investigation and is therefore appropriate for research into new and emergent topics (Dawson, 2007, Yin, 2016). Accordingly, a qualitative research approach was used in this study to have an in-depth understanding of how the use of RCMs can be improved within the Australian construction industry based on insights from construction industry professionals (CIPs) involved in the material selection process. Since the use of RCMs is not widespread in Australia (Chileshe et al., 2015), the use of a qualitative research approach enabled the researchers to connect with professionals with prior experience in using RCMs and therefore were best placed to comment on the use of such materials.

Data Collection: A literature review is an essential component of any research project that helps to relate a new study to the existing body of knowledge (Snyder, 2019). Following this notion, the current study commenced with a review of research on the use of reprocessed materials for construction applications. This helped to establish the research problem and set the purpose of the study. Subsequently, 31 semi-structured interviews were conducted with CIPs involved in material selection decisions for construction projects and having prior experience in using RCMs. According to Saunders et al. (2019), semi-structured interviews can be used for collecting qualitative data, where the data collection is guided by pre-determined themes, existing literature, or preliminary data. Since this study adopted a qualitative research approach and the data collection was informed by the initial literature review, semi-structured interviews were deemed appropriate for the study. The use of semi-structured interviews enabled the researchers to gather specific information that could be compared while also exploring other insights that arose during the data collection process. Considering limitations with expertise available in the use of RCMs, a combination of purposive and snowball sampling techniques was used to connect with experienced CIPs. Due to restrictions imposed on physical interactions with the spread of COVID-19, most of the interviews were conducted virtually, with few face-to-face interviews. Interviews were conducted until the saturation point was reached, which is the point beyond which the collection of additional data does not generate new insights (Mason, 2010). The profile of interviewees based on professional background and experience is presented in Figure 2.

Data Analysis: The interviews were recorded with the consent of the participants and transcribed verbatim. On average, the interviews lasted for around 45 minutes. Thematic analysis, which is a foundational method for qualitative data analysis (Braun and Clarke cited in Saunders et al., 2019), was used to analyse the interview data. As the first step, the transcripts were read through multiple times to become familiar with the data. This was followed by coding, which involved categorizing similar data under specific codes. An initial set of codes were developed based on the literature review, and these were refined and added onto as the analysis progressed. These codes were then combined under broader themes which were refined subsequently to develop a coherent understanding of interventions that can be implemented to enhance the market uptake of RCMs. NVivo 2020 software developed by QSR International was used to organize the data and undertake the thematic analysis.

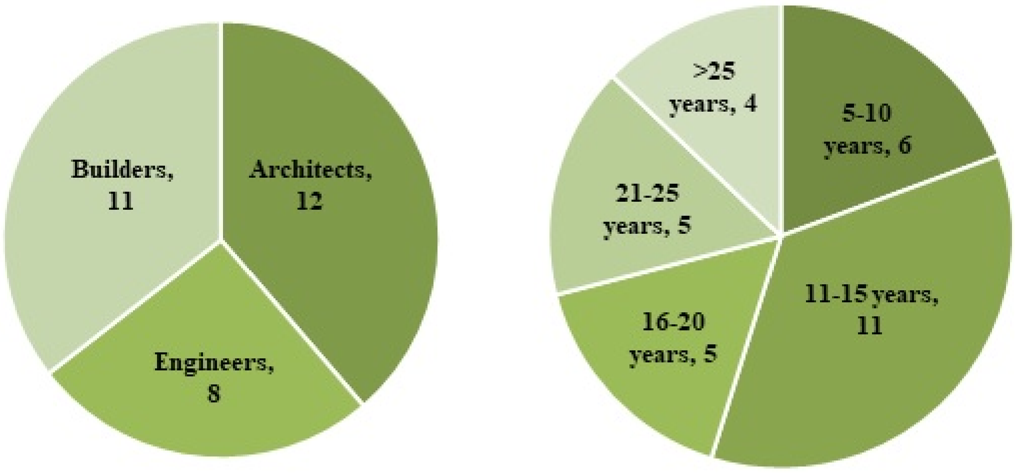

Figure 2: Profile of interviewees based on professional background and years of experience (**Criteria, number**)

4 Interventions to Encourage the Uptake of RCMs

Interview findings showed that a combination of informational and structural interventions could be used to encourage the uptake of RCMs among CIPs. These are discussed in detail under the following subsections.

4.1 Interventions at the Supplier Level

Two informational interventions to be implemented at the supplier level (i.e., waste processing companies that supply RCMs to construction markets) were identified through the interviews. Firstly, *suppliers must improve their marketing techniques/strategies*. Herein, most interviewees suggested a shift towards electronic marketing techniques such as websites through which users can readily access information regarding material availability, costs, potential applications, and any other pertinent information, which takes the friction out of the process of sourcing RCMs. Secondly, *systems must be developed to track reprocessed materials to their previous uses*. Traceability is vital for materials such as reprocessed timber where its new use heavily depends on previous uses (e.g., treated timber might not be suitable for reuse due to contamination with copper-chrome-arsenate).

Three structural interventions to be implemented at the supplier level were also identified through the interviews. Firstly, *suppliers of RCMs must improve and guarantee the quality of RCMs*. Currently, there is uncertainty around the quality of RCMs available in the market, which increases the probability of CIPs *not* specifying such materials. Therefore, interviewees from all backgrounds highlighted that the waste recovery industry must be better organized as a specialized industry with enhanced quality control procedures and offer performance guarantees with their product offerings. Moreover, obtaining quality certifications such as ISO 9001 was also recommended since it would make it easy to get RCMs approved through building assessment processes. Most interviewees also emphasized that *suppliers must ensure timely and consistent market supplies of RCMs*. Construction projects are generally constrained by tight deadlines, and material supply chains must therefore be highly responsive to meet project demands. However, gaps in the supply of RCMs were noted in terms of limited product availability and high lead times, which is mainly an issue for builders who are directly involved in material procurement. This, therefore, calls for reliable supply chains capable of supplying large enough quantities of reprocessed materials on demand. Ultimately, the importance of *streamlining waste recovery processes to reduce the cost of manufacturing RCMs* was emphasized since most RCMs are currently more costly to use than virgin alternatives, which makes them less appealing in competitive construction environments.

4.2 Interventions at the Government Level

Under informational interventions, the Government must take leadership and *demonstrate the feasibility of using RCMs through government projects*. Since the long-term performance of RCMs has not been proven, it presents a risk on the part of CIPs. Having case study projects is, therefore, crucial to demonstrate that RCMs can be used successfully as replacements for virgin materials. As expressed by an architect with expertise in heritage conservation and adaptive reuse, getting CIPs to use RCMs is "*just about getting the information out there and demonstrating good case studies so that people can see how they can be used and how successful that can be*". It should be noted that there are already some projects, especially in the road infrastructure sector, which are using RCMs. However, the interviewees noted that such projects are still gaining ground and are not representative of everyday practice.

The interviewees also identified four structural interventions which can be implemented at the government level to promote RCM use. Most interviewees highlighted that *government incentives could encourage the adoption RCMs*. The Australian Government currently promotes the use of local suppliers in construction projects through the Industry Participation Plan. Study findings highlight that a similar approach can be followed for encouraging the use of RCMs, especially in government projects, where builders who propose to use RCMs are favoured at the tender stage over those who use virgin materials. Alongside incentives, the Government can *impose mandates or targets for the use of RCMs in construction projects*. While driving the use of RCMs among CIPs, such targets or mandates will make it easy for them to convince clients, who are not otherwise interested in sustainable practices, to use reprocessed materials. However, such mandatory requirements must be enacted with caution since it might not always be possible to economically use RCMs, especially for projects located in areas without local supply sources. Next, the Government must actively engage in *developing standards and specifications for RCMs.* They must ensure that standards and specifications do not restrict the use of RCMs and update these documents as new reprocessed materials enter the market. Notable improvements have been made in civil infrastructure specifications to facilitate the use of RCMs over the last few years. However, building specifications have limited provisions regarding RCMs and, therefore, should be amended. Finally, the Government should *set out a clear pathway to obtaining approvals for using RCMs which are not already covered through specifications*. An engineering professional highlighted that the guidelines around approval processes are not very clear, and CIPs, therefore, resort to materials that are readily approved.

4.3 Interventions at the Level of Non-governmental Organizations

Allocation of higher credits for the use of RCMs in sustainability rating schemes was recognized by several interviewees as a non-governmental structural intervention that can encourage the use of RCMs. With growing concern around sustainability, more and more projects are focused on achieving sustainability ratings such as LEED (Leadership in Energy and Environmental Design), Green Star, LBC (Living Building Challenge) or ISCA (Infrastructure Sustainability Council of Australia) certification. They also act as marketing tools (Hampton and Clay, 2016), especially for residential and commercial development projects, where they are used to attract environmentally conscious occupants. Therefore, incorporating more credits for sustainable material use with a specific focus on RCMs within these rating systems can drive the use of such materials among CIPs. The attention of the Green Star building tool on mitigating embodied emissions was identified as a forward step in this regard since such reductions can be achieved by using RCMs. As a non-governmental informational intervention, *environmental consultancy service providers (e.g., Ecologically Sustainable Development (ESD) Consultants)* can play a crucial role in *encouraging RCM use by advising CIPs on using such materials*. Based on their expertise, they can advise CIPs on what RCMs are available, what research has been done and what materials are allowed for use under different circumstances.

4.4 Interventions at the Level of Educational Institutes

As an informational intervention, CIPs must be provided with background *knowledge on using RCMs as part of their curriculums* so that they can build upon this knowledge later through practice. According to the interviewees, CIPs coming through technical colleges or universities must be educated on aspects such as the availability of RCMs, where to find information about these materials and how they can be incorporated into construction works. If this awareness is not created during the early stages or is not readily available on offer, it is less likely for them to get interested in alternative material solutions such as RCMs later since the industry is primarily focused on using virgin materials.

4.5 Collaborative Interventions

Some interventions require the collective efforts of different stakeholder groups identified above, and three such informational interventions were identified through the study. The first is to *develop a database of RCMs and associated suppliers*. Therefore, the majority of interviewees recommended the development of a centralized database that contains information on what RCMs are available, who the suppliers are and the material properties. The database should ideally be in an electronic format, either as a website or a mobile application, and can be developed by a governmental or non-governmental body. Input from suppliers is also needed here to update the database with their product offerings. Having such centralized databases can cut down the time required to source RCMs when compared to reaching out to individual suppliers, thereby minimizing the impact on project timelines. Secondly, both *Government and non-governmental bodies (e.g., professional bodies and sustainability groups) can organize educational initiatives to improve awareness regarding RCMs among CIPs.* This can be in the form of workshops, exhibitions, CPD programs, guidance material, and case studies. It is interesting to note that such initiatives have become more commonplace with professional bodies declaring climate emergencies, non-governmental bodies such as ISCA and Green Building Council focusing on sustainability certifications and the Government targeting net-zero emissions. Finally, several interviewees emphasized the importance of *research to improve RCMs and determine their suitability for construction applications*. Suppliers, educational institutes and both governmental and non-governmental bodies can play an active role here, and findings from such research can then feed into the process of developing standards and specifications for reprocessed materials. These findings are summarized in Table 1.

Table 1: Summary of interventions to enhance the uptake of RCMs

<table>
<tr><th colspan="4">Informational Interventions</th></tr>
<tr><th>Supplier</th><th>Governmental</th><th>Non-Governmental</th><th>Educational Institutes</th></tr>
<tr><td>Improve marketing techniques/strategies

Develop systems to track reprocessed materials to their previous uses</td><td>Demonstrate how reprocessed materials can be used through government projects</td><td>Environmental consultancy service providers advising CIPs on the use of reprocessed materials (e.g., ESD Consultants)</td><td>Educate CIPs on the use of reprocessed materials as part of construction curriculums</td></tr>
<tr><td colspan="3">Development of a database of reprocessed materials and associated suppliers</td><td></td></tr>
<tr><td></td><td colspan="2">Initiative to improve awareness regarding reprocessed materials and their benefits among CIPs (e.g., forums, workshops, guidance material etc.)</td><td></td></tr>
<tr><td colspan="4">Publicize research to improve reprocessed materials and determine their suitability for construction applications</td></tr>
<tr><th colspan="4">Structural Interventions</th></tr>
<tr><th>Supplier</th><th>Governmental</th><th>Non-Governmental</th><th>Educational Institutes</th></tr>
<tr><td>Improve and guarantee the quality of reprocessed materials

Ensure timely and consistent supplies of reprocessed materials

Streamlining waste recovery processes to reduce the cost of manufacturing reprocessed materials</td><td>Provide incentives to encourage the use of reprocessed materials

Impose mandates or targets for the use of reprocessed materials in construction projects

Develop standards and specifications for reprocessed materials

Development of a clear pathway to obtaining approvals for using reprocessed materials not covered by specifications</td><td>Allocation of higher credits for the use of reprocessed materials in sustainability rating schemes</td><td></td></tr>
</table>

5 Discussion

To enhance the uptake of RCMs, waste processing companies that supply RCMs need to improve material quality and supply consistency while minimizing material costs. Improving the quality of RCMs was identified as a pertinent requirement by Jayasinghe et al. (2022) as well due to the strong relationship between material quality and customer satisfaction. Rose and Stegemann (2018) support the need for removing supply inconsistencies and highlighted the importance of large-scale centralized suppliers capable of supplying RCMs in bulk. Moreover, Oyedele et al. (2014) stressed the importance of value-engineering waste recovery processes to reduce the cost of RCMs. The findings also emphasized that suppliers should improve their marketing efforts while improving material traceability, and this is supported by the findings of Bao et al. (2020) which highlighted the need for birth certificates to prove material origins. Developing case study projects were identified as a requirement at the government level, and this aligns with Shooshtarian et al. (2020), which shows that reference projects can provide much-needed experience in using RCMs for CIPs. The authors also support developing standards and specifications and setting mandatory procurement targets as avenues for promoting the use of secondary materials. While the need for incentives has been recognized by Oyedele et al. (2014), setting out transparent material approval processes has *not* been highlighted in previous literature. The importance of building awareness around the use of RCMs has been recognized by multiple studies, with CIPs being educated on RCM use through educational institutes, professional bodies, and other governmental and non-governmental bodies (Oyedele et al., 2014, He and Yuan, 2020). Herein, developing RCM databases recognized as a timely requirement through this study has been backed by Oyedele et al. (2014) and Rose and Stegemann (2018). Finally, the role of sustainability rating systems in advancing the use of RCMs was affirmed by Oyedele et al. (2014) where the authors identified this as a top-ranked strategy for enhancing the use of recycled materials.

6 Conclusions

The use of RCMs remains limited within the construction industry, and without this consumption aspect, resource recovery operations will not be sustainable in the long run. Therefore, through this study, we attempted to identify interventions that can be implemented to enhance the market uptake of RCMs. Sixteen informational and structural interventions that can be implemented at different levels within the construction industry were identified through a series of semi-structured interviews with CIPs. These interventions, if implemented successfully, will be able to address both personal (e.g., attitudes, knowledge, perceptions) and contextual (e.g., price, quality, supply, regulations) factors that limit CIPs from using RCMs. This will ensure sustainable consumption within the construction industry, a primary goal under UNSDGs, which in turn highlights the importance of this study. By being based on a sound theoretical basis, the study also contributes to furthering the theory of PEB. In considering study limitations, although statistical generalisability is not a requirement for qualitative studies, the lack of such generalisability might be considered a limitation. However, these findings form the basis for further quantitative studies, which can cover a broader spectrum of participants from the construction industry.

7 Acknowledgement

The authors wish to acknowledge the Australian Government's financial support through an Australian Government Research Training Program international (RTPi) Scholarship for PhD studies and support from the University of South Australia.

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Barriers and Enablers of the Adoption of Recycled Materials Usage in Asphalt Pavement for the USA and Australia: A Systematic Review

Timothy Cassidy[1], **Muhammad Nateque Mahmood**[1*] **and Argaw Gurmu**[1]

[1]School of Architecture & Built Environment, Deakin University,
1 Gheringhap Street Geelong VIC 3220, AUSTRALIA

timothy.g.cassidy@gmail.com; n.mahmood@deakin.edu.au; argaw.gurmu@deakin.edu.au
* Corresponding author

Abstract:
There is a global push for developing more sustainable infrastructure, including the use of recycled materials in asphalt pavements. It is apparent that using recycled materials offers environmental and economic benefits as it diverts waste materials away from landfills whilst also reducing the need for new virgin aggregates and binders. The initial research identified previous reviews that had focussed on a single material did not investigate barriers or lacked a structured framework. As such, this study sought to address these gaps, with a focus on Australia and the United States. This study conducted a systematic literature review to identify barriers and enablers to the use of recycled materials in asphalt pavements. The initial literature search yielded 425 results. Then, after a screening of article titles and abstracts for relevance, 294 articles were deemed eligible for inclusion in the study. The study found the most prominent recycled material in the existing literature was Reclaimed Asphalt Pavement in both USA and Australia. The barriers identified in the literature were lack of reliable information on performance, lack of mix-design information, inadequate test methods, production issues, impaired re-recyclability, and detrimental effects on workers' health and safety. This study also identified that the known enablers are not yet fully understood and require further research to better overcome barriers. It is expected that regulatory government agencies, civil construction contractors, and asphalt companies will benefit from this research

Keywords:
Asphalt pavements, qualitative analysis, reclaimed asphalt pavement (RAP), recycled materials, rejuvenators

1 Introduction

There is a problem with increasing waste production and decreasing landfill capacity globally. As a result, recycling waste materials has gained significant interest in high-volume industries such as new asphalt pavement construction (Li et al., 2019). Interest in recycled material usage in pavements has been further generated due to the diminishing source of virgin materials for asphalt production (Clark & Gallage, 2020). Incorporating recycled materials into asphalt pavements is a potential solution to both of these problems. The use of recycled materials may also have financial benefits, through cost savings as fewer virgin materials are required for the production of asphalt pavements (Franke & Ksaibati, 2015), and potentially improve the functional performance of pavements (Rahman et al., 2020). However, some hold concerns that asphalt mixes containing recycled materials are inferior to, and do not perform as well as, those comprised entirely of virgin materials (Tabakovic et al., 2010).

This research has primarily focused on Australia and the United States. As the location of this research was based in Australia, there was an inherent desire to positively influence the sustainability and functionality of Australian roads. The United States was selected to complement and compare with the Australian data for several reasons. Firstly, the structure of the respective asphalt industries in each country is quite similar, with the vast majority of material being manufactured and placed by private contractors working for governments. The two nations also share an interest in reducing the impacts of climate change, having set targets of net zero emission by 2050 (The White House, 2021; Commonwealth of Australia, 2021). Whilst these similarities mean that learnings from one country could be reasonably applied to the other, there are sufficient differences between the regions which allow for comparative insights to be identified.

Various waste materials have been recycled into asphalt pavements in Australia and the United States. The most prevalent recycled material used in both countries is Reclaimed Asphalt Product (RAP), which comprises of re-processed aggregates and binders from asphalt which have reached the end of their serviceable life (Rebbechi & Petho, 2014). Other materials which have been recycled in asphalt mixes include Recycled Asphalt Shingles (RAS), steel slag, plastics, waste tyre rubber, and many others (Rahman, et al., 2020). Academic research regarding the use of these recycled materials has been critically analysed to determine the extent, and suitability of, their use in American and Australian applications. Whilst there was a significant focus in the literature on the economic, environmental and performance characteristics of mixtures, there is scope for further objective research on the barriers preventing more recycled material implementation. This paper aims to fill this knowledge gap by conducting a comparative study of the factors affecting the use of recycled asphalt materials in the United States and Australia whilst seeking to identify barriers and enabling factors. The use of a systematic literature review may also assist in identifying which materials and technologies have received the greatest amount of focus in research literature and which areas may be underdeveloped.

2 Purpose of the Research

In Australia, a review of waste materials with potential for usage in asphalt pavements was undertaken (Rahman, et al., 2020). The review described the waste management issue, and the potential role asphalt can play in solving this problem. The paper provided an overview of some selected waste materials which could be utilised in asphalt mixtures. In the United States, a recent review of ‘Green Asphalt Mixes’, including the usage of recycled materials, had been carried out (Pouranian & Shishehbor, 2019). The study assessed the sustainability of common green technologies against performance criteria (e.g., rutting, moisture susceptibility, thermal and fatigue cracking resistance) and their environmental impacts (e.g., greenhouse gas emissions and energy consumption). It was found that the usage of waste materials in pavements offered advantages in terms of performance and/or environmental impacts, particularly when used in combination. However, it was found that limited research existed on the usage of different materials and technologies in combination with each other.

Collective industry bodies and government organisations in Australia, such as Austroads, Australian Flexible Pavement Association (AFPA), and Australian Road Research Board (ARRB), have previously undertaken research projects. These have included literature reviews and published research regarding the usage of recycled materials in asphalt pavements. Relevant literature from Austroads has included Part 4E of the Austroads Guide to Pavement Technology published in 2009 (Andrews & Rebbechi), which provides an overview of recycled material usage in asphalt pavements. Austroads has also conducted and published research results from a three-year study on maximising the re-use of RAP (Lee, et al., 2015). This included a 2015 survey by a working group that identified the main areas of concern in the industry to be: Stockpile management, RAP binder, RAP mix production, RAP content and mix design, Mix Performance, and other (including RAP and WMA or rejuvenators). The viability of using recycled plastics in asphalt and sprayed sealing applications (Chin & Damen, 2019) was also studied by Austroads. Similar organisations have conducted research in the United States. The National Asphalt Pavement Association (NAPA), Federal Highway Administration (FHWA), and American Association of State Highway and Transportation Officials (AASHTO) have conducted much of their research. For instance, NAPA has published research on recycled materials in asphalt pavements, including a literature review published in 2020 on the use of recycled plastics in asphalt (Yin, et al., 2020). NAPA has additionally published survey data on the current production and usage of recycled materials and WMA in Asphalt pavements each year from 2010 to 2019 (Williams, et al., 2020). Although such research has been quite comprehensive, this paper differentiates itself from the existing work through the use of a rigorous systematic literature review on barriers and enablers to the usage of recycled materials.

3 Research Methodology

A systematic literature review (SLR) has been adopted because it constitutes a unique tool for establishing the knowledge boundaries of existing studies on a particular subject (Wuni, et al., 2019). Further, an SLR is an objective, replicable and transparent tool to examine existing studies on a subject (Levy & Ellis, 2006). As such, it strengthens the methodological rigour of the research and ensures analytical objectivity. Furthermore, considering the rapid growth of research publications and the organic nature of literature, a SLR is a useful tool for keeping up-to-date with developments on a subject (Wuni & Shen, 2019). Following the definition of the research problem, the first stage of the SLR involved the collection of data. To collect data, keywords were identified, an appropriate database was selected, a full search string was developed, and the search was conducted. Following this, rapid screening of the titles and abstracts of articles was undertaken to determine their eligibility for inclusion in the study. Subsequent to the data collection phase, the articles were analysed to identify materials and technologies applicable to recycling in asphalt pavements, as well as barriers or enablers for their further implementation and use. It is anticipated that the use of secondary data will provide comparative insight into the difference in the use of recycled materials between the two regions, whilst also providing the opportunity for learnings from how different regions manage and re-use waste in recycled asphalt pavements.

3.1 Data Acquisition

To enable data collection utilising the SLR, the research problem was defined as the use of waste materials in asphalt pavements. This led to the selection of the keywords ‘asphalt pavement’ and ‘recycled materials’. From this, ‘flexible pavement’ was identified as an alternative term to asphalt pavements along with the other forms of the word ‘recycled’ (e.g., recycle, recycling, etc). Scopus was selected as the database for the search. It provides comprehensive coverage of high-quality peer-reviewed articles, has meticulous inclusion criteria and indexing processes, and provides up-to-date publications (Zhao, et al., 2021). Additionally, the Scopus database has been used widely in this area of research, making it appropriate for the study (Xiao, et al., 2021).

A literature search in the Scopus database was carried out using the above-mentioned keywords in the following search string “asphalt pavement* OR flexible pavement*” AND “recycle* material*” in the title, abstract, and keyword sections of published studies. The time frame of the search was approximately the last 10 years, with articles being included from the years 2010 to 2021 to only include recent studies, whilst still allowing for insights into the change of the researcher's interest in the field over time. The countries searched were restricted to Australia and the United States to only obtain articles from the countries being compared in this study. The search was also contained by document type only to include journal articles as they are often peer-reviewed to ensure academic integrity (Mattus, 2007). Finally, only English language articles were sought. After initial screening, this search identified 426 publications. The Preferred Reporting Items for Systematic Reviews and Meta Analyses (PRISMA) framework is illustrated in Figure 1.

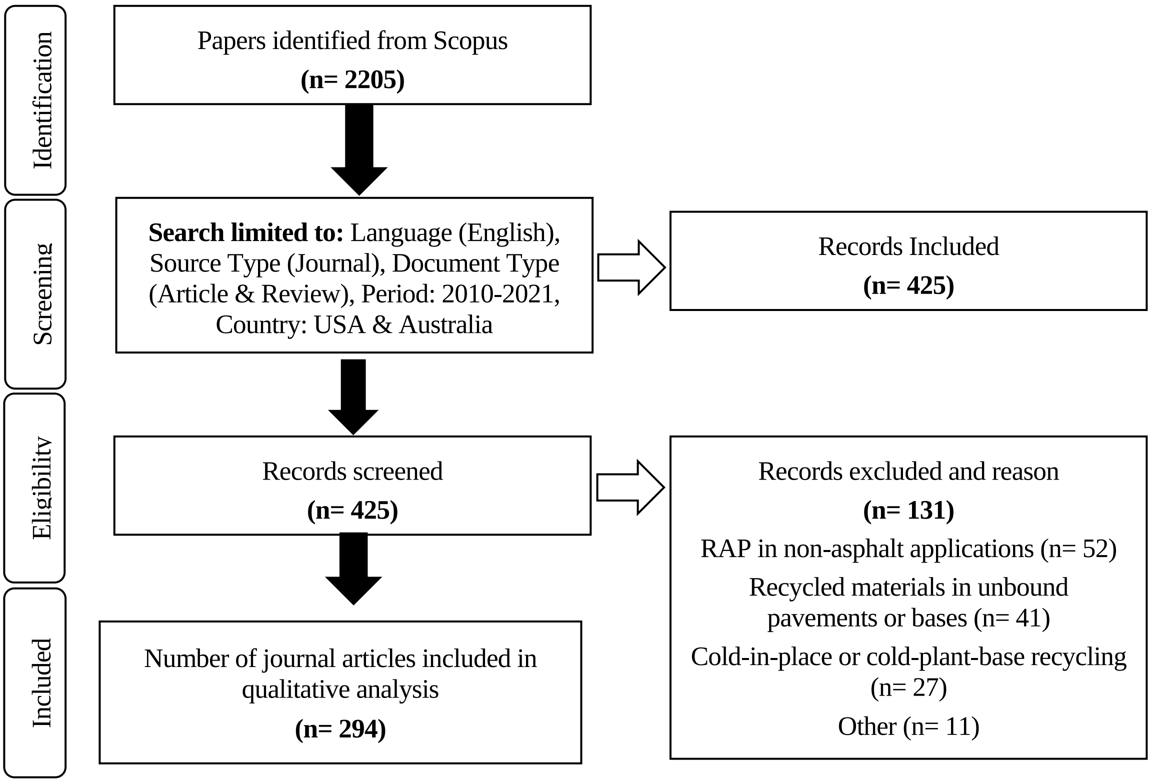

Figure 1. PRISMA Framework

The titles and abstracts of articles were then screened for their relevance resulting in the exclusion of 131 articles. The vast majority of these articles were rejected as they did not deal with the usage of recycled material in asphalt pavements. This resulted in the final inclusion of 294 journal articles for descriptive and thematic analysis.

4 Findings and Discussion

4.1 Characteristics of Studies Included in the Analysis

At least 294 articles have been published over the past decade regarding the use of recycled materials in asphalt pavements. This demonstrates that there is an interest amongst researchers to better understand how recycled materials can be used in asphalt pavements. Figure 2 shows an increasing trend has been observed over the past decade which indicates that this interest has been increasing. The first five years of the decade (2011-2015) had an average of 16 articles per year, whilst the following six years (2016-2021) had an average of 37 articles per year, more than double the preceding five years.

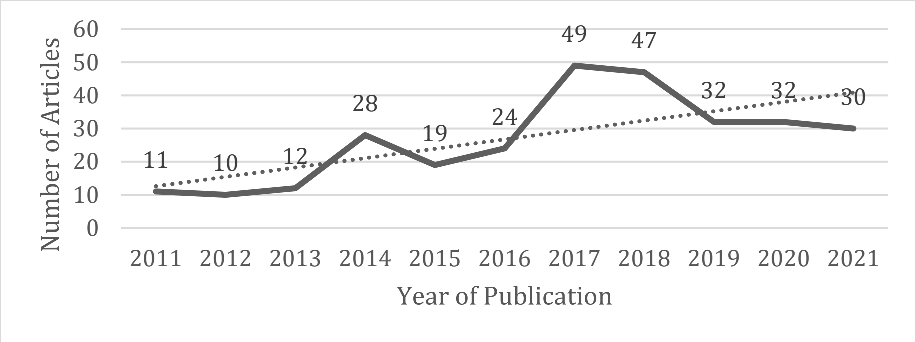

Figure 2. Annual publications trend on recycled materials in asphalt.

Moreover, analysis showed that these included articles were published across 56 different sources, indicating that interest in the usage of recycled materials is present in a wide range of areas. At least 10 articles or more on the usage of recycled materials in asphalt pavements were published in Construction and Building Materials (66), Transportation Research Record (46), Journal of Materials in Civil Engineering (44), Road Materials and Pavement Design (36), International Journal of Pavement Engineering (11), and Journal of Cleaner Production (10), as shown in Figure 3.

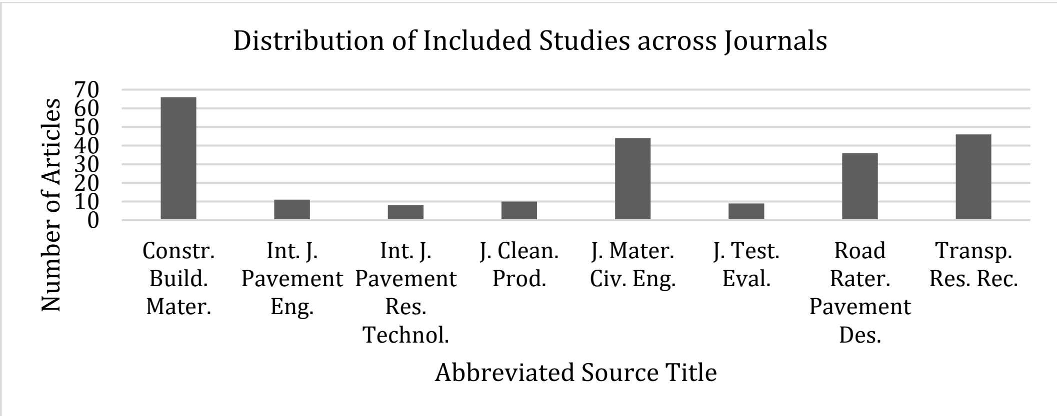

Figure 3. Distribution of included studies across journals

4.2 Recycled Material Usage in Asphalt Pavements in Australia and the United States

Available recycled materials for use in asphalt pavements for Australia and the United States have been identified from the analysis of the included literature, as shown in Figure 4. From the Scopus search, it was found that by far the most common recycled material to be researched was RAP (210). This correlated with RAP being the most recycled material in the United States in 2019, with 89.2 million tonnes recycled (Williams, et al., 2020). For context, this quantity was more than Australia’s total solid waste production of 75.8 million tonnes in 2019. Other materials of interest in the identified articles included RAS (114), Recycled Concrete Aggregate (16), Crumb Rubber (14), Recycled Plastics (10), Steel Slag (4), Fly-Ash (2), and Glass (2).

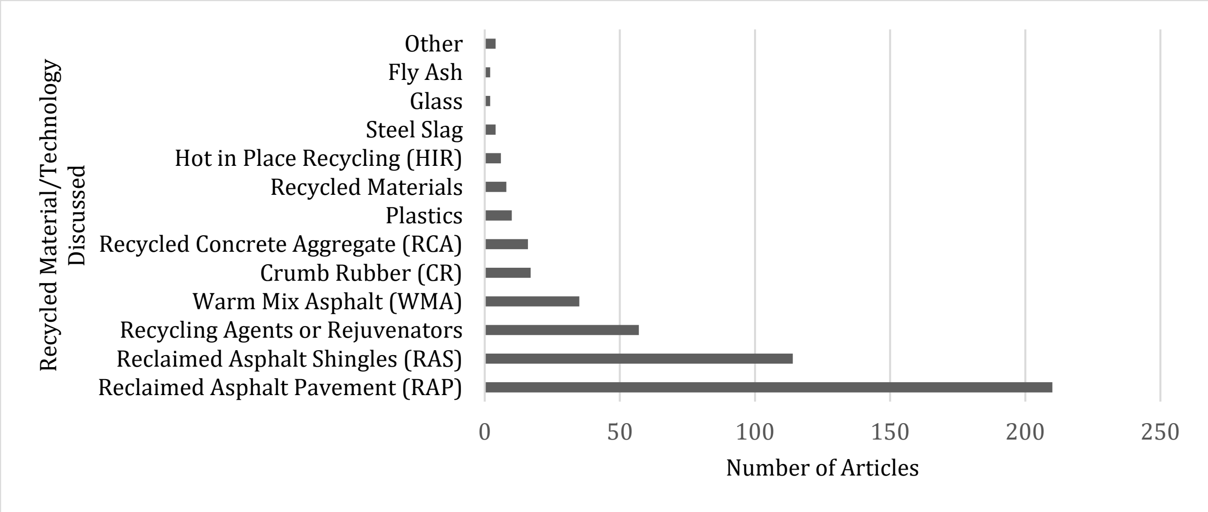

Figure 4. Number of articles by material/technology.

4.3 Barriers to Recycled Material Usage in Asphalt Pavements

The most prevalent barriers the research sought to overcome were those associated with performance, particularly issues with mixtures containing RAP. The barriers identified through existing literature are described below.

4.3.1 Inferior Functional Performance

Based on the SLR, the most common performance characteristics analysed in the researched articles were cracking resistance, rutting resistance, moisture susceptibility, and fatigue. Of these characteristics, cracking resistance, particularly in low-temperature climates, was featured in the greatest number of articles. It was consistently evidenced in the articles that as the RAP, or RAS, percentage was increased, the cracking resistance was reduced, especially in colder climates (Coleri, et al., 2018). With RAP, there was also some concern amongst regulatory agencies that the use of greater percentages could result in mixtures that were too stiff, lack workability, difficult to compact, and more susceptible to failures such as cracking or rutting (Mogawer, et al., 2012).

4.3.2 Issues with Source Materials

Articles were found regarding issues relating to the source materials, these included stockpiling practices, heterogeneity of recycled materials and availability. For example, RAP is asphalt pavement that has been reclaimed for use and is typically generated by milling or demolition of existing asphalt pavements (Ashtiani, et al., 2019). As such, RAP is known for being a heterogeneous material (Cherif, et al., 2021) because stockpiles can include severely aged and relatively fresh asphalt millings. This heterogeneity of RAP may be a problem for research consistency as one study containing ‘high quality’ RAP may find that the performance of mixtures with 40% RAP to be adequate, whilst another study using ‘low quality’ RAP may find that any mixtures containing more than 10% RAP exhibit inferior performance.

4.3.3 Lack of Knowledge of Environmental and Economic Benefits

Work is ongoing on how to fully quantify the benefits of recycled material usage in asphalt pavements through Life Cycle Assessments (Yang & Al-Qadi, 2017; Nizamuddin, et al., 2021). The ability to fully measure these benefits will help governments and private companies make informed decisions about the sustainability and cost benefits of using recycled materials in asphalt pavements. In addition, this quantification would assist in monitoring the progress towards, and ultimate accomplishment of, relevant United Nations Sustainable Development Goals (SDGs) and respective national targets.

4.3.4 Lack of Mix Design Information

Another area of concern addressed in the research was to what extent the recovered binders from RAP or RAS should influence pavement design. In the United States, under the Superpave system, bituminous binders are classified under a performance-based system which specifies a temperature range in which pavements exhibit suitable performance characteristics (Elkashef, et al., 2017). The addition of an aged binder recovered from RAP and RAS materials potentially affects the grading of this binder as it blends with the added virgin bitumen. The articles indicated that the current research is incomplete on how much RAP binder is recovered, to what extent it blends with virgin binders, and how its properties differ from wholly virgin mixes (Afzali et al., 2019).

4.3.5 Inadequate Test Methods

When designing new pavements and incorporating RAP, it is crucial to consider the properties of the binder being recovered as they can vary significantly from one RAP source to another. Current methods to extract and recover asphalt binder from RAP to assess these properties require large amounts of material, and subsequently large amounts of toxic solvents (Filonzi, et al., 2020). Additionally, concerns exist about the lack of test methods sufficiently practical for routine use in the design of asphalt mixes containing recycled materials (Im & Zhou, 2017).

4.3.6 Production Concerns

Aggregates need to be heated before mixing into asphalt to remove moisture. For virgin aggregates, this is done directly. However, it is not possible to heat RAP directly as it can result in burning or significant altering of the binder properties. Therefore, the RAP is heated through thermal transfer from virgin aggregates which have been ‘super-heated’. As the percentage of RAP increases, the temperature the virgin aggregate needs to be heated to also increases. For instance, a mix with 50% RAP would need to be 608°C (Hossain, et al., 2017). This increases the amount of fuel required, and subsequently increases greenhouse gas emissions.

4.3.7 Impaired Re-Recyclability

Many of the asphalt pavements currently coming to the ends of their serviceable lives were originally designed with some percentage of RAP, creating a critical scientific question of the second-generation of RAP (Wang, et al., 2019). As first-generation RAP is already a material which has already been aged, containing a stiffer oxidised binder, the potential proliferation of these undesirable characteristics after a second usage life could be an area of concern.

4.3.8 Detrimental Worker Health and Safety Effects

At the turn of the century, an Australian study identified that excess fumes were a dominant health and safety concern involved with the use of RAP (Oliver & Anderson, 2000). However, in this research only two articles were found which addressed negative impacts on a worker’s health. One of these articles addressed the potential exposure of workers to silica dust during the milling process for producing RAP (Hammond, et al., 2016), whilst the other addressed concerns regarding the historical contamination of post-consumer RAS with asbestos (Haas, et al., 2019). None of the articles which featured crumb rubber or waste plastics addressed concerns about the health and safety hazards posed to workers. This was of concern as the heating of plastics releases numerous harmful chemicals (Conlon, 2021).

4.3.9 Attitudinal Barriers

Attitudinal barriers to the use of recycled materials were expected to be an issue as concerns had been expressed by pavement professionals in previous Austroads surveys (Lee, et al., 2015). However, attitudinal barriers did not appear to be a prominent issue in the literature. Concerns held regarding the perceived increased brittleness and decreased cracking resistance of mixes containing high percentages of recycled materials were largely supported with the focus instead being, “how might these challenges be overcome”, rather than, “how might the perceptions of individuals be changed”.

4.4 Enablers to Recycled Material Usage in Asphalt Pavements

The greatest incentives and, hence, enabling factors to use recycled pavements are the potential environmental and economic benefits. The enablers to the use of recycled materials in asphalt pavement identified through SLR are described in the following sub-sections.

4.4.1 Economic Benefits

From an economic perspective, the use of recycled materials in asphalt pavements has potential to reduce the cost of manufacturing as fewer virgin aggregates and binders are required (Kocak & Kutay, 2015). This increases the potential profitability for manufacturers, whilst enabling governments to achieve more value for taxpayer dollars (Im, et al., 2016). For the industry as a whole, the use of recycled materials increases the cost competitiveness of asphalt as a pavement material and creates a point of difference relative to other products.

4.4.2 Environmental Benefits

The articles demonstrated that the use of recycled materials offers both real and perceived environmental benefits. The use of RAP as a raw material reduces the amount of new virgin materials which are required, reduces the amount of bitumen which needs to be processed, and waste asphalt is re-directed away from landfills (Vidal et al., 2013). This, in turn, reduces green-house gas emissions as quarrying of virgin aggregates and refining of bitumen from crude oil is not required. The environmental benefits have been driven by the increasing cost of asphalt, the scarcity of quality aggregates, together with the need to preserve the environment (Al-Quadi et al., 2007). Plastics have been used for similar reasons, with the addition of plastics to the mixture as an additive prior to the addition of binder capable of replacing 15-30% of aggregates (Huang, et al., 2007).

4.4.3 Superior Functional Performance

Although potentially more prone to cracking, mixtures containing increased RAP or RAS content have exhibited greatly improved rutting resistance due to the stiffer aged binder (Zhang, et al., 2017). This was reinforced in an Australian study of RAP used in combination with multigrade binders which found it exhibited superior resistance to rutting when compared to non-RAP mixes (Clark & Gallage, 2020). Crumb rubber meanwhile, has the potential to improve the properties of asphalt mixtures and provide a suitable means for the disposal of used rubber vehicle tyres (Picado-Santos, et al., 2020). Research on the use of crumb rubber in asphalt found it was one of the best ways to recycle waste tyres (Wang, et al., 2020). Although mixtures incorporating crumb rubber are initially more expensive, their increased durability potentially results in life cycle cost savings (Picado-Santos, et al., 2020). The addition of plastics to modify the binder before production of asphalt mixtures has also been found to improve performance (Huang, et al., 2007). The use of Styrene Butadiene Styrene (SBS) or High-density polyethylene (HDPE) can produce mixtures with desirable properties such as less susceptibility to temperature variations, lower fatigue, higher resistance, a longer life, and less likely to suffer permanent deformations (Movilla-Quesada, et al., 2019). Research has also found that the use of waste polymers in binder within mixes containing RAP can alleviate some of the above-mentioned performance concerns (Daryee, et al., 2020).

4.4.4 Improved Mix Design Understanding

Crucial to the successful implementation of recycled materials in asphalt mixes is the appropriate mix design methodology (Meroni et al., 2020). The properties of bitumen recovered from RAP or RAS have been considerably aged so, improved understanding of their blending with virgin binders will help to better inform mix design methodologies and decisions (Zhang, et al., 2019). Further, it was found that although the use of RAP slightly increases stiffness, the use of 5%-10% should be achievable without the need for other mix design changes (White, 2019). Using greater percentages, however, will likely require the use of softer binders or rejuvenators.

4.4.5 Rejuvenators

The SLR identified that performance concerns, particularly around poor cracking performance can be overcome through the use of rejuvenators, also known as recycling agents (Xu et al., 2020). Some materials used as rejuvenators are recycled materials in their own right such as waste engine and cooking oils (Taherkhani & Noorian, 2020). This technical approach appears to be the most effective way of overcoming performance however, the SLR indicated there is significant work required to fully understand its effects on the blending of old and new binders.

4.4.6 Warm Mix Asphalt

Whilst Warm Mix Asphalt (WMA) was a common subject area of research, it has been found that the environmental benefits of WMA are largely offset by the greater environmental impacts of the raw materials used, particularly some additives (Vidal, et al., 2013). However, the use of WMA technology has been shown to improve performance of mixtures containing RAP in terms of workability, moisture damage resistance, and rutting resistance (Behnood, 2020). Further investigation into the combination is still required (Pouranian & Shishehbor, 2019).

4.4.7 Government Mandates and Regulation

As many governments and regulatory agencies place restrictive limits on the amount of recycled material which can be incorporated into pavements, typically around 10-30% (Abed, et al., 2018), it was anticipated this would be identified as a barrier. However, no research was found which proposed facilitating the greater use of recycled materials by making their inclusion a requirement for government projects. This was potentially due to the United States' unsuccessful experience in mandating the use of crumb rubber in 1994 (before the science had been fully developed) which resulted in a reduction in usage (Williams, et al., 2020).

4.5 Discussion and Analysis

Interestingly, there was a close relationship between the barriers and enablers identified in the literature review. For instance, in regards to functional performance, it was found that the use of some recycled materials could have adverse effects on certain properties, whilst other recycled materials had been found to improve aspects of functional performance. Therefore, it would be practical to promote the use of recycled materials in applications where their presence improves properties which are priority; i.e. using higher percentage RAP mixes where rutting is of greater concern than cracking. This intertwined relationship also existed between the economic and environmental barriers and enablers to the use of using recycled materials. Although it is apparent that using recycled materials in asphalt pavements offers benefits in both of these regards, the quantification of these is not yet fully understood. Enabling governments and companies to measure these benefits would assist in the tracking of progress towards various goals and targets relating to sustainability and climate, thus promoting the use of asphalt as a pavement material now and into the future.

5 Conclusion and Further Research

This research has identified the available recycled materials for usage in asphalt pavements in the United States and Australia. The most commonly used and researched material was found to be RAP. The primary barrier to the further use of recycled materials was found to be the inferior performance of mixtures containing recycled materials. However, increasing knowledge of rejuvenation technologies and the design of mixtures containing recycled materials will likely improve this situation. From this, RAP is recommended as the most appropriate recycled material for usage in asphalt pavements in both countries; and that research into rejuvenators should continue. With regard to the usage of plastics, more research into the health effects (to ensure a comprehensive understanding) is recommended prior to implementation. Moreover, the existing literature identified through the SLR did not find policy and attitudinal barriers to be widely prevalent. The use of systematic literature review is inherently prone to publication bias as certain journals may favour particular areas of research over others (Rothstein, et al., 2005). The exclusion of countries other than the United States and Australia and the use of only the Scopus database may have resulted in important research trends from other territories being missed.

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Estimating the Life Cycle Energy Consumption of Urban Residential Buildings Based on a New System Boundary: An Empirical Study of China

Lei Liu[1*], Vivian W.Y. Tam[1], and Khoa N. Le[1]

[1]School of Engineering Design & Built Environment, Western Sydney University, Locked Bag 1797 Penrith NSW 2751, AUSTRALIA

leiliu.m.chn@gmail.com; vivianwytam@gmail.com; k.le@westernsydney.edu.au
* Corresponding author

Abstract:
Building energy consumption, as one of the biggest emitters worldwide, has been an urgent social issue to be solved along with the global abnormal climate occurring frequently. Undoubtedly, accurate estimation is a useful way to help improve energy conservation policymaking and energy services adjusting. Although there is a consensus about the life cycle energy boundary of buildings which is mainly comprised of embodied and operational energies, calculating errors still existed under such system boundary. Certainly, part of the reason comes from methods' limitations, but interestingly, some recent studies suspected the indirect contribution of mobile energy such as occupants' daily commuting and travel on building energy. To fill the gap between estimated and actual energy consumption, this paper proposes an extended life cycle energy system of buildings, which includes embodied, operational, and mobile energies. Then, an empirical study in China is conducted, which adopts a hybrid life cycle assessment method (H-LCA) combined with macro and micro data to estimate the life cycle energy consumption of urban residential buildings from 2005 to 2019. Results show that there was a moderate increase in building energy consumption, but the embodied and operational energy intensities decreased dramatically. Besides, the life cycle energy consumption estimated was higher by about 6.6%-19.6% than that of other studies, and the contribution of mobile energy to total energy consumption increased significantly from 5.49% in 2005 to 23.86% in 2019. Admittedly, this study provides a new energy system idea for the next studies in the field.

Keywords:
Energy consumption estimation, Life cycle energy, Mobile energy, Urban residential buildings

1 Introduction

Significantly, extreme weather events have occurred frequently these days worldwide. A month-long heatwave and record low rainfall have resulted in an unprecedented drought in China. The wildfires have been burning in several countries in Europe and the Mediterranean, beginning in June (The Center for Disaster Philanthropy, 2022). As shown under Figure 1, There is a significant positive correlation between increased energy consumption and natural disasters. Therefore, energy-saving issues were paid notably attention again, especially in the construction industry. Most focused on sustainable fields like green buildings, recycling technologies, and clean energy, thereby making daily energy use sustainable and environmental-friendly (Florides et al., 2002). However, as their benefit on environmental impact is difficult to be quantified in certain aspects, some wrong usage and perception of specific energy conservation actions were adopted (Pei et al., 2022). Thus, it is necessary to get clear feedback by estimating the current energy consumption state as well as predicting the next development trend. Admittedly, accurate estimation and prediction not only help governments formulate energy conservation policies but also makes practitioners adjust energy services. Unfortunately, there is still a significant difference between estimated and actual values, although advanced technologies and methods were applied. After determining current energy conservation efficiency, Du et al. (2021) investigated the actual energy consumption change of urban and rural residential buildings in China. The results showed that real energy savings only accounted for 47-55% of the predicted value in urban areas, and 45-46% for rural areas. Referring to some review and research articles about the life cycle energy estimation of buildings (Tam et al., 2022, Fenner et al., 2020, Yu et al., 2021), it can be found that the current life cycle energy scope is not complete. some started to explore the impacts of mobile energy on building energy consumption. To fill the concept gap and to estimate building energy consumption more accurately, this paper will extend the life cycle energy boundary of buildings and take the urban residential buildings in China as an empirical study to verify its reasonability. No matter what the outcomes are, it will provide a new idea and pathway for the next studies to study the dominant components of the life cycle energy consumption of buildings better.

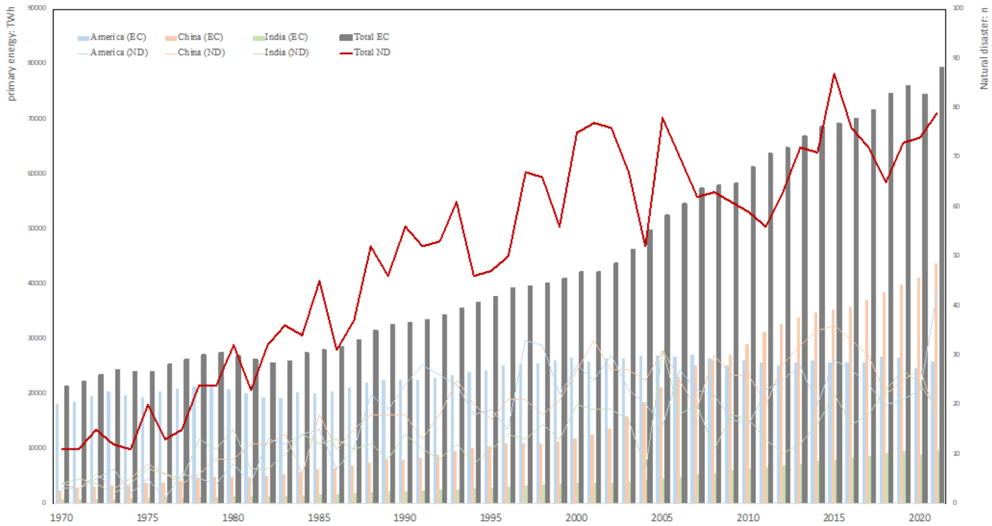

Figure 1. The amount of energy consumption and natural disasters in main countries from 1970-2021(British Petroleum, 2022).

2 Literature Review

In fact, an accurate estimation has to consider the two influencing factors at least: system boundary, and methods selection (Venkatraj and Dixit, 2022). The former limited the research scope, and the latter raised the computational accuracy. Due to their different identifications in previous studies, the estimated results are always diverse. Thus, it needs to pay more attention to the logicality, integrity, and concreteness of fundamental theories -life cycle energy of buildings, and energy consumption estimation methods- based on the purpose of this study.

2.1 Life cycle energy of buildings

Life cycle assessment (LCA) was proposed in the 1990s and then developed rapidly across the world. It was applied broadly in some important industries such as electromechanical and steel, especially the construction industry (Ekvall, 2005). From small fundamental materials to big buildings modules design, each activity can be identified with a unique life cycle scope and then be assessed. As the GB/T 51161-2016 of "Standard for energy consumption of buildings" showing, building energy consumption is limited in the energy input from outside to keep up the occupants' daily indoor demands during the operation stage, such as the natural gas for cooking, electricity for cooling, and coal for heating (China''s Ministry of Housing and Urban-Rural Development, 2016). It was found to account for over 75% of total energy consumption in building fields (British Petroleum, 2022). However, the current mainstream findings showed the importance of embodied activities which is related to the life of building materials, from extraction to ending up waste disposal. It was showed that embodied energy consumption has reached up to 51.2% in 2020 in China (State Statistical Bureau, 2020), becoming the biggest energy consumption source in the construction industry. However, some studies recently start paying more attention to the indirect impacts of part of transportation energy on building itself, called “mobile energy”. They thought occupants’ daily commuting and trips related to the building environment should be recognized as building energy (Pérez-Neira et al., 2020). It was proved that the choice of travel mode depends on the building location to a large extent. Because of the long distance between workplace and home and long commuting time, citizens prefer to use private vehicles (Tam et al., 2022). Thus, mobile energy was considered as an important building energy type. Fenner et al. (2020) found it significantly made up 24% of total energy consumption. After the review of life cycle energy boundaries development (Figure 2), it is the time to redefine the life cycle energy boundary of buildings (LCE-B) and explore the impacts of mobile energy on building environment.

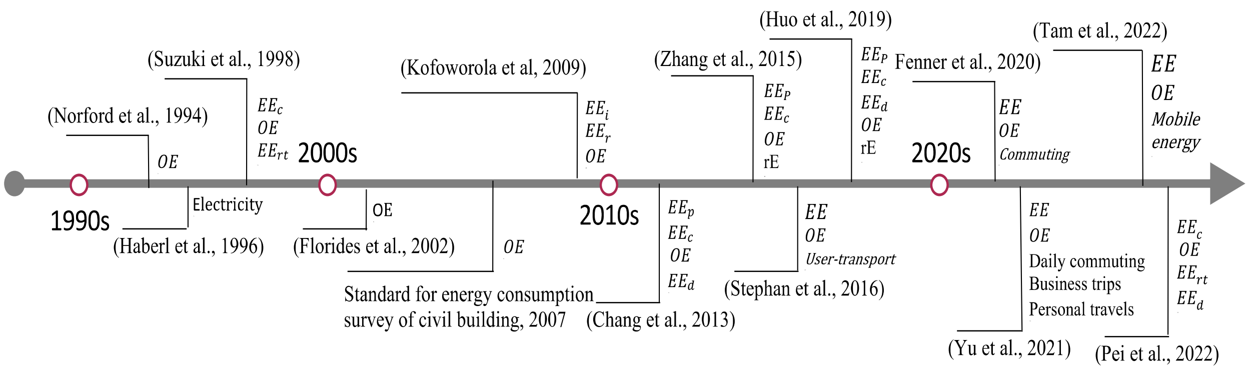

Figure 2. The development of life cycle energy boundaries of buildings in past decades.

2.2 Energy consumption estimation

To date, there were lots of methods used for estimating building energy consumption. However, the significant calculating errors among them cannot be ignored (Du et al., 2021). An appropriate approach selection based on the research purposes determines the estimation accuracy to a large extent. Tam et al. (2022) summarized the major building energy consumption estimation methods, elaborating on the application of three dominant energy sources in different conditions. After analyzing the characteristics, they can also be simplified into two categories: bottom-up and top-down, as shown from Figure 3. A significant difference between them is that they are from micro and macro perspectives respectively. The former paid more attention to materials inventory, involving a great number of materials information and construction activities in the manufacturing stages. Nevertheless, because of the complicated processing procedures and sectors interaction on-site, many details were always ignored unconsciously or considered repeatedly (Azari and Abbasabadi, 2018). Although the latter can be more accurate to calculate energy consumption by the difference between input and output data, it cannot narrow the objects’ scope, namely identifying the focus areas for building energy efficiency (Zhang et al., 2015). Overall, which method is selected below depends on the specific study purpose and the accessibility of raw data.

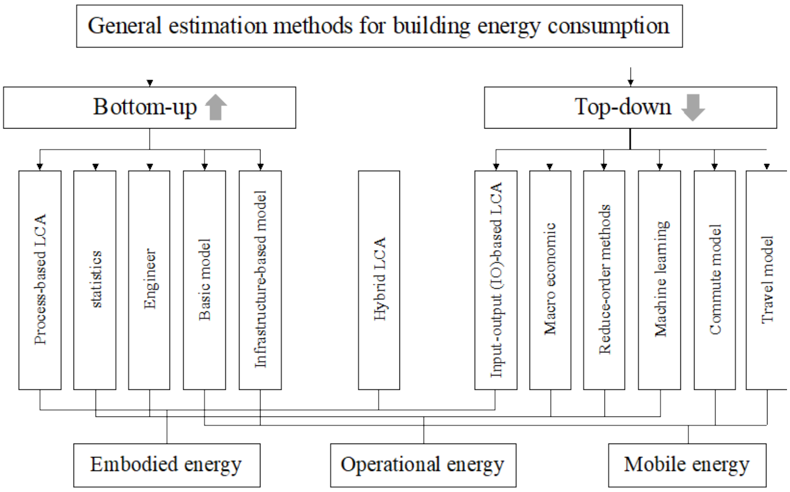

Figure 3. A summary of general estimation methods of life cycle energy consumption of buildings.

3 Research Methodology

3.1 An extended building energy framework

Based on the systematic review of the life cycle energy of buildings above, an extended system framework was developed in this study (Figure 4), which covered all direct and indirect building energy consumption phases and activities. From cradle to grave, and ending up beyond life, it can be divided into three main categories: embodied energy (EE), operational energy (OE), and mobile energy (ME). EE involved the building materials which existed through the whole building process, including extraction, manufacturing, construction, retrofit, demolition, waste disposal, and reuse/recycling. OE refers to the occupants' daily living demands in the building operation process, including heating, water heating, cooling, ventilation, lighting, equipment, water use, and cooking. It had three consumption forms: daily fuels, electricity, and centralized heating. Also, three main energy consumption paths had to be referred to: direct consumption, transformation loss, and others. Besides, this study added indirect ME as a dominant energy category in the life cycle system. It involved the building materials transportation in its life, and the daily commuting and trips related to the building location in the use stage. Overall, an intact life cycle energy framework needs to contain these activities and phases mentioned above.

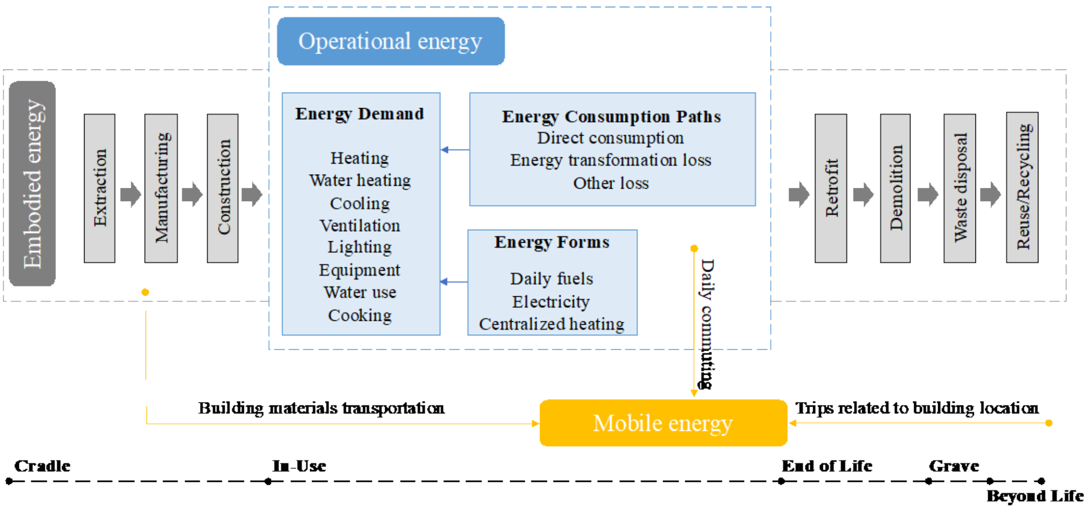

Figure 4. An extended life cycle energy framework of buildings.

3.2 Hybrid-LCA estimation approach

According to the summary of building energy consumption estimation methods as well as the new framework for the life cycle energy system of buildings in section 2 above, this study adopted a hybrid-LCA approach to estimate the three main energy sources respectively and then sum up. Since it is based on the micro with macro perspectives, both detailed materials data and macro energy input and output were collected. It can bridge the gap between macro and micro estimation procedures compared with other single perspective, thereby reducing calculation errors as much as possible. Further description and analysis are shown below.

3.2.1 Embodied energy

Given the accessibility and complexity of original material information collection, EE was limited in four parts: the materials production (EE_P), the construction stage (EE_c), the recurrent maintenance (EE_r), and the reuse/recycle stage (rE). It can be expressed as Eq. 1-4 below.

$$EE = EE_P + EE_c + EE_r - rE \quad \text{Eq. 1}$$

$$EE_P = e_m + e_p = \sum m_i M_i + \sum f_{j,i} F_j \quad \text{Eq. 2}$$

where e_m is the feedstock energy; e_p is the processing energy; e_l is the labor energy; m_i refers to the quantity of raw material (i); M_i refers to the energy consumption of material (i) extraction per unit; $f_{j,i}$ represents the amount of fuel (j) in material (i) manufacturing; F_j represents the energy transform of fuel (j).

$$EE_c = e_c + e_d + e_w = (C_{h,i} + C_{a,i}) \sum_i^n TE_{f,i} + \sum MC_i T\mu + \sum f_{j,a} F_j \quad \text{Eq. 3}$$

where $C_{h,i}$ denotes the human labor coefficient of material (i); $C_{a,i}$ denotes the energy consumption coefficient of construction activity (i); $TE_{f,i}$ indicates the total energy intensities of fossil fuel-based energy source (i); MC_i represents the energy content of machinery (i) per hour, T equals to the operational time, μ is the energy coefficient of correction of machinery. $f_{j,a}$ is the amount of fuel (j) of activity (a) in waste disposal stage; F_i is same as above.

$$EE_r = \sum m_i M_i \left[(L_b / L_{mi}) - 1\right] \quad \text{Eq. 4}$$

where m_i & M_i are same as above; L_b represents the life span of residential buildings; L_{mi} denotes the life span of the material (i).

$$rE = \partial \cdot EE_P \quad \text{Eq. 5}$$

where ∂ is the percent recycling rate (∂=5%) (Zhang et al., 2015).

3.2.2 Operational energy

In general, OE can be regarded as the sum of three kinds of sources: daily fuels (OE_f), electricity (OE_e), and centralized heating (OE_h). Since the huge use of electricity and thermal power is always measured in nation and province units, it is better to assess energy consumption from a macro-economic perspective. Therefore, this study refers to the official Energy Balance Table (EBT), which is regarded as one of the main sources to collect energy data in different industries of China. Although it contains seven major sectors, the construction industry does not be listed separately. Thus, a split model for building energy collection was developed, as shown from Figure 5. The basic energy consumption (①) involves 3 categories in the EBT: “Wholesale, retail trade, hotel, and restaurant”, “Others”, and “Residential consumption”. Due to different industry statistics standards, part of transport energy consumption in relevant industrial companies (②) should be excluded. Besides, as the heating consumption in ① was obviously less than that of centralized heating (③) focused on northern China in winter, appropriate correction needed to be carried out. Besides, some significant operational energy consumption in other industries (④) should be added, such as cogeneration buildings transportation hub buildings, and so on.

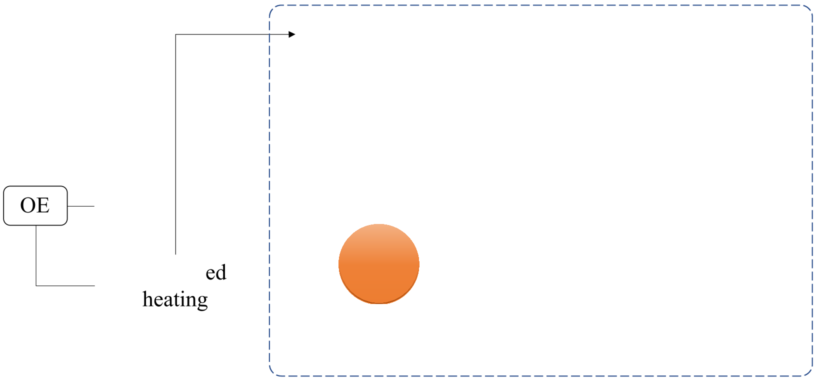

Figure 5. A split model used for energy consumption statistics based on EBT.

3.2.3 Mobile energy

In the study, ME was defined into two parts: building materials transportation, and daily commuting and trips. Specifically, ME_t refers to energy use in materials, waste, and labor transportation processes from the starting places to the construction sites, which was usually classified as embodied energy in the past. ME_c is usually regarded as a part of urban transportation energy, and mainly results from private cars. In fact, it is most affected by the specific building location. They can be expressed in Eq. 6-7 below.

$$ME_t = \sum_{i=1}^{8} \frac{N_i \times S_j}{V_k} \times L_i \times (E_{k,E} + E_{k,F}) \quad \text{Eq. 6}$$

where N_i represents the weight of building material (i) use per unit; S_j refers to the floor area of structure type (j); V_k indicates the volume of transport vehicle type (k); L_i denotes the transport distance of material (i) from the material manufacturing to the construction site; $E_{k,E}$ is the average truck diesel consumption of transport vehicle type (k) under empty load; $E_{k,F}$ is the average truck diesel consumption of transport vehicle type (k) under full load.

$$ME_c = PVO_i \times VMT \times E_i \quad \text{Eq. 7}$$

where PVO represents the amount of private vehicle ownership (type i); VMT denotes the amount of Vehicle Miles Travelled. Ou et al. (2020) developed the “Anti-log-transform” to assess the annual average mileage of private vehicles, and finally it is estimated of 12,377 kilometers; E_i= the energy intensity of private vehicle type (i).

3.3 Case study and data processing

Given the convenience and availability of energy consumption data, this study takes China as an empirical study to determine the effectiveness of the extended life cycle energy system. One of the main reasons is that the macro data released by the government are authoritative and convincing. Also, this time span was selected from 2005 to 2019 yearly. According to the estimation equations and collection principle listed above, the sources of virgin data as well as data processing are elaborated below.

1. Most of EE and OE data pertaining to the base year were obtained from China Building Energy Consumption Research Report 2016-2021 CABEE (2016), (2017, 2019, 2020,

2021, 2022). it involves the national EE_P, EE_c, and OE, including public buildings, and urban and rural residentials.

2. Given the characteristic of mobile energy, it can be found that daily commuting and regular trips in China are more suitable for city dwellers. Besides, the availability of EE and OE is simple in rural areas, and people can use local and sustainable materials. Therefore, according to the actual activity environment, the urban residential buildings were chosen as the research objects in this study.

3. Official data shows that the urban residential buildings' floorage accounted for approximately 42% of national floorage up to 24.4 billion m2 in 2018 (THUBERC, 2020). In fact, it was found that there is no direct correlation between built location and the consumption of building materials. Therefore, 42% can be used for the exchange coefficient between national and urban EE_P and EE_c. Besides, based on the same estimation process, Dixit (2019) concluded that EE_r is about 0.5% of EE_P. Besides, since the transportation of materials was classified as mobile energy, the raw EE_P data should be adjusted significantly. Meanwhile, rE was defined as 5% of EE_P according to the systematic review of (Zhang et al., 2015).

4. For the missing OE_f, OE_e, and OE_h data from 2005 to 2009, the building energy consumption research report 2021 can be referred to (CABEE, 2021). it informed that the centralized heating use increased by about 3% rate annually, and 8% for electricity consumption. Thus, the increase rate can be used for the missing data estimation.

5. In the calculation process of ME_t, PVO data was from the National Bureau of Statistics (2005-2019); VMT data referred to the "Anti-log-transform" developed by Ou et al. (2020), which was used to assess the annual average mileage of private vehicles. Finally, it was determined as 12377 kilometers.

4 Findings and Discussion

Based on the proposed life cycle system and the Hybrid-LCA method above, the cumulative life cycle energy consumption of urban residential buildings in China from 2005 to 2019 was obtained. As shown under Figure 6. It was clearly seen that there was a moderate increase in the past 15 years, except for a significant jump from 2010 to 2012. Besides, compared with 390.10 Mtce in 2005, the amount of energy consumption increased nearly tripe times by 2019. It certainly indicated that the construction industry in China flourished these days. However, along with the multi-pressures of citizens and society like poor working conditions, living cost increase, birth rate reduction, and environmental protection demand, it is difficult to expect such a growth trend can sustain for a long time. In this case, better estimating has to refer to the latest policies and technologies. On the other hand, Figure 7 indicates the energy intensity change of three main energy sources: embodied, operational, and mobile energies. there was an obvious growth trend in operational and mobile energies, but the embodied energy consumption fluctuated at 450 Mtce after 2012. It showed that as the living standard improved, the daily energy services and trip demands increase significantly. But advanced energy conservation technologies curbed the growth of embodied energy. Also, the decrease in embodied and operational energy intensities benefited from the promotion of green buildings to a large extent. Despite all this, the newly built floor area should also be further reduced to meet environmental requirements. Besides, the constant increase of mobile energy intensity probably contributed to the shortage of car charging equipment, so citizens preferred to fuel automobiles.

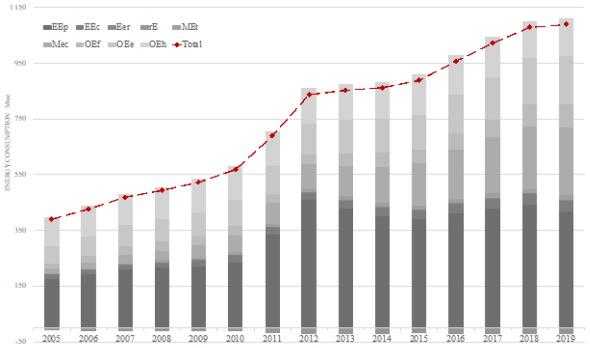

Figure 6. Life cycle energy consumption of urban residential buildings from 2005 to 2019

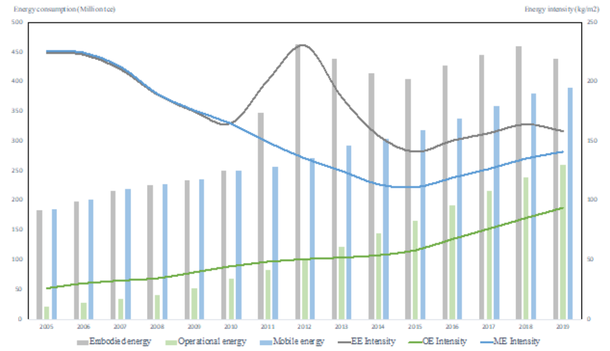

Figure 7. Energy consumption and intensity in the different categories of urban residential buildings in China

In the comparison of sub-energies consumption proportion (Figure 8), it can be found that EE_P, ME_c, and OE_e were the top 3 energy consumption contributors, and the EE_P even reached up to about 460 Mtce. Also, their changes during the range of years selected were significant such as 183-463 for EE_P and 17-244 for ME_c. It was attributed to the building materials manufacturing roughly and chaotic construction management on-site, so it has to further improve processing technologies and measures. Meanwhile, enhancing the convenience of vehicles' charge, daily environmental awareness like switching off the lights when you leave, as well as utilizing solar devices can effectively reduce the amount of other energy categories. In the next studies, it is inevitable to further discuss the feasibility of these solutions above. Besides, mobile energy has to be paid more attention to as it increased so fast from accounting for 5% of total energy consumption in 2005 to 24% of that in 2019. Of this, daily commuting and regular trips have become increasingly popular (4% to 23%) with higher living quality demand. Fortunately, the proportion of operational energy consumption decreased by 36%, which benefited from the sustainable development policies and the practice currently. Under the huge demand for residential buildings in China, how to reduce embodied energy consumption is still challenging.

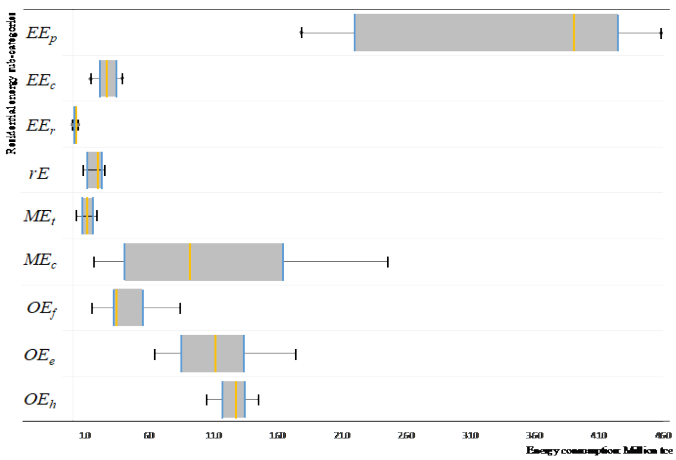

Figure 8. Comparing the energy consumption change among 9 sub-energy categories.

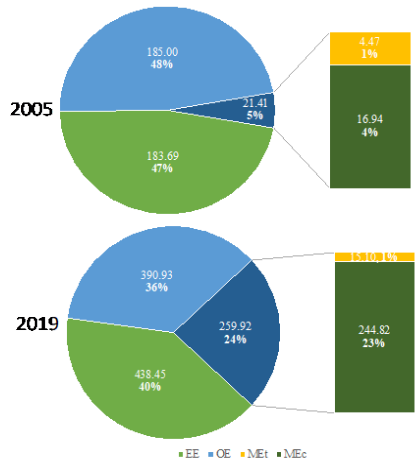

Figure 9. Energy consumption proportion of three energy sources.

To verify the accuracy of energy consumption estimation, it is useful to compare it with others' results. But given the availability of reference data, the base year of 2012 was selected, as shown under Table 1. Compared with other estimated results, the life cycle energy consumption of urban residential buildings calculated in the study was far higher than that of others (6.6%-19.6%). It is mainly because of the addition of mobile energy. Surprisingly, the estimated result from Zhang et al. (2015), based on a life cycle approach, was approximately 20% lower than that of this study. After a text-mining analysis, it was found no considering the positive impact of transporting building materials on building energy consumption. Besides, the average energy intensity was found around 240 kg/m2. It will be a useful reference for next studies about building energy conservation.

Table 1. Life cycle energy consumption comparison between the estimated results and other references for urban residential buildings in China (Mtce).

<table>
<tr><th></th><th>EI (kg/m^2)</th><th>LCE-B</th><th>EE_p</th><th>EE_c</th><th>EE_r</th><th>rE</th><th>OE_f</th><th>OE_e</th><th>OE_h</th><th>ME_t</th><th>ME_c</th></tr>
<tr><td>Results</td><td>248.40</td><td>837.15</td><td>458.23</td><td>25.91</td><td>2.35</td><td>23.46</td><td>33.77</td><td>111.49</td><td>127.06</td><td>10.95</td><td>90.84</td></tr>
<tr><td>CABEE (2022)</td><td>260.33</td><td>784.214</td><td>469.162</td><td colspan="2">25.903</td><td>/</td><td colspan="3">289.149</td><td>/</td><td>/</td></tr>
<tr><td>Zhang et al. (2015)</td><td>198.64</td><td>673.04</td><td>323.4</td><td>61.67</td><td>/</td><td>15.17</td><td colspan="2">200.14</td><td>103.00</td><td>/</td><td>/</td></tr>
<tr><td>Zhang and Wang (2016)</td><td>239.75</td><td>740.46</td><td colspan="2">449.82</td><td>4.2</td><td></td><td colspan="3">286.44</td><td>/</td><td>/</td></tr>
<tr><td>Shan et al. (2020)</td><td>226.25</td><td>731.60</td><td colspan="3">425.00</td><td>/</td><td colspan="2">160.60</td><td>146.00</td><td>/</td><td>/</td></tr>
</table>

Note: $EI = EE/S_c + (OE + ME)/S_s$ where S_c represents the completed building floor area of urban residential buildings in 2012, equaling to 2,007,492,000m2; S_s is the total building floor area in 2012, equaling to 21,077,299,100m2.

5 Conclusions

With the improvement of environmental protection awareness worldwide, buildings energy conservation has become one of the most urgent social issues to be solved. accurate energy consumption estimation is an effective pathway to help governments formulate policies and practitioners adjust energy services. In this study, an extended life cycle energy system was proposed for the assessment of urban residential building energy consumption in China (national level) during the period from 2005 to 2019. The system was divided into three energy consumption sources: embodied, operational, and mobile energies. Based on a hybrid-LCA estimation approach and domestic statistical data, both direct primary energy consumption and supply-chain inputs were considered. The results indicated that the life cycle energy consumption increased significantly from 390.10 to 1089.29 Mtce with an average growth rate of 7.8%. Although the embodied and operational energy intensities decreased because of the application of energy-saving measures, the mobile energy intensity grew up moderately. Unfortunately, mobile energy has played a critical role in energy consumption, the proportion increasing from 5% to 23%. Also, it can be found that the sub-energy categories of EE_P, ME_c, and OE_e were the top 3 of energy consumption sources, and their change during the range of years selected were significant. Besides, after a comprehensive comparison of the estimated results from different studies, it was concluded that the life cycle energy consumption estimated in this study was higher by 6.6%-19.6% than that of the other 4 similar studies. Significantly, it proved the importance of mobile energy on building energy consumption.

The life cycle energy system presented here is contribute to the macro-analysis of building energy consumption worldwide. The results could show their characteristics and main sources in China's construction industry, which is valuable for policy-making and service adjusting of reduction strategies. Moreover, some limitations should be paid attention to: parts of conversion coefficients and data were from other studies, so their authority cannot be verified. It should be improved along with the enrichment of data sources. Besides, it is more valuable to study the details at the provincial level then.

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Behavioral Attitudes of Construction Professionals towards the Industry's Waste Minimization Culture: A Factor Analysis of Key Influential Factors

Benjamin Kwaku Ababio[1*], Weisheng Lu[1] and Prince Antwi-Afari[2]

[1]Department of Real Estate & Construction, The University of Hong Kong, Pokfulam, HONG KONG
[2]Department of Civil Engineering, The University of Hong Kong, Pokfulam, HONG KONG

bababio@connect.hku.hk; wilsonlu@hku.hk; pantwiaf@connect.hku.hk
* Corresponding author

Abstract:
Addressing the global challenge of construction waste generation has the potential to improve the sustainability and efficiency of the industry. Yet, construction waste minimization (CWM) is poorly practiced across projects in Sub-Saharan Africa, and can be generally linked with awareness, attitude, and behaviour of construction professionals. This study therefore places emphasis on the social aspect of CWM, and aims at examining the behavioural attitudes of professionals towards the industry's waste minimization culture. To achieve the aim of this study, relationships between key influential factors of waste-reduction behaviour of construction professionals are critically evaluated, with focus on Ghana, a developing country in the sub region. Using questionnaire survey based on existing literature and the theory of planned behaviour, factors that influence waste minimization behaviour was obtained from 112 construction professionals and analysed using exploratory factor analysis. The study reveals that intentions and attitudes are strong predictors of pro CWM behaviour, and professionals generally demonstrate a good sense of awareness towards waste minimization culture. However, external factors can create an enabling or disenabling environment for the right waste minimization behaviour. Four main clusters of influential factors are found to be essential to the development of waste minimization culture; industry related factors, team relationships, project specific and cultural factors, and motivational factors. The findings of this research should guide industry stakeholders, especially organization decision makers, to focus on key areas that need to be developed to realize social change and informs construction professionals about the different factors that affect CWM behaviour.

Keywords:
Behavioural attitude, Construction waste minimization (CWM), Factor Analysis, Ghana, Professionals

1 Introduction

The construction industry has been pivotal to the growth of many economies over the past decades, especially in developing countries (Deloitte, 2020). Despite providing infrastructural needs, contributing to national GDP and global economies (with expected growth of about USD 8 trillion by 2030), and providing employment for close to 9% of the world's working population, the construction industry (CI), a significant contributor to many other sectors, has also been a miscreant, leaving negative consequences as a result of its actions (Lu and Ye 2022). The sector has been culprit for land depletion, unsustainable energy and natural resource consumption, emission of gases, and uncontrolled generation of waste (Yang *et al*., 2020). Compared to others, the CI does not only consume massive amounts of natural resources, it generates fairly higher amounts of waste which tends to create not only environmental issues but results in dire societal and economic consequences (Lu and Yuan, 2011).

In the big cities of developing countries, the waste generated by construction, renovation and demolition activities is almost 2.3 times greater than that of municipal solid waste with nearly one third of such waste illegally placed outside of landfill, polluting the environment, obstructing rivers, and promoting floods during the raining seasons (Lee *et al*., 2021). Agyekum (2013) reports of a wide variation in wastage rates of up to 30% of total materials purchased for construction projects in Ghana. The Sub-Saharan Africa region, particularly Ghana, has not been able to decouple economic growth from its use of natural resources hence, as the CI grows, a rapid increase in resource depletion is expected, making waste generation a more crucial subject which has sparked an increased public concern over its implications.

Attempts have been made by government institutions to raise awareness and sensitize industry actors to adopt essential waste minimization strategies such as reducing at source; reusing materials and leftovers from other sites, among others. However, due in part to the socio-cultural and behavioural variations among professionals, the implementation of these strategies has not been as successful as anticipated (Agyekum *et al*., 2013). Susceptibility of industry players to embrace new changes is always an important factor in the implementation of new methods or ways of doing things. Hence, to effectively achieve minimization of construction waste, it is essential to consider attitudinal and behavioural elements regarding waste minimization on construction projects.

Many existing studies have focused on various aspects of construction waste minimization and management strategies. While some studies like Xu *et al*. (2020) develop technical solutions to the problem, others such as Bao *et al* (2021) propose that the resolution lies in policies and legislative instruments. Notwithstanding the relevance of both themes of research related to construction waste management, little attention has been given to other themes such as behavioural components for the adoption of waste minimization strategies. The limited studies that touch on behavioural elements mostly investigate factors that affect construction workers waste minimization behaviour from a static perspective and often focus primarily on onsite waste minimization (Yates, 2013). Secondly, empirical studies on the subject based on classic behavioural theories often exclude the significance and interdependencies among behavioural factors (Wang and Yuan, 2011). In light of this contextual backdrop, this study aims to address the gap by examining the interdependencies of waste minimization behavioural factors among construction professionals using Ghana as a case study. To achieve the aim of the study, two key objectives are established and are presented in the research questions below;

1. What perceptions do construction professionals have on waste minimization?
2. What factors influence professionals' behavioural attitudes towards waste minimization on construction projects?

Through the use of questionnaire survey targeted at construction professionals, an attempt is made to answer these crucial questions. The results obtained are analysed using statistical methods including Factor analysis, one sample T-test. The outcome of the analysis would provide meaningful insight on behavioural traits of construction professionals and help establish key relationships between influential factors that impact waste-reduction behaviours. Such accumulated knowledge will serve as a starting point for developing practical measures to influence the right attitude towards construction waste minimization. This paper aims to contribute to construction practice by eliciting wider discussion among construction stakeholders and to instigate policymakers to invest in positive interventions in a developing CI. Consequently, this paper contributes to the ongoing academic discussion about waste management practices and in a wider perspective, how it can help reduce depletion on natural non-renewable resources.

2 Theoretical Background

Grounded in the Theory of Planned Behaviour (TPB), this study perceives behaviour as a combination of various factors that feed into the intention to act (Li *et al.*, 2018; Theo and Loosemore, 2001). TBP as proposed by Ajzen in the late 90's has since been applied to investigate a wide range of industry-related behaviours, including technology use, supply chain activities, and productivity (Judge *et al.*, 2019). The core premise of this theory is that an individual's systematic decision or action is influenced by their subjective norms, perceived control, individual attitudes and external influence to have consistent. Ramayah *et al*. (2012) extended TPB to predict recycling behaviour by incorporating environmental awareness and knowledge. According to Begum *et al*. (2009), factors such as the organization's size, the education and training background of workers and the waste management practices applied, influence the attitude and behaviour of an individual towards waste management. These organizational factors are often fundamental, and management determines what they are for its employees. Top management, for example, will determine specific waste management plans adopted on a construction project for project workers. However, Murray (2013) emphasizes that when it comes social contexts, both internal variables such as personal beliefs and values, as well as external factors such as organizational standards, laws, and peer pressure, may influence individual's behaviour intention differently. Usually, an individual's perception or belief contributes highly to his intentions, and according to TPB, the greater the intention, the higher the likelihood of a specific behaviour. Hence, it is also important to consider factors that will affect one's intention for a successful change in behaviour. In any case, it is asserted that in order to increase the level of positivity in waste perceptions among professionals, the undesirable behaviour that has been in practice for a long time must be effectively altered. As suggested by Kim & Nguyen (2020), an interdisciplinary approach between all stakeholders is essential for successful waste minimization practices. Numerous literature reviews have identified the factors both positive and negative that affect the attitude towards waste minimization strategies in construction – such factors provide potential variables for this study. Lui *et al*. (2019) argue that a deeper understanding of these factors from the perspective of different countries is critical, as each country has its own set of laws and criteria. Such findings underpin and support the purpose of our study.

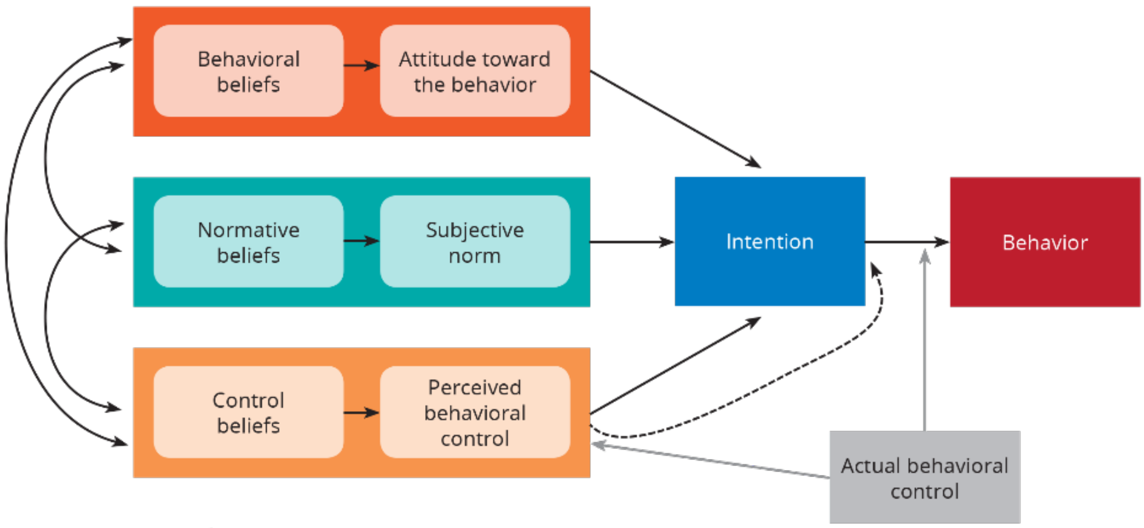

Figure 1. Factors that influence a planned behavioural pattern; adopted from Theo and Loosemore (2001)

3 Research Methodology

This study employs a positivist paradigm philosophy, which is understood in context of a deductive framework, to test factors that influence waste minimization behaviour. The choice of empirical approach is well-supported in current construction and building management literature which provided insights and variables for a questionnaire survey (c.f. Edwards *et al*. 2020). Data collected from the survey was then analysed using Principal Component Analysis to draw inferences and provide discussion on emerging theme groupings of components, as well as further discussion of these. A three-step "iterative model" approach was used to construct the data gathering instrument and rigorously assess its validity.

- Step 1: Identification of waste minimization influential factors from literature - Following a bibliometric filtering process, a list of potential factors was gathered from 44 articles for the study (See Table 2).

- Step 2: Data collection, clarity and validation - A structured questionnaire survey was conducted to elucidate knowledge on two main aspects; perception on waste minimization issues (which used as a benchmark for their behaviour towards waste minimization) and factors that affect waste minimization behaviour. Respondents were asked to rank their level of agreement to 9 perception themes and the level of significance of 15 influential factors of waste minimization behaviour. This was done to clarify and confirm the list of factors that influence the behaviour of professionals towards waste minimization mined from previous literature.

- Step 3: Data analysis and reliability test - Cronbach alpha was applied to test for the reliability of the survey results. The alpha value obtained was 0.875, greater than the minimum of 0.7 recommended for further analysis (Norušis, 2011). Upon satisfaction of data reliability, frequency distribution was adopted to determine perception on construction waste minimization issues based on level of agreement with 9 theme statements. Additionally, mean scores were used to determine the central trend of influential factors that impact waste minimization behaviour. The significance of factors was analysed using a one sample T-test. The study further adopts exploratory factor analysis to uncover the variables which measure similar or same fundamental aspect from a set of 15 potential barriers (Twum-Ampofo *et al*., 2019).

In the event samples are used, the study population must be defined; the method of selecting the sample and the response rate should be stated as should any attempt to establish if the sample or response is biased. All statistical or other quantitative analyses must be checked carefully for applicability and accuracy before submission.

Some papers present very early stages of the research. This should not prevent the author to discuss potential research methodology that can be adapted based on the nature of the research problems/questions identified or type of data expected at this stage. Research is iterative in nature and researchers continuously modify their research methodology in light of new information and changes in circumstances.

3.1 Sampling for the main survey

The targeted group of professionals were project managers, consultants, site engineers and individuals who have been involved in the management or supervision of construction projects in three of Ghana's largest cities; Accra, Kumasi and Takoradi. The selection of the geographical scope was based on the assumption that these cities accounted for the greatest number of construction projects within the country. Moreover, most construction consultancies and contractor firms had strategically located their headquarters in at least one of these cities. Based on the assumption that medium-sized firms typically have relatively good organizational set up and also represent the largest group of construction firms that undertake projects across the country, professionals belonging to D2 contractor firms were earmarked to undertake in the survey on their attitude towards waste minimization on those projects. Per this benchmark, a population size of 380 companies were identified as being fully registered with the MWRWH as D2 contractors within the three metropolises. To reduce the population to a manageable sample, Yamane's sample size formula was employed (Islam, 2018): $n = \frac{N}{1+N(e)^2}$; $n = \frac{380}{1+380(0.10)^2} = 79$, where n is the sample size, N is the population size and e is the desired level of accuracy (±10%) at 90% confidence interval.

Consequently, a sample size of 79 D2 construction firms were selected at random in accordance with a study by Hoe (2006). In addition, database of the Institute of Architects and the Institute of Surveyors in Ghana also revealed a total number of 154 fully registered estimating and architecture firms (in good standing) in all 3 cities. From the list of consultants derived, telephone calls were made, from which 33 companies made up of 19 architectural firms and 14 quantity surveying companies were willing to take part in the study. These firms were therefore purposively and conveniently sampled for the study. The sampling method is justified by Ghansah *et al*. (2021) as being relevant in considering unique traits, knowledge, and expertise of specific respondents. For each consultancy and construction firm, at least one professional was set to take part in the survey and report on behalf of the organization. A total of 112 questionnaires were administered to the professionals in the organization comprising 33 consultants and 79 from construction. The demography of respondents constitutes Project Managers (30%), Construction Managers (20%), Cost Estimators (14%), Architects (10%) and Site Engineers (16%). Upon retrieval of questionnaires, the study attained a response rate of 67.86 %, which is considered sufficient for statistical analysis (Mellahi and Harris, 2015).

4 Findings and Discussion

4.1 Professionals' perception on construction waste minimization issues

Awareness and perceptions of professionals on the various waste related issues are used as a foundational basis to understand their attitudes towards waste management of construction projects. A total of nine perception themes were adopted to deduce the behavioural traits of professionals in the construction industry. A Likert scale was employed as a tool to allow respondents to express their viewpoints on pre-determined waste minimization issues. Construction professionals ranked their level of agreement with the theme statements on a scale of 1-5; 1= 'Strongly Disagree', 2= 'Disagree', 3= 'Neutral', 4= 'Agree', 5= 'Strongly Agree'. The results depict that the majority of survey respondents have some level of knowledge on waste minimization issues. The statistical means of the survey responses skewed in opposite directions for different perception themes (as presented in Table 1). This suggests that whereas there may be signs of positive behaviour towards certain aspects of waste minimization, there is significant number of respondents who answered with contradictive perceptions which indicates a lack of full awareness which could negatively affect their attitude. For instance, some respondents agreed with the statement "waste has no value", and also believe that waste management is beyond the control of project team. These perceptions do not promote the right behavioural attitude towards waste generated and hinders the utilization of the 3-R approaches in dealing with construction waste.

Table 1. Mean frequency distribution of professionals' perceptions on construction waste minimization

Code	Perception Themes	Mean	Sign	Std. Deviation
PT1	Waste is an inevitable by-product	2.43	+	1.387
PT2	Waste has no value	4.32	-	0.989
PT3	Implementing waste plans in construction projects are cost ineffective	2.88	+	1.315
PT4	Waste management is leads to profit maximization	3.79	+	1.298
PT5	Adoption of environmentally friendly measures depends on their profitability	2.75	+	1.326
PT6	Waste management is beyond the control of project members	4.35	-	0.726
PT7	Time spent on waste management is a loss of production time	2.12	+	1.174
PT8	Contractors are responsible for minimization	2.03	+	1.404
PT 9	Recycled or reused materials are less quality	2.99	+	0.893

4.2 Influencing factors of waste minimization behaviour

For the factors that influence professional’s behaviour towards waste minimization, the respondents were asked to score the level of significance of each identified variable on a 1 -5 Likert, where 1= ‘Not Significant’, 2= ‘Slightly Significant’, 3= ‘Fairly Significant’, 4= ‘Significant’, 5= ‘Very Significant’. Mean score statistics and one T- sample test was employed to analyse the significance of the identified factors that affect construction waste minimization behaviour. One sample T-tests was deemed sufficient at a significance level of 5% to compare the sample mean to a hypothesized value of 4 (considered significant on the Likert scale). Table 2 shows that "awareness of waste minimization strategies" and “coordination along value chain” are the main influencing factors having the highest mean of 4.03 and 4.01 respectively, which is greater than the hypothetical mean value (4 = Significant). Using a sample T-test, all the identified factors were further tested at confidence level of 95 ($P < 0.05$). The test revealed that all fifteen variables were statistically significant.

Table 2. One Sample T-test of factors that influence waste minimization behaviour

	One sample T-test, Text value =4, 95%confidencial interval of the difference				
Influencing factor	**Mean**	***t***	***df***	**Sig. (two tailed) *P*-value**	**Remarks**
Supply chain management for construction processes	3.60	-3.519	226	0.001	Significant
Stakeholder relationships	3.23	-3.470	226	0.000	Significant
Competition	3.31	-3.934	226	0.009	Significant
Social value and recognition	3.72	-2.423	226	0.012	Significant
Prioritization of waste issues	3.60	-3.402	226	0.358	Significant
Incentivization and financial value	3.51	-2.511	226	0.451	Significant
Commitment and role allocation	3.53	-4.334	226	0.112	Significant
Knowledge sharing and education	3.76	-2.811	226	0.000	Significant
Awareness of waste minimization strategies	4.03	2.357	226	0.357	Significant
Coordination along value chain	4.01	1.099	226	0.039	Significant
Market availability	3.76	-3.599	226	0.132	Significant
Innovation and technological advancement	3.72	-4.221	226	0.128	Significant
Legislation for construction waste management	3.83	-3.567	226	0.141	Significant
Construction material properties	3.36	-1.572	226	0.010	Significant
Space and convenience	2.90	-2.058	226	0.001	Significant

4.3 Factor analysis

Owing to the number of different influencing factors identified, factor analysis, a components reduction technique, was adopted to streamline related variables as well as to identify the variables that measure the same or similar fundamental aspect (Ahadzie, 2007). This method is useful for identifying clusters of related variables, making it ideal for condensing multiple variables into fewer dimensions that are easily understood. Exploratory factor analysis requires strong relationship among groups of variables to enable the reduction of a dataset's dimensionality while increasing interpretability at the same time. Hence, adopting such a technique requires a large number of variables, typically between 15 and 50 (Twum-Ampofo et al., 2019). Fifteen (15) factors that influence waste minimization behaviour are employed as the main variables of the study. Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy was the statistical measure used to determine whether the collected data were 'factorable'. Bartlett's test of sphericity, which considers Chi-Square approximation values, was also undertaken to establish the potential correlations which suggests that clusters exist in the variables. According to Ababio (2019), a factor analysis is considered acceptable if the Chi - Square approximation from the Bartlett's test of sphericity is significant ($p < 0.05$) and KMO is above 0.5 with an upper limit of 1. Results confirmed that KMO sampling accuracy of the study of 0.805 and chi square approximation of $\times 2 = 1720.638$ ($p < 0.05$), implying the data can be analysed using PCA.

Communalities were then determined for the variables. Communalities are explained as the amount of a measured variable's variance that is helpful in identifying the latent variables in the model (Field, 2000). Communality extractions greater than 0.5 suggest that the extracted factors account for a large portion of the variable variance. For this study, all fifteen identified variables had an extraction value > 0.50, implying the results were adequate for the next step. After passing the compliance tests, the data was subjected to extraction using principal component analysis. To determine the number of factors to be extracted, the Guttmann-Kaiser rule which states that only factors with an eigen value of >1 should be retained, and the Cattel scree test which considers components above this baseline only, were utilized. Per this baseline, only the first four components qualified to be retained (See Figure 2). All extracted variables were then explained within one of the four components. The total variance explained by each extracted component is as follows: The first principal component (Component 1) accounted for 21.374% of the total variance, while Component 2 accounted for 20.931%. Component three contributed 17.240%, while component four contributed 8.952%. Overall, the total components extracted explain 68.498% of the variation in the data set and meet the cumulative proportion criterion of variance, which states that the extracted components should closely illustrate greater than or equal to 50% of the variation.

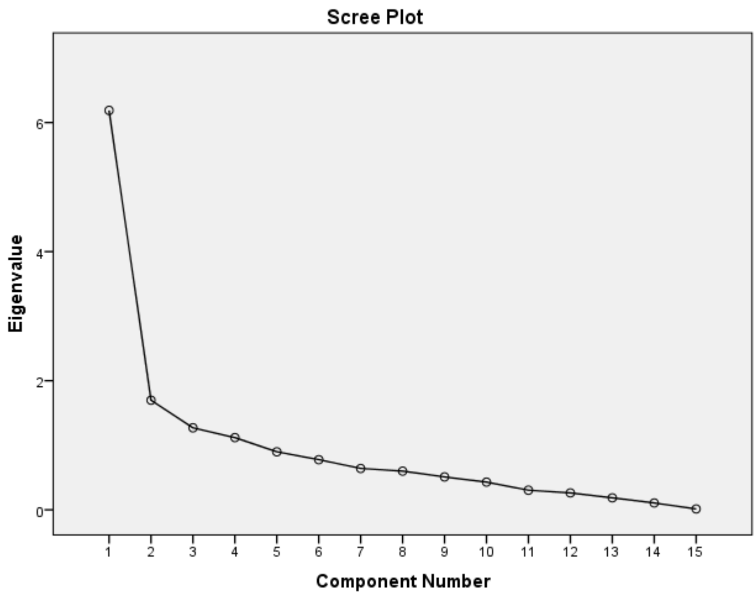

Figure 2. Scree plot of component extraction

Varimax method of orthogonal rotation was adopted to optimize the extracted values and improve the clarity of the results for factor analysis, as suggested by Cardoso and Cruz Almeida (2016). The result of this optimization process is presented in Table 3. Based on an examination of the inherent relationships among the variables within each component, the following interpretation has been provided: component 1 is termed as vision and direction factors; component 2 is recognized as inter-organizational relationship factors; component 3, human factors; and component 4, motivational factors. Finally, the reliability of the four optimized components is tested using Cronbach's alpha coefficient. According to (Norušis, 2011), the alpha threshold for a component to be considered as reliable is a minimum of 0.7. The coefficient for each component was greater than 0.7, i.e. Component 1 (0.807), Component 2 (0.817), Component 3 (0.757), and Component 4 (0.719). The 4 main components extracted from the factor analysis are explained below.

Table 3. Rotated component matrix

Variables	**Components**			
	Component 1	Component 2	Component 3	Component 4
BAF 3	0.616			
BAF 9	0.555			
BAF 12	0.754			
BAF 13	0.722			
BAF 14	0.717			
BAF 1		0.800		
BAF 2		0.717		
BAF 7		0.573		
BAF 10		0.656		
BAF 11		0.606		
BAF 5			0.683	
BAF 8			0.851	
BAF 15			0.593	
BAF 6				0.893
BAF 4				0.861

Extraction Method: Principal Component Analysis; Rotation Method: Varimax with Kaiser Normalization; a. Rotation converged in 6 Iterations

4.3.1. Vision and Direction factors

This component accounts for the greatest of the total variance; 21.374% and is made up of factors; “Awareness of waste minimization strategies”, “Competition”, “Innovation and technological advancement”, “Legislation for construction waste management”, and “Construction material properties”. These factors set the path by providing the necessary framework and guidance for the inculcation of the right behaviour towards construction waste minimization. The result showed that “Innovation and technological advancement” had the highest eigen loading factor and is critical to the waste minimization behaviour within this component. As posited by Tian *et al*. (2012), innovation drives change within the construction sector and such change progressively alter human elements such as behaviour. Turkyilmaz *et al*. (2019) also suggest that competitive environments dictate actions of its key players, hence the behaviour traits of construction professionals can be changed by the demand and competition by organizations with regards to construction waste management practice. A vision for effective waste minimization behaviour will better be promoted if backed by legislation and sufficient guidelines (Blaisi, 2019).

4.3.2. Inter-organizational relationship factors

The underlying component comprises 5 essential factors and explains 20.931% of the total variance. These barriers elucidate relationships and network of construction value chains and how they ultimately affect waste minimization behaviour. “Supply chain management for construction processes” had the highest loading factor within this component, and explains the systems that are in place between key processes, delivery schedules, material information among others. It is essential that “Stakeholder relationships” are taken into consideration as poor relationships could instigate the development of negative behaviour patterns (Osmani, 2008). “Commitment and role allocation” and “Coordination along the value chain” ensure that waste minimization responsibility is individualized and guided by organizational function by way of collaboration and coordination ensuring the right commitment from both professionals and business organizations (Lui *et al*., 2019).

4.3.3. Human factors

17.240% of the total variance is explained by this component. Being the 3rd largest component, it comprises three key factors namely; “Prioritization of waste issues”, “Knowledge sharing and education”, and “Space and convenience”. Human factors have significant influence on waste minimization behaviour or workers. For instance, unfamiliarity with appropriate methods could influence bad judgement. Therefore, knowledge sharing and progressive education among professionals is essential to breed the positive waste minimization behaviour. Such factors could drive a reorientation and change behavioural patterns which would see construction professionals prioritizing waste management issues. The findings are consistent with Li *et al*. (2015) report on designers’, a category of professionals, behaviour towards waste minimization. It is also posited that waste minimization strategies are adopted faster if they provide convenience. Hence to effectively alter professional behaviour, the element of rendering other unsustainable practices inconvenient is necessary (Lee *et al*., 2021).

4.3.4. Motivational factors

Component 4 comprises “Incentivization and financial value”, and “Social recognition” and explains 8.952% of the total variance. Financial incentives had a loading factor of 0.893 highlighting its relevance in contributing to waste minimization behaviour of professionals. Several barriers inhibit the demonstration of appropriate construction waste management behaviour and a very relevant to the subject is the cost of implementing waste management plans (Abarca-Guerrero *et al*., 2017). Hence, creating financial value by incentivizing professionals to prioritize waste issues is a motivating strategy that proves essential (Hasmori *et al*., 2020). Another important factor to influence waste minimization behaviour is social value and recognition. Typically, professionals would like to be linked with responsible environmental management (Campbell, 2007). This quest of reputation and potential recognition drives the demonstration of appropriate behaviour towards construction waste.

5 Conclusion and Further Research

Behavioural change is a key solution towards the minimization of material waste generated in the construction industry (Ertz *et al*, 2021). This study examined construction waste minimization culture in a developing country, Ghana from the perspective of professionals including project managers and construction consultants. The study delves into the perceptions of professionals on key waste minimization issues and provides information on factors that influence their waste minimization behaviour. The results depict that “awareness of waste minimization strategies”, “innovation and technological advancement”, “coordination along value chain”, and “legislation for construction waste management” are the major influencing factors for the inculcation of the right waste minimization behaviour. The use of exploratory factor analysis discovered that some factors identified shared similar fundamental aspect, hence principal component analysis (PCA) extracted four components that influence construction waste minimization behaviour. They are, vision and direction, inter-organizational relationships, human factors, and motivation factors.

For practice, insights from this study provides policy makers, value chain actors, construction advisors and practitioners in the construction industry, key factors that have to be focused on to inculcate and germinate the right waste behaviour on construction projects, which would translate to a wider industrial reorientation. The study recommends multiple stakeholder collaboration and knowledge sharing on waste minimization issues, organizational commitment uptake of waste minimization responsibility, and government intervention by way of policy and legislation as these will have the most immediate effect on waste minimization behaviour of construction professionals especially in developing countries like Ghana.

The limitation of the study lies in the boundaries and method adopted for the research. Albeit seeking responses from experts through survey of a sampled target group, a broader population would have given much clarity for the purposes of generalization. Further research into other emerging economies in Sub-Saharan Africa is needed in order to enable extrapolation, as this study solely used Ghana as a case for developing countries. Additionally, qualitative methods such as interviews could have given more context to some of the influencing factors. The complexities of factors that affect waste minimization is critical to construction management research, hence, future studies can focus on explaining the correlations and causal relationships between factors to enable the global industry strategize appropriately.

6 Acknowledgement

The paper constitutes part of a research project undertaken at the University of Hong Kong, Department of Real Estate and Construction with funding from the Hong Kong PhD Fellowship Scheme (PF20-45263), and the Kwame Nkrumah University of Science and Technology. The authors would like to thank the Foreign Commonwealth and Development Office, Ghana for financially supporting this project.

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Enhancing the Decision-Making Process of Life Cycle Assessment Towards Circular Economy Measurement in the Construction Industry

Prince Antwi-Afari[1*], Thomas S.T. Ng[2], Ji Chen[1], Benjamin I. Oluleye[3], Maxwell F. Antwi-Afari[4] and Benjamin K. Ababio[5]

[1]Department of Civil Engineering, The University of Hong Kong, Pokfulam, Hong Kong
[2]Department of Architecture and Civil Engineering, City University of Hong Kong, 83 Tat Chee Avenue, Kowloon Tong, Hong Kong
[3]Department of Building and Real Estate, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong
[4]Department of Civil Engineering, College of Engineering and Physical Sciences, Aston University, B4 7ET, Birmingham, UK
[5]Department of Real Estate and Construction, The University of Hong Kong, Pokfulam, Hong Kong

pantwiaf@connect.hku.hk; thomasng@cityu.edu.hk; jichen@hku.hk; benjamin.oluleye@connect.polyu.hk; m.antwiafari@aston.ac.uk; bababio@connect.hku.hk
*Corresponding author

Abstract:
Life cycle assessment (LCA) has become one of the key methods used to assess the environmental impact of materials. The adoption of LCA to also assess circularity of construction materials has been proposed and ongoing in extant studies. However, LCA results for circular economy (CE) analysis are fraught with several challenges such as not accounting for reuse possibilities, lack of pragmatic applicability at design and development stages, challenges with system boundaries and inability to assess social implications of product system. In this study, the system boundary of LCA is extended to cradle-to-cradle to include the impacts of the end-of-life reuse pathways in assessments while adopting the predictive building systemic circularity indicator to also measure the recoverability potential of modular steel slabs. The adoption of this integrative iterative approach should enhance the determination of impacts and recovery potentials of materials across several dimensions. It was identified that the circularity and impact potentials of the product system is influenced by the recyclability plan, recycled content, average product utility and normalisation factor of the case slab. To ensure practical realisation of CE, there is therefore the need to plan the end-of-life reuse pathways and determine the impacts of various decisions across product systems from the beginning-of-life.

Keywords:
Circular Economy, Construction Industry, Cradle-to-Cradle, Life Cycle Assessment, Modular buildings

1 Introduction

The construction industry (CI) is well-known for its effects on the environment such as high energy consumption, enormous waste production, excessive greenhouse gas emissions and natural resource depletion (Oluleye *et al*., 2022). However, the advent of the circular economy (CE) concept could decouple the production system of industries including the CI to reduce its effects on the environment through a restorative and regenerative design process (Ellen MacArthur, 2015). Adopting total/systemic circularity in the CI should also enhance the reduction of natural resource consumption through efficient nutrient cycling systems, closed-loop supply chains, and digitalised end-of-life (EoL) waste management schemes (Antwi-Afari *et al*., 2021). However, to appreciate the implementation of CE principles within the CI requires effective methodological approaches which should be able to assess the environmental, economic, social, and technical implication of decisions across materials / product system.

Life cycle assessment (LCA) is a key scientific methodological tool used to evaluate the environmental impacts of materials. However, its effectiveness in assessing the circularity of materials is fraught with several challenges such as lack of pragmatic application at the design and development stage, challenges with system boundaries and allocation of impacts, inability to assess social implication of materials, and biases and inconsistency in results (Hossain *et al*., 2020). Antwi-Afari *et al.* (2022a) also reviewed several circularity indicators which could be adopted to assess the various dimensions of CE in assessments. The study purported that the consideration of only one indicator or method to assess the impacts of circularity across multiple dimensions was not feasible, but rather a combination of different indicators or methods could suffice the assessment of some key dimensions of CE.

Existing methodological approaches of extant studies have been on combining industrial ecology methods such as LCA, life cycle cost, social-LCA, material flow analysis and input-output analysis to assess the impacts of things across product lifecycles (*c.f.* Meglin *et al.*, 2022). Other studies also combine operation research methods such as analytic hierarchy process, technique for order of preference by similarity to ideal solution and game theory with industrial ecology methods or complex science methods such as system dynamics, agent based modelling and discrete event simulation to understand the impacts of decisions across the environment, economic, and social dimensions of circularity assessments (*c.f.,* Kamali *et al*., 2019; McAvoy *et al.*, 2021).

However, irrespective of the improvement in assessments, the existence of indicators or methods for evaluating the technical dimensions of CE such as design and disassembly parameters, reverse cycles, system conditions and business models remain unexplored in the CI. Existing indicators for technical dimension such as material circularity indicators (MCI), circular economy toolkit and circular economy indicator prototype is insufficient for long term infrastructures such as buildings. Therefore, Verbene (2016) enhanced the MCI to develop the building circularity indicators (BCI). Cottafava and Ritzen (2021) also improved the BCI to develop a predictive BCI by using the design criteria for circularity assessments. Nonetheless, Antwi-Afari *et al.* (2022b) further enhanced the BCI equations by using the four building blocks of CE *viz.* circular product design, reverse cycles, system conditions and business models to assess the recovery potentials of buildings.

In this study, LCA system boundary is extended to C2C and combined with the predictive building systemic circularity indicator (PBSCI) which adopts the four building blocks for assessing the recovery potentials of buildings, to assess the impacts and recovery potentials of modular steel slabs. The extension of LCA to C2C enable the assessment of the potential impacts of reusing/recycling the materials into the next production system after EoL. Also, the consideration of the PBSCI method enables assessment of some key dimensions such as the technical, social, and inferred economic decisions of the product system. Hence, the combination of these two methods provides a better way of assessing some key dimensions of implementing CE across product lifecycles.

2 Enhancing methods for circularity assessments

Implementing CE principles across product lifecycles present an opportunity to achieve sustainable development. To determine the effects of CE principles on a product system, several indicators, methods and models have been proposed in extant literature. For example, Saidani *et al.* (2019) reviewed 55 circularity indicators which could be applied to assess the circularity of products across system levels. The identified indicators were grouped into criteria which could be adopted to assess specific dimensions of CE. However, the complexity of CE measurement requires a robust method which should measure the impacts of product system across several dimension and not just a single dimension at a time. Iacovidou *et al.* (2017) also reviewed several methods which could be applied to measure the circularity of materials across product lifecycle towards the development of a complex value assessment for resource recovery measurement. The study showed that existing methods are not robust enough to measure the circularity of materials without neglecting negative trade-offs.

For instance, Niero and Kalbar (2019) adopted LCA to assess the relationship between LCA and C2C indicators. The use of LCA was able to show the potential positive impacts of recycling materials but could not account for the effect of different design criteria on impact assessments. Magrini *et al.* (2021) combined LCA, life cycle cost and social-LCA to identify the economic impact of waste prevention schemes to guide the decision for employing waste prevention strategies in communities. The use of the industrial ecology methods was able to provide decisions on project prioritization based on reduction of impacts but could not show the key criteria in designs which should be targeted to enhance waste prevention and reuse in the project. Franklin-Johnson *et al.* (2016) proposed a performance assessment indicator to assess the reusability of materials in the next production system. The adoption of the indicator could provide a value-based approach for decisions on materials usage but could not account for the environmental impacts of materials at EoL. McAvoy *et al.* (2021) also adopted system dynamics and LCA to improve impact assessment of some long-term materials. The use of this approach provides means whereby the dynamism in LCA impact assessments could be catered for, but its usage provides an extension in environmental impact assessment only and not any other dimensions of CE.

Therefore, to enhance the assessment for CE, existing studies such as Cottafava and Ritzen (2021) combined embodied energy and embodied carbon with predictive BCI to determine the impacts and recovery potentials of eight residential buildings in Europe. The adoption of this approach provided means to consider not only the recovery potentials of the case buildings, but also their embodied energy and carbon after demolishing. Peralta *et al.* (2021) also combined the endpoint indicators of LCA and C2C to develop an enhanced assessment model to determine the impact potentials of an eco-design product. The combination of LCA and C2C enables a double-edge assessment whereby the LCA evaluates the rate of reduction of the negative effects on the environment while the C2C measurement assesses the rate of positive impacts of applying circularity principles to the product system. Eberhardt *et al.* (2019) also extended LCA system boundary to C2C and adopted EoL allocation approach to determine the impacts of reusability of buildings at EoL. The study opined that the savings in environmental impact are influenced by the material composition catalogue, the number of use lifecycles and the service lifecycle of the building components. Saade *et al.* (2022) also adopted MCI, LCA and material flow analysis to determine the circularity and environmental impacts of urban projects. It was assayed that circularity indicators could be assessed alongside environmental impact indicators to provide a systemic overview of impact assessments for urban projects.

In this study, LCA system boundary is extended to C2C to capture the potential impacts of reuse/recycling of materials after EoL while also considering the impact indicators of C2C as a method in PBSCI assessment to determine the recovery potentials of modular steel slabs. The adoption of this iterative method should help assess both the environmental, social, and technical dimensions of applying circularity principles to the product system of the modular units. Also, the use of this combined method enhances the identification of the processes in the circular design of the product which influences its circularity and environmental impact potentials and provide guidance to the selection of alternative processes which should augment the circularity and lessen the environmental impacts of the assessed material or product system.

3 Research Methodology

LCA was adopted to assess the potential environmental impacts of the modular steel slabs based on ISO 14040 and ISO 14044 standards. The LCA comprises of four main steps namely, the goal and scope definition, lifecycle inventory analysis, lifecycle impact assessment and the interpretation (ISO 2006a, b). To extend the system boundary to C2C the LCA should also follows the requirement of EN 15978 (2012) which states that allocation and system expansion could be adopted for a C2C system boundary, but they should be reported separately. In this study, the system boundary was extended to C2C to cater for the impacts of reuse/recycling of the materials at EoL while crediting the product system for potential impacts of the EoL activities. Only material-related impacts were assessed and the attributional LCA method which quantifies the potential environment impact to the product system was adopted for this study.

The lifespan of the modular steel slabs was set to 100years according to the specification of the prefabrication company which used a special stainless steel for producing the modular slabs which is like the conventional honeycomb panels used in spacecraft. The functional unit of assessment to enable comparison with other similar studies was set at $1m^2$ gross floor area per year. To reduce burden-shifting, the LCA was conducted using the IMPACT 2002+ LCIA method which combines the midpoint and endpoint impact indicators in assessments (Jolliet *et al.*, 2003). The study also considered all the midpoint impact characterisation in assessment. Hence, based on the required results for assessment and comparison, either impact scores could be obtained and used. The lifecycle inventory of the background system was based on Ecoinvent database embedded in the SimaPro software v. 7 (Ecoinvent, 2013f). The lifecycle inventory of the foreground system was modelled using the primary data obtained from the construction company such as bills of quantities, ad-hoc spreadsheets of design criteria and EoL strategies for the modular slab. Local databases such as China Light and Power and Chinese Lifecycle Database were used as much as possible, but when it was lacking, it was supplemented with other databases from Hong Kong and US lifecycle inventory.

3.1 Case Slab

The case slab area is $2505.204m^2$ for an 11floor modular steel structure located in Changsha, China. The slab is made up of an enhanced stainless steel of similar structure to the conventional honeycomb panels used in spacecraft. The slab is designed to a six-degree seismic fortification and a grade two fire resistance. The slab is manufactured and assembled in the factory for the construction of the modules of the building. Dry connections were used to join the parts of the modules together to enhance their disassembly at EoL. Table 1 lists some key inventory information of the modular building and the modular steel slabs specifically.

Table 1. Characteristics of the case slab

Parameters	Specifications
Structure	Modular Steel
Gross floor area	2505.204m^2
Number of households	33
Number of floors	11
Percentage of prefabrication	100%
Lifespan	100years
Quantity	94.332 tons
Transport distance	91.60Km (from Xiangyin to Changsha)
Recycled content	Recycled content (35%) recyclability at EoL (100%)

3.2 PBSCI Analysis

To determine the recovery potentials of the case slab, the adopted recyclability plan of the modular building (Table 2) was obtained and fed into the PBSCI model. The PBSCI measures the circularity index of the case slab using the four building blocks of CE. The PBSCI consists of four main stages *viz.* the material circularity index (MCI), product circularity index (PCI), system circularity index (SCI) and building circularity index. Since the case study is not the whole building but the slabs, the system circularity index is the final index used for comparison in this study. This does not affect the PBSCI analysis since the recyclability plan of the case slab is inputted at the first stage of the analysis (during the calculation of the MCI). A more detailed explanation of the PBSCI analysis could be found in Antwi-Afari *et al*. (2022a, b).

$$MCI_p = \max\left(0, 1 - (\frac{0.9}{X_p})(\frac{1}{N}\ X\ \frac{\left(1-NV_{RC_{(p)}}\right)+\left(1-F_{RU_{(p)}}\right)}{2})\right) \text{---- Eq. (1)}$$

Where $NV_{RC_{(p)}}$ is the fraction of feedstock from non-virgin sources for the material p; $F_{RU_{(p)}}$is the fraction of the material or product to be used for reuse, refurbishing, remanufacturing, and recycling; N is the normalization factor; X_p is the product utility.

$$\mathrm{N} = \sum_{i=1}^{n_b} \frac{F_{i\,total_{(p)}}}{F_{d\,total_{(p)}}} \text{ ---- Eq. (2)}$$

where n_b is the number of building blocks of CE (4 in this case).

$$F_{d\,total_{(p)}} = \sum_{i=1}^{n_b} F_{btotal_{(p)}, \max\, = n_b} \text{ ---- Eq. (3)}$$

Where $F_{btotal(p)}$ is the number of building blocks considered for the assessment in product p.

$$F_{i\,total\,(p)} = \sum\left(\frac{f_{i_{CPD_p}}}{f_{d_{CPD_p}}} + \frac{f_{i_{RC_p}}}{f_{d_{RC_p}}} + \frac{f_{i_{SC_p}}}{f_{d_{SC_p}}} + \frac{f_{i_{NBM_p}}}{f_{d_{NBM_p}}}\right) \text{---- Eq. (4)}$$

where $fi_{(\mathrm{CPD,RC,SC,or\ NBM})_p}$is the sum of the assigned weights to the DfSC criteria *i* of a particular building block for product p,

where $f_{d_{CPD,RC,SC,or\ NBM_{(p)}}} = \sum_{i=1}^{n} f_{i_{\left(CPD,RC,SC,or\ NBM_{(j)}\right),max}} = n$ ---- Eq. (5)

thus, the sum of the number of the assigned weights of DfSC criteria *i* of a particular building block for product p.

$\propto = 0.9$, ---- Eq. (6) i.e., a constant established by the Ellen McArthur Foundation (2015).

$$X_p = (\frac{L_p}{L_{av_p}})(\frac{U_p}{U_{av_p}}) \text{ ---- Eq. (7)}$$

where L_p is the product lifetime; L_{av_j} is the average lifetime of similar product on the market; $U_p$is the intensity per use of the product; U_{av_p} is the average intensity per use of similar products on the market. The intensity per use ratio is usually set to one due to lack of data.
By considering the recyclability plan in the MCI calculations, MCI becomes the same as the PCI. Also, because the modular steel slabs are the only material which are being considered in the structural system of the building in this study, the SCI becomes the same as the MCI.

Table 2. Company's recyclability plan for the modular building based on DfSC checklist

Building Blocks	Key Performance Indicators (KPIs)	Design for System Circularity (DfSC) Criteria	Weightings
Circular Product Design (CPD)	Connection Type	Dry connections (e.g., click, magnetic, Velcro etc.)	1.00
	Connection Accessibility	Freely accessible	1.00
	Production	Producer-non consumer (what is made may come from what has already been made but producers have systems in place to reuse what has been made)	0.67
	Entropy Production	Compensated product transformations i.e., designing products for easy disassembly and easy return to their natural state	1.00
	Product EoL Reference Value	The products performance and EoL are determined and set from the design stage	1.00
	Expert Systems	Expert systems are available but not for all materials and processes in the product system	0.75
	Material Toxicology	The toxicology of some of the materials of the product is known and substituted	0.67
	Energy for Operations	Renewable energy is used for the EoL stage only	0.25
	Water Stewardship	Water from the production system is treated and cleaned, let flow into water streams	0.67
System Conditions (SC)	Company's Integration	Transdisciplinary thinking along value chains only	0.67
	Product Pricing	Product pricing does not include environmental elements, but initiatives are put in place to give back to the environment	0.50
	Stakeholders Collaboration	There exist collaboration between only a few key stakeholders	0.33
	Regulations and Incentives	Some key regulations and a few incentives are available	0.50
	Job Allocation	The product system is made in such a way that jobs could be available but getting the materials back is the main priority	0.50
	Procurement Routes	Improved procurement routes where materials sources are known but the effects of their processes are barely considered in decision making	0.50
	Materials Sourcing	Vernacular materials are considered but they are compared with others and the least costly is chosen	0.50
	Effects of Production Activities	Controlled and sustainable activities which benefits locally only, but their global effects may not be known and vice versa.	0.50
Reverse Cycles (RC)	Material Traceability	Product / material passport is available only at the design/production stage and not linked to the product throughout its life cycle	0.33
	Material Banks	Some of the building designs and materials are available to be sampled by buyers online	0.50
	Materials Production	The product is made of > 20% of recycled materials	0.50
	Materials Upcycling	> 50% of the materials or components of the product will be upcycled at EoL	0.75
	Take-back Systems	A take-back system is available, but not a full integrated EoL logistics which could get all	0.50

		recyclable materials / components back to the material processing firms	
	Waste Collection	Only minimal technologies such as QR codes for informal waste collection and payments are employed	0.33
	Linking of Data at EoL	Enabling technologies are used to feed some generic products to a database for general processing	0.33
	Materials Collateral Effects	The company with the licensed product only have the right to reuse its materials at EoL	0.10
	Nutrient Cycling System	Nutrient cycling is not considered in the design, but considered during the recycling process to separate biological from technical nutrients	0.50
New Business Models (NBM)	EoL Business model	Business models where producers close the loop of their production system through servicing of materials or parts of the products are adopted	1.00
	Firms Collaborations	The business model adopted for the product is such that it can work within several different economic and market settings	1.00
	After sales Strategies	Aftersales services are not considered during the design stage, but only considered for marketing purposes	0.67
	Partnerships	No partnership of any sort is established	0.10
	Service Business Model	Product as a service is not thought of at the design stage and is only adopted during sales / marketing. Hence, trade-offs of adopting a particular product as a service approach may be unknown	0.50

Table 2 recyclability plan was used for the base scenario. Three other case scenarios were modelled for the PBSCI and compared to the base scenario results to understand the influence of the recyclability plan on the potential recoverability of materials at EoL. Scenario one was modelled after a linear case model at EoL (0% recyclable and lowest weighting for all criteria in the recyclability plan). Scenario two was modelled after an absolute circular model at EoL (100% recyclable at EoL and highest weighting for all criteria in the recyclability plan) while scenario three was modelled after an optimal case model (at least 80% of the steel slabs should be recycled at EoL and optimal weighting for all criteria in the recyclability plan).

3.3 EoL Allocation Methods

For a C2C system boundary the impacts from reuse, recycling, or energy recovery of the materials at EoL are modelled as avoided impacts according to EN 15978 (2012) guidelines. Thus, crediting the impacts of beyond system boundary in a detailed manner for substitution of virgin materials. The quantity of materials disposed of at the landfill and those recycled were modelled based on the adopted recyclability plan of the case company using the PBSCI tool. The 0/100 EoL allocation approach was adopted to express the allocation of impacts beyond system boundary for the whole analysis. The 0/100 EoL allocation approach credits the impacts of the EoL reuse pathways to the product system producing the recycled material.

4 Findings and Discussions

4.1 Recovery Potentials of the Case Slab

The average product utility of the case slab was modelled at 100years. The designers of the modular slab also assayed that the slab should be 100% recyclable at EoL due to the enhanced technology and materials used to produce it at the factory. By inputting the obtained weightings of the DfSC checklist based on the company's recyclability plan for the product system and the forecasted recyclability of the slab at EoL into the PBSCI model, it could be deduced from the Fig. 1 that the MCI of the case slab at EoL would be 50.4% of mass recyclable. The normalisation factor (N) which shows the rate of circularity of the recyclability plan of the product system was also 0.59 for the base scenario. The closer N is to one, the circular the recyclability plan and vice versa. Since, the case slab had no other sub-assemblies, the MCI was the same as the SCI. Also, because N is already considered in the MCI, the PCI is the same as the MCI. The non-circularity of the case slab at the base scenario was 49.6%. This shows that despite the design effort to attain 100% recoverability of the slab at EoL, the modular steel slabs cannot be said to be 100% circular when other KPIs of obtaining a systemic circularity are considered in the assessment. Hence, the recoverability potential percentage of the case slab at EoL from the PBSCI analysis should be a true reflection of the product's circularity and not just the forecasted circularity based on design.

To explore these ideas further, three other scenarios were modelled and compared to the base scenario to examine the effects of designing the slab for disassembly and the adopted recyclability plan of the product system on the overall circularity of the product at EoL. Scenario one (the linear case) was modelled as explained in the methods and its N was 0.10. Scenario two (the total circular case) was also modelled as explicated in the methods and its N was 1.00. Scenario three (the optimal case) was also modelled as elucidated in the methods to obtain N as 0.625 based on the existing technologies and possibilities as expounded in the current discourse. The circularity indices of the compared scenarios are presented in Figure 1.

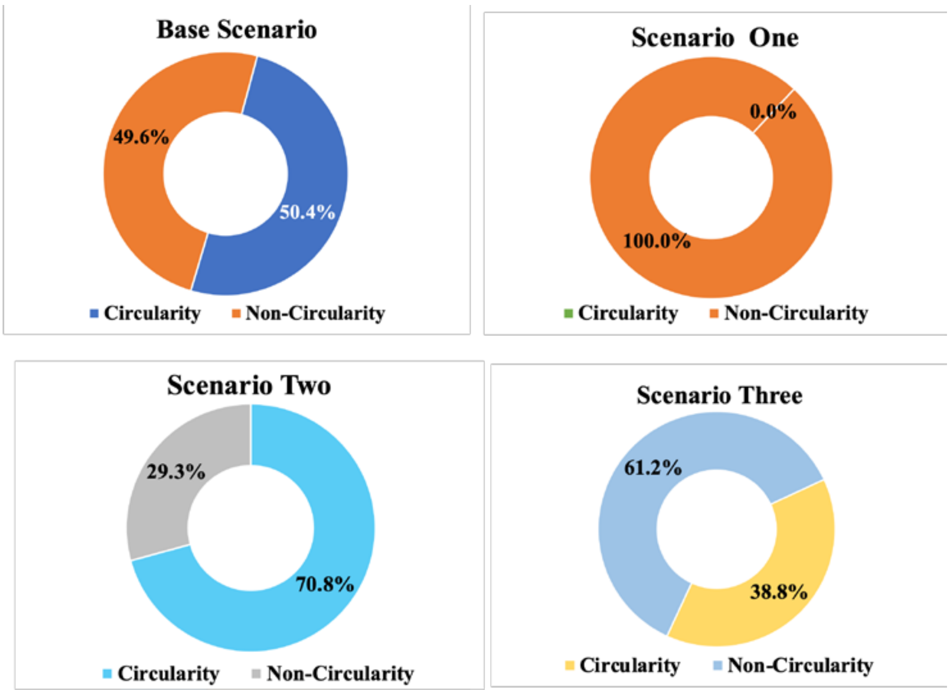

Figure 1. Circularity index of the modular steel slab

It can be deduced from Fig. 1 that the MCI of the case scenario one was 0% at EoL with a non-circularity of 100%. This means that eventually the slab would be sent to a landfill at its EoL since it was not designed or produced to be reused and there were also no well-established recyclability plans for the product system to ensure its circularity at EoL. For scenario two, despite having a forecasted recyclability at 100% and the highest weightings for all DfSC criteria, the MCI of the case slab was 70.75% of mass recyclable while 29.25% of mass was non-recyclable at EoL. This is because the case slab was made up of 35% recycled content and

65% of virgin sources. Hence, despite the EoL design plan forecasted at 100%, the whole slab product system cannot be said to be circular because majority of the materials were obtained from raw materials extraction which may have other impacts on other dimensions such as the environment, economic and social impacts which needs to be considered beyond the technical circular product design capabilities. In case scenario three, the MCI of the slab would be 38.8% of mass recyclable while 61.2% would be non-recyclable at EoL. The MCI of scenario three is less than that of the base scenario because it was modelled that only 80% of the case slab should be recycled at EoL amidst the claims of the prefabrication company to be able to achieve 100% recyclability. The assumptions in the optimal case were made based on the existing technologies, the opportunity to use recycled content in the production of the slab, the present design for disassembly factors, the surrounding system conditions and contemporary reverse cycles available for the case product system. The findings corroborate with the notion that achieving 100% circularity of a product system may not be possible in a real sense, but the right product utility, reverse cycles, business models, and disassembly factors should all be considered from the beginning of life of a product system to ensure a total/systemic circularity across the whole product system (Antwi-Afari *et al.,* 2022a). Not considering these from the beginning of life may lead to a circular technical product, which may not be circular or sustainable across other dimensions in its product system.

4.2 Environmental Impact of all Scenarios

By adopting the 0/100 EoL allocation approach, the environmental impact of all the scenarios across the product lifecycle from C2C was determined using the LCA method. The midpoint results of the case slab are shown in Table 3 and are expressed in percentages in relation to the highest impacts in each category in Fig. 2. It can be deduced from Table 3 that scenario one (the linear case) would induce higher impacts across several impact categories such as global warming (170856 kg CO_2 eq.), non-renewable energy (1749987 MJ primary), mineral extraction (329.39 MJ surplus) and respiratory inorganics (164.20 kg PM2.5 eq.). It could be examined from Table 3 that scenario two (the circular case) would also induce impacts in other impact categories when compared to the other scenarios such as aquatic ecotoxicity (5467481 kg TEG water), respiratory organics (25.55 kg C_2H_4 eq.) and land occupation (932.86 m^2org.arable). Most studies (*c.f.,* Kamali *et al*., 2019; Figueiredo *et al*., 2021) focuses on assessing impact categories which relates to the built environment without considering the effects of the built environment activities on other industries. Hence, despite the circular case leading to more circularity of the product system than other scenarios based on the PBSCI results, it could still lead to impacts in other impact categories which may not be the main concern now considering the existing planetary boundaries. Notwithstanding, to prevent burden shifting, it is advisable to look at all impacts in assessment to influence the choice of decisions.

It should be reiterated that the impacts of the scenarios in the LCA-C2C assessment do not match the adopted recyclability plan as used in the PBSCI analysis accurately. This is because some key technologies and renewable energy usage which were assumed to be adopted for some scenarios could not also be assumed in the LCA. Hence, the data of the base scenario was used for all the other three assumed scenarios which were compared to the base scenario in the PBSCI analysis. Thus, an actual circularity of a product system of 70.8% with all the available data should produce impacts which should be less than that obtained in this study. Notwithstanding, by using only percentage of the mass of materials recyclable at EoL in the LCA-C2C assessment still show how designing for systemic circularity could improve the circularity of products and reduces it overall environmental impacts especially in global warming, mineral extraction, and non-renewable energy consumption.

The global warming potential per m^2 of the modular steel slabs in the case building was 38.64 kg CO_2 / m^2 for the base scenario, 68.2, 28.28, and 44.95 kg CO_2 / m^2 respectively for scenario one to three. It can be deduced that by comparing with the base scenario, scenario one would induce 76.5% kg CO_2 / m^2 more in global warming potentials. Also, comparing the linear case (scenario one) and the circular case (scenario two), scenario two should save at least 141% kg CO_2 / m^2 in global warming potentials. By combining the PBSCI analysis with the LCA-C2C, the decision to select a particular material, product or scenario of a product system should now incorporate the environmental, social, technical, and inferred economic dimensions of the product system. The PBSCI analysis also measures the circularity of the recyclability plan by considering the KPIs of the product design, reverse cycles, system conditions and business models adopted for the whole product system / supply chain. The extension of the LCA to C2C should also enhances the consideration of EoL impacts and provide more intricate details on the impacts of the materials or product system after EoL.

Table 3. Midpoint results of lifecycle impacts of all the scenarios of the case slab

Impact category	Base Scenario	Scenario 1	Scenario 2	Scenario 3
Carcinogens	2120	4195	1296	2593
Non-carcinogens	11266	22124	7006	13727
Respiratory inorganics	101.24	164.20	82.33	113.71
Ionizing radiation	247866	234356	262323	241984
Ozone layer depletion	0.010	0.004	0.013	0.009
Respiratory organics	22.72	16.06	25.55	21.15
Aquatic ecotoxicity	4986721	4005907	5467481	4735392
Terrestrial ecotoxicity	1022794	1548532	823264	1139890
Terrestrial acid/nutri	2051.11	3240.85	1676.52	2292.02
Land occupation	816.87	576.21	932.86	755.76
Aquatic acidification	645.5	1065.19	516.82	729.48
Aquatic eutrophication	3.65	6.46	2.73	4.23
Global warming	96803	170856	70851	112617
Non-renewable energy	1026349	1749987	772525	1180965
Mineral extraction	277.84	329.39	260.71	288.59

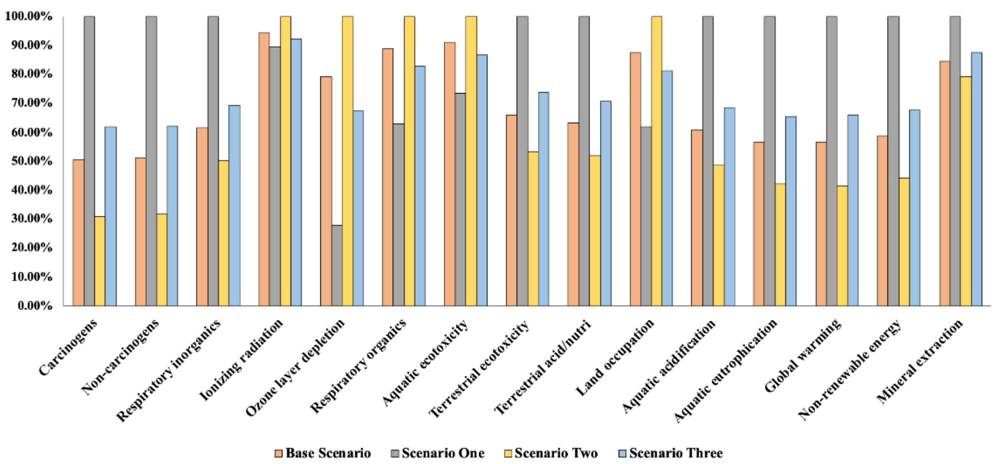

Figure 2. Lifecycle of all scenarios of the modular steel slab

5 Conclusion and Further Research

To ensure the practical implementation of CE, there is the need to be able to measure the improvement which circularity adoption brings to a product or product system across several sustainability dimensions. Existing methods such as LCA and its derivatives could be adopted to provide the potential environmental impacts of a circular product or process but its usage for other dimensions of circularity is fraught with several challenges. In this study, LCA system boundary was extended to C2C and combined with the predictive building systemic circularity indicator to measure the circularity and impact potentials of modular steel slabs in a residential building in China. The adoption of this combined iterative methods provided means for assessing not only the environmental and technical implications of circularity adoption but also, the ensuing impact potentials across the product lifecycles and beyond system boundary.

Three case scenarios were modelled and compared to the base scenario to illustrate this method. The recyclability plan, product utility, recycled content and forecasted recyclability of the base scenario were obtained and fed into the PBSCI model to determine the recovery potentials of the case slabs at EoL. It was identified that the rate of recoverability of the case slabs were hugely influenced by the normalisation factor which is calculated from the adopted recyclability plan of the product system. Also, the average product utility, recycled content during the production of the slabs and the forecasted recyclability at EoL based on the slab design also influences the circularity indices of the whole product system. The various scenarios were also assessed using LCA-C2C while taking note of the percentages of mass of materials recyclable at EoL and including the impacts of the EoL reuse pathways in assessments. It was identified that the modular steel slab should induced 38.64 kg CO_2 / m^2 in climate change for the base scenario while the circular scenario should save at least 141% kg CO_2 eq. in climate change when compared to the linear scenario.

The adoption of this iterative integrative method for determining the impacts and recovery potentials of products or product systems is not to provide an absolute means of guiding decisions on which materials or scenarios to adopt for a product system but rather to present a more comprehensive method where several key dimensions of CE could be considered in assessments. For instance, it can be inferred from the analysis that a product designed to be 100% circular at EoL does not necessarily mean that the production system and impacts of having that product is circular across all dimensions or impact categories. Hence, to attain a total/systemic circularity requires a consideration of the four building blocks and its key performance indicators thoroughly from the beginning of life of product system, by measuring each criterion methodically as much as possible and making sure that each indicator in the product system is chosen with the circularity and sustainability of the whole product system in mind.

It should be noted that the key performance indicators provided under each building blocks of CE in this study is not exhaustive and would require further research and expert judgement to enhance them to measure specifically the vital indicators which should influence the circularity of a product system within the construction industry. Also, artificial intelligence models could be adopted to enhance the prediction of the forecasted recyclability of the case slab based on design rather than depending on expert judgement only. Moreover, sensitivity analysis could be done in the LCA-C2C to assess the influence of several input parameters on the result of the LCA-C2C such as changes in travelling distances, use of different lifecycle impact assessment methods and LCA databases.

6 Acknowledgement

The paper constitutes a part of a PhD research project currently undertaken at the University of Hong Kong, Department of Civil Engineering, and fully funded by the Hong Kong PhD Fellowship Scheme, HKPFS (PF18-17313) under the Research Grants Council of the Hong Kong Special Administrative Region, China.

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A Decision Support Tool for Designing out Waste in Construction Projects: A Conceptual Framework

Nguyet Tong[1*], Niluka Domingo[1] and An Thi Hoai Le [1]

[1]School of Built Environment, Massey University, Auckland 0632, NEW ZEALAND

nguyetnuce@gmail.com; N.D.Domingo@massey.ac.nz, A.lethihoai@massey.ac.nz
* Corresponding author

Abstract:
Construction activities are expected to grow steadily worldwide, leading to creating a massive volume of construction and demolition (C&D) waste. Findings from previous works show that designers' lack of competencies and experience is one of the main causes of C&D waste. Hence, decision support tools can be applied to support designers in implementing designing out waste (DoW). However, existing studies tend to focus on design technologies for waste reduction rather than decision-making support tools to help designers select optimal design solutions for C&D waste minimisation. The primary aim of this study is to develop a conceptual framework for the future development of a DoW decision support tool for designers. The study employs a narrative literature review conducting a critical literature review on design strategies for DoW implementation, C&D waste estimation models, and cost-benefit and environmental impact analysis of both construction and demolition waste to establish a holistic support tool. The tool will be fully engaged in the design process to provide real-time analysis of the waste outcomes for the decision-making process.

Keywords:
Construction and demolition waste, decision support, designing out waste, minimisation.

1 Introduction

Construction and demolition activities have generated a major proportion of waste in landfills, such as 44% in the UK, 44% in Australia, 29% in the US, and 25% in Hong Kong. The global average of C&D waste is about 35% (Kabirifar et al., 2020). C&D waste has been causing adverse environmental impacts, natural resource exploitation and the depletion of landfill sites. In addition, waste generation also leads to significant pressure on the project budget due to tons of material losses, and additional costs for waste handling, transportation and landfills (Ajayi and Oyedele, 2018a). In order to minimise those negative impacts of C&D waste, waste preventive measures must be put in place.

Among solutions for waste reduction throughout all stages of the building process, waste minimisation measures in the design stage are decisive and effective to prevent C&D waste (Osmani et al., 2008). For example, appropriate design decisions can reduce one-third of construction waste (Osmani et al., 2006). Designing out Waste (DoW) principles are introduced by the Waste and Resources Action Programme (WRAP), namely design for reuse and recovery, design for off-site construction, design for materials optimisation, design for waste efficient procurement, and design for deconstruction and flexibility (WRAP, 2009). The effectiveness of DoW depends not merely on architectural technologies but also on designers' behaviour, attitude and capacities (Wang et al., 2015). However, the lack of designers' experience and competencies is one of the main reasons for construction waste (Wang et al., 2014). Designers are also not willing to engage in DoW due to a lack of understanding of design waste causes (Osmani et al., 2008).

Therefore, a decision support tool is necessary to support designers in selecting design solutions for waste minimisation. However, existing waste management tools (such as DoWT-B, SMARTWaste) do not effectively support designers, because those tools are separated from the design process and can only be used when the bill of quantities is available. Additionally, although the potential of BIM in C&D waste minimisation has been highlighted in extant literature (Nikmehr et al., 2021); there is no BIM-based support tool for decision-making process during the design stage. Liu et al. (2015) develop a BIM framework to support efficient design strategies for construction waste minimisation, including clash detection, design errors, visualisation, design coordination and communication. Other BIM studies specifically focus on architectural technologies, such as a model to minimise rebar offcuts (Porwal and Hewage, 2012) or an algorithm for selecting alternative floor layouts to reduce material waste (Bilal et al., 2019). Other BIM-based tools for C&D waste estimation tend to predict the total amount of waste rather than consider the waste hierarchy and the source of waste generation to select effective DoW measures (Akinade, 2017, Xu et al., 2019). Furthermore, existing cost-benefit analysis and environmental impact assessment models cannot reflect the impact of specific design solutions towards C&D waste minimisation. To date, there is a lack of holistic waste analysis tools to support designers in DoW decision-making during the design process.

Hence, this study aims to develop a conceptual framework for the future development of a decision support tool for designing out waste in construction projects. To achieve this aim, the paper tries to provide a critical literature review of design strategies for DoW implementation, existing models for C&D estimation, cost-benefit analysis and the environmental impact assessment of both construction and demolition waste to provide a holistic decision-making analysis.

2 Literature Review

2.1 Waste management hierarchy

The C&D waste management hierarchy is considered the most effective strategy for C&D waste management (Spišáková et al., 2022). The waste management hierarchy is divided into five levels as shown in Figure 1. The highest priority is waste prevention, offering the most effective strategy for natural resource conservation. Followed by waste reuse when products or components are reused for the same purpose or for another use without changing their properties of form. There is a high potential for adopting this method in construction, such as the reuse of bricks and roofs. When reuse is no longer applicable, recycling is adopted to recover and reprocess the waste materials to make the same or different materials. The recovery and disposal are the least flavour options in the waste hierarchy. The waste hierarchy is used to guide and rank the waste management decisions and evaluate the efficiency of the waste management process.

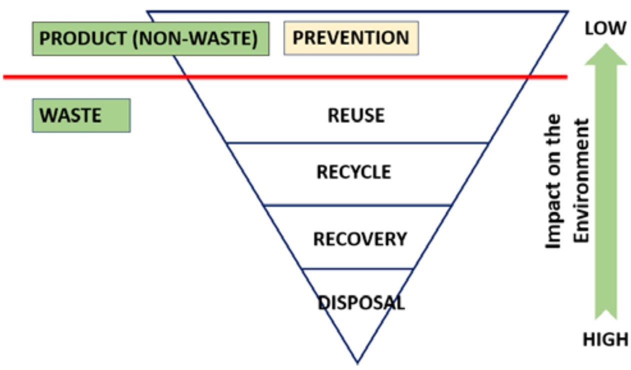

Figure 1. Waste management hierarchy
(Source: Directive 2008/98/EC (EC, 2008))

2.2 Designing-out waste

Owing to the potential contributions of DoW to C&D waste minimisation and resource efficiency, many attempts have been made to encourage the DoW adoption from the early design stage. For example, WRAP (2009) identifies five DoW principles to defeat C&D waste and protect natural resources. Osmani (2015) and Laovisutthichai et al. (2020) establish a framework to help designers implement DoW in different design stages of the RIBA Plan of Work. Other researchers focus on design solutions to implement DoW effectively. Primarily, designers should understand five DoW principles to assess the opportunities for DoW adoption to minimise C&D waste as following.

(1) *Design for off-site construction* is a key dimension of DoW, including modular construction, prefabrication, and preassembled building components. This design principle will help to enhance quality, conserve resources, and reduce waste in the construction and deconstruction of buildings (Wang et al., 2014, Ajayi and Oyedele, 2018a). According to a case study conducted by (Tam et al., 2007), prefabrication adoption can help to prevent 100% of waste generation and up to 84.7% saved for waste reduction. Many BIM-based tools were developed to support parametric design for off-site construction, such as for modular construction (Banihashemi et al., 2017), and prefabricated building (Liu et al., 2019).
(2) *Design for reuse and recovery* is preferred solutions to reduce the load to landfills when waste generation cannot be prevented. This can contribute to significant economic and environmental benefits, such as cost savings in landfill charges and new material purchase, the conservation of natural resources, and the reduction in carbon emissions. To maximum the reuse and recycling rate, reusable and recyclable materials should be encouraged in construction projects, especially for the C&D waste with high economic and environmental impacts, such as concrete, brick, metal and rebar waste (Shi and Xu, 2021).
(3) *Design for deconstruction and flexibility* plays a vital role in the material and component reuse process at the end of life of buildings. Deconstruction could be designed for four purposes: building relocation, component reuse, material reuse and material recycling. Building component reuse is the most preferred deconstruction method as it needs least energy and resources (Akinade et al., 2015). BIM can support to develop a BIM-based model for disassembly parameters to support the reuse of building components (Sanchez et al., 2021).
(4) *Design for resource optimisation* refers to simplification, standardisation, and dimensional coordination, as this method will help to improve the constructability of the building and prevent avoidable off-cuts. This results in reductions in both construction and end-of-life waste (Osmani et al., 2008, Ajayi and Oyedele, 2018a). For example, a reduction by 8.75% construction waste can be achieved by using an algorithm for dimensional coordination of floor layouts (Bilal et al., 2019).
(5) *Design for resource-efficient procurement* is to select resource-efficient procurement methods. Ajayi et al. (2017)'s study found that procurement of waste-efficient materials and use of minimal packaging, Just-in-Time delivery, over ordering prevention are the key strategies to minimise waste through the material procurement process. For example, pre-cut materials and modular construction generate lower waste output than materials offcut and in-situ methods. Materials with high content of recycled materials and minimal packaging are other effective reduction measures. In addition, accurate bills of quantity and material specification will help to prevent over-ordering (Ajayi and Oyedele, 2018b).

Previous studies have highlighted various benefits of DoW adoption, not only reductions in C&D waste from the early design stage but also economic and environmental benefits. Many efforts have been made to support designers during the design process; however, existing tools tend to focus on design technologies rather than assess the impact of DoW alternatives on C&D

waste minimisation. Hence, it is necessary to develop a waste analysis tool which is actively engaged in the design process to support designers in the selection of DoW measures.

2.3 C&D waste analysis in the design stage

C&D waste refers to any materials generated as waste during the construction and demolition stages. The main sources of waste during the construction stage include excavated soil, packaging waste, and material remains due to offcuts, breakages, losses, etc. Meanwhile demolition waste depends on adopted DfD measures, construction procedures, selected materials and demolition techniques (Llatas, 2013).

A holistic waste analysis needs to consider both construction and demolition waste to aid designers in selecting effective design solutions for waste minimisation. In terms of decision-making factors, C&D waste estimation is the fundamental criterion to assess the performance of DoW alternatives. C&D waste is estimated and categorised by the waste management hierarchy, which will enable designers to assess the efficiency of DoW solutions. In addition, the analysis of cost-benefit and environmental impacts is also essential in the decision-making process for DoW. C&D waste minimisation can offer various environmental and economic benefits, such as reductions in greenhouse gas emissions, decreases in natural resource exploitation, profit from selling salvage waste, and savings in landfill charges (Zoghi and Kim, 2020); however, selecting reusable and recyclable materials may increase the project cost and contain more adverse environmental impacts.

2.3.1 Waste estimation

Predicting waste outcomes is the primary criterion to choose effective design solutions to facilitate DoW. However, existing estimation methods are based on historical and statistical waste data without adequate consideration for detailed design information (Table 1). These methods can only estimate the approximate total amount of waste without consideration of waste types and project specifics, therefore, cannot play a role in analysing C&D waste from an individual project.

Table 1. Estimation methods for C&D waste.

Estimation methods	Description	References
Physical layout forms	The waste volume is estimated according to the physical layout forms of the waste on site.	(Lau et al., 2008)
Construction area	The waste estimation is based on Waste Index and Gross Floor Area. Waste Index is the amount of waste generated per m2 of Gross Floor Area (GFA).	(Poon et al., 2001) (Jalali, 2007)
Building components	The waste estimation is based on Component Index and the type & number of components. Component Index is the amount of waste generated per unit of each construction component.	(Jalali, 2007)
Material stocks and flows in a region	The waste estimation in a region is based on the study of the dynamics of collection and flow of construction materials.	(Cochran and Townsend, 2010)
Construction databases	The waste estimation is based on packaging & demolition factors and material quantities obtained from budget documentation.	(Llatas, 2011)

Several waste estimation tools were developed to estimate C&D waste, such as SMARTWaste (BRE, 2008), Net Waste Tool (WRAP, 2011b), and the Designing out Waste Tool for Buildings - DoWT-B (WRAP, 2011a); however, these tools are not helpful for designers as they are detached from the design process, and therefore not actively engaged in the design stage to identify potential opportunities for waste reduction.

In recent years, BIM has been increasingly studied as an approach for C&D waste estimation. Because BIM contains geometric and semantic information of each building element which allows more fast and accurate estimation of C&D waste amount and type (Table 2).

Table 2. Previous studies on BIM-based tools for C&D waste estimation.

Reference	Waste type	Tools	Waste estimation method
(Cheng and Ma, 2013)	Demolition waste	BIM API	Original waste = material volume*volume change factor*density. Recycling and reuse data are customized by users.
(Lu et al., 2017)	Construction and demolition waste	BIM API	Waste generation of the component = quantity of the component * waste generation level Waste generation level is stored in Design Options – Waste Generation (DO-WG) database.
(Kim et al., 2017)	Demolition waste	Framework of BIM-based estimation	Demolition waste = material volume*volume change factor*density.
(Akinade, 2017)	Construction waste	BIM and Adaptive Neuro-Fuzzy Inference System	A prediction model based on waste data of 117 UK building projects. However, the model cannot estimate the waste by type.
(Guerra et al., 2019)	Construction waste	Algorithm of quantification	Construction waste = Purchased materials – Needed materials
(Xu et al., 2019)	Construction and demolition waste	Algorithm of quantification	Original waste = material volume*volume change factor*density. Recycling and landfill quantities are defined based on different rates.
(Bakchan et al., 2019)	Construction waste	Framework of BIM-based estimation	Construction waste = Purchased materials – Needed materials.
(Quiñones et al., 2019)	Demolition and construction waste	BIM API	C&D attributes database is integrated into BIM to predict the amount and type of waste. C&D waste attributes, including type of waste and waste generation rate, are assigned to corresponding elements.
(Su et al., 2021)	Demolition waste	Algorithm of quantification	Original waste = material volume*volume change factor*density. Recycling and landfill quantities are defined based on different rates

The advantage of using BIM is to provide automated and accurate quantification of each component by material type, which enables designers to assess the source of waste generation for further design improvements towards waste minimisation. However, existing BIM-based estimation tools fail in classifying waste by the waste hierarchy to evaluate the impacts of DoW principles on waste minimisation and resource efficiency. In some studies, the amount of recycling and reuse waste are calculated based on the recycling rate in total waste amount instead of considering the waste treatment at the source of generation. Furthermore, DfD for component and material reuse is not considered when estimating demolition waste. Apart from the tool established by Quiñones et al. (2019), estimation tools for construction waste only consider material remains while packaging waste and soil from excavation are also main waste sources and contribute to a substantial proportion of construction waste (Ajayi et al., 2017). In addition, measuring construction waste by the difference between the amount of purchased and needed materials is not practical during the design process as purchase records are not available. Hence, it is fundamental to developing a C&D waste database for automated estimation from the early design stage.

2.3.2 Cost-benefit and environmental impact analysis

Economic performance is a decisive factor in C&D waste management (Hamidi et al., 2014). The decision-making analysis needs to consider both the cost and benefits of different DoW alternatives. The C&D waste disposal cost includes transportation costs, collection and classification charges, and recycling or landfill fees (Shi and Xu, 2021). Meanwhile reuse and recycle waste can bring benefits from savings in purchasing new materials or selling reusable and recyclable materials (Hamidi et al., 2014). When conducting the cost-benefit analysis for demolition waste, the initial construction cost of DfD is calculated. Because choosing appropriate materials for DfD may increase the project cost, designers must ensure that the cost of DfD and disposal does not exceed the benefits from recoverable materials (Akinade et al., 2015).

Regarding environmental impact analysis, C&D waste can cause adverse environmental impacts due to collection, classification, transportation, recycling process, and waste landfill. Waste transportation depends on the waste treatment methods, transportation modes, and the distance to new construction sites for relocation, recycling centres or landfill sites (Shi and Xu, 2021, Xu et al., 2019). Recycling activities also bring positive effects on the environment due to savings in exploiting natural resources for new materials (Su et al., 2021). Total environmental impacts are the sum of all adverse and positive impacts on environmental protection. When recycling waste releases large emissions, the landfill rate should be increased; however, if the recycling emissions are small, recycling should be prioritised (Xu et al., 2019).

Different waste treatment scheme has different impacts on the performance of cost-benefit and environmental impact. However, the limitations of existing waste estimation models hinder an accurate analysis of cost-benefit and environmental impact as C&D waste is not categorised according to the waste hierarchy.

3 Research Methodology

A narrative literature review is used in this study to critique and synthesise the literature on designing out waste strategies, waste estimation models, and economic and environmental analysis of waste output to develop a conceptual framework for a decision support tool for designing out waste in the construction projects. The keywords were used in the critical literature review are “design” AND (“construction waste” OR “demolition waste”) in the title, keywords, and abstract fields via Scopus database for searching the relevant literature within the scope of the study. Scopus was chosen because Scopus has accurate performance with wider coverage of journal publications than other databases (Chadegani et al., 2013). Initially, 129 articles and conference papers in English language from 2000 to 2022 were found through title screening. Then abstracts of 129 papers were carefully checked. 5 additional papers were identified from reference screening. Finally, 37 papers were chosen, including 19 papers on designing out waste principles, 18 papers on C&D waste estimation, cost-benefit analysis, and environmental impact.

4 Conceptual Framework for a decision support tool for designing out waste in construction projects

The literature review showed the limitation of existing waste tools in decision support for DoW implementation. C&D waste estimation is not categorised by the waste hierarchy, as a result, economic and environmental analysis is not accurate due to inappropriate waste estimation. Therefore, developing a comprehensive tool is necessary to support designers in selecting effective design solutions and facilitating DoW adoption. A conceptual framework is developed for future development of a decision support tool for designing out waste in construction projects (Fig. 2). The framework aids a holistic analysis of both construction and demolition waste to support designers in the decision-making process. This provides not only C&D waste estimation but also cost-benefit analysis and environmental impact assessment of DoW solutions. DoW measures may contribute to a reduction in the amount of contribution waste but may not support preventing the end-of-life waste, or may lead to increases in project cost and worse impacts on the environment. Therefore, the framework will aid designers to assess the amount of generated waste as well as the economic and environmental impacts of both construction waste and end-of-life waste to make optimal design decisions.

4.1 C&D waste estimation

Waste estimation functionality is the primary requirement of a decision-making support tool for DoW. The framework is developed to deal with the limitations in existing waste estimation models, including no waste classification by waste hierarchy management, and neglect of soil, packaging waste and DfD in C&D waste estimation. First, to measure the efficiency of DoW solutions, the amount of C&D waste must be classified according to the waste hierarchy, including reuse, recycle, recovery and disposal in landfills (BRE, 2008). As a result, designers can easily assess the performance of selected design solutions towards waste minimisation and resource efficiency. The waste estimation model also needs to provide accurate quantities, type, and root cause of waste generation. This will aid designers to find the place for design improvements. In terms of construction waste, material remains, packaging, and soil are estimated as the main causes constituting the total amount of construction waste (Llatas, 2013). Meanwhile, the end-of-life waste depends on demolition methods. If DfD is considered in the design stage, the waste is categorised according to the deconstruction plan (Akinade et al., 2015). Otherwise, demolition waste will be sorted for recovery or disposal in landfills.

4.2 Cost-benefit and environmental impact analysis

The cost-benefit and environmental impact analysis is based on the waste treatment scheme. In the framework, C&D waste is estimated by waste hierarchy to facilitate the analysis process. For environmental impact assessment, the carbon emissions are estimated because carbon dioxide is the most common and harmful gas in the CDW disposal process (Shi and Xu, 2021). Carbon emissions are released from transportation and handling activities. Handling activities are related to collection and classification on-site, reuse and recycling process, recovery and disposal in landfill places (Xu et al., 2019). However, the environmental impact can also be saved due to reusable, recyclable and recovery waste (Su et al., 2021). In terms of cost-benefit analysis, benefits are gained from selling salvage construction materials and savings in purchasing new materials. While costs are related to transportation, handling activities, and construction and demolition cost. Construction and demolition cost depends on whether DfD is adopted in the design stage.

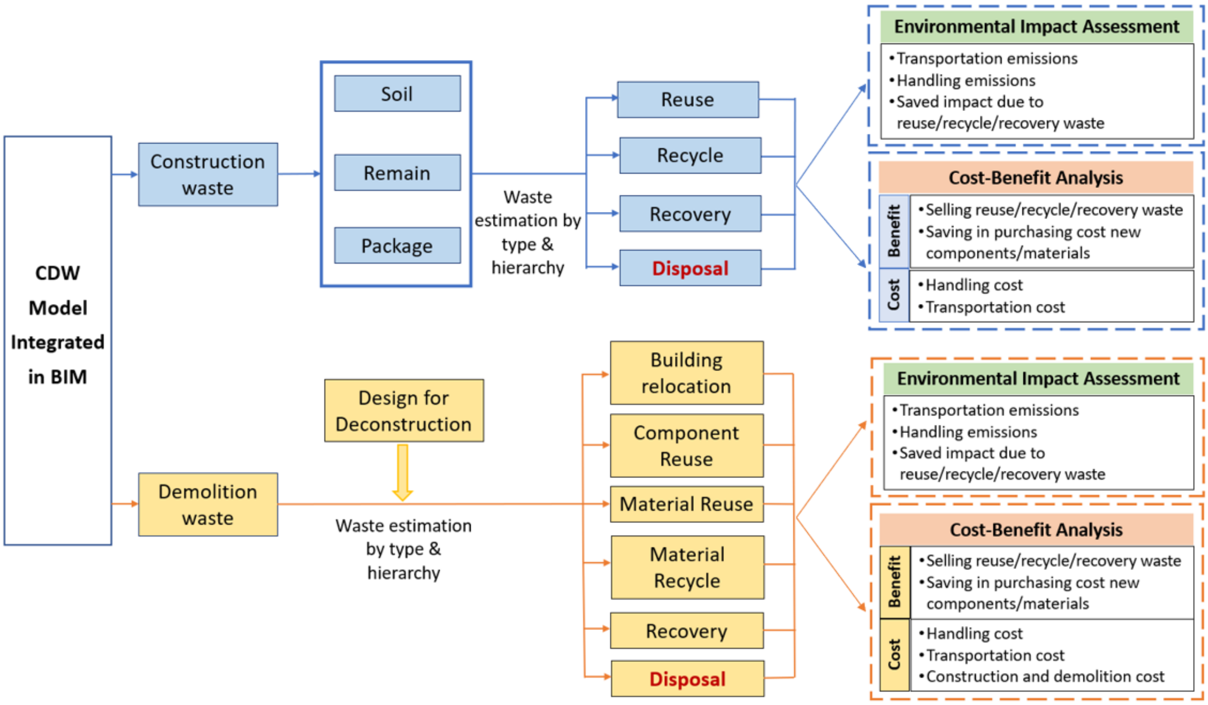

Figure 2. Conceptual framework for a decision support tool for designing out waste

4.3 C&D waste model integrated in BIM

To fully support designers in DoW decision-making, the tool needs to be actively used in the design stage. However, existing tools are not fully engaged in the design process to support designers. In order to address these limitations, the C&D waste model integrated into BIM is a promising approach to facilitate real-time decision-making analysis. This will reflect the impacts of different DoW solutions on waste estimation, cost-benefit analysis, and environmental impact assessment. C&D waste attributes are assigned to corresponding components, which enables designers to find which components generate a significant amount of waste to decide whether design alternatives are needed for improvements. When it comes to any design changes, the C&D waste model can provide automatic and update decision-making analysis that directly reflects such design changes.

It is important to define the C&D waste attributes input to the C&D waste model, including attributes for waste estimation, cost-benefit analysis, and environmental impact assessment. However, such attributes do not available by default in the database of BIM modellers. Hence, developing a comprehensive waste database is a critical requirement for a decision support tool for designing out waste in construction projects.

5 Conclusion and Further Research

Recently, researchers have paid increasing attention on minimising C&D waste from the early design stage instead of only focusing on solving C&D waste when it already generated. Major efforts are spent on design technologies to implement DoW, while there is no holistic support tool for designers in decision-making process. In addition, the limitations of existing waste estimation and analysis tools do not actively aid designers to assess the impacts of design solutions on waste outcomes. Waste treatment scheme and the place of waste generation are not considered in existing tools; therefore, designers cannot assess the efficiency of design options and find the place of significant waste generation to propose alternatives for improvements towards C&D waste minimisation. A conceptual framework is developed for a decision support tool for designing out waste. The support tool is expected to address the limitations of existing waste tools and provide decision-making analysis of waste estimation based on the waste hierarchy, cost-benefit analysis, and environmental impact assessment. The decision support tool is integrated into BIM to actively engage in the design process, and hence provide real-time analysis for decision-makers. C&D waste database plays an important role in a comprehensive decision-making analysis. To make most of limited resources for developing a waste database, efforts are spent on areas with significant impacts in waste minimisation on construction projects. Hence, future research will investigate the building elements generating significant C&D waste, and effective design strategies to implement DoW.

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Exploring Critical Success Factors for Promoting a Circular Economy in New Zealand Construction

Kam Yuen Cheng[1*] and Yuwei Xia[2]

[1]Engineering and Architectural Studies Department, Ara Institute of Canterbury, 130 Madras Street, Christchurch, NEW ZEALAND
[2]William Corporation, Level 4/2 Cathedral Square, Christchurch Central City, Christchurch 8011, NEW ZEALAND

kam.cheng@ara.ac.nz; ywxia555@outlook.com
* Corresponding author

Abstract:
The circular economy (CE) focuses on a restorative and regenerative economy by designing and keeping resources, components, and materials at their highest utility and value. Scholars worldwide have brought up this concept and emphasised it in the construction industry. Though precedent studies have shown the environmental benefits of the CE approach in the construction industry, circular buildings are still rare. New Zealand practitioners face profound challenges in integrating circular economy principles into construction projects. This research aims to investigate the critical success factors (CSFs) for implementing a circular economy in New Zealand's construction industry. This research comprises a focused literature review, questionnaire survey of industry practitioners and factor analysis, followed by a conclusion. The Relative Importance Index (RII) will be used to scale the ranking of those factors. A total of 20 factors impacting the adoption of a circular economy in NZ's built environment have been identified and categorised into four categories: Design Inputs, Organisational Strategies, Information Management and Governmental Support. The identified factors are scaled and prioritised by industry experts and practitioners. The outcome of this research shows that Awareness of circular economy, Reuse and recycling, Engagement of standard components from upstream players and Collaborative working and engagement with every stakeholder sit at the top four positions. Therefore, it would provide practical guidance to the construction industry practitioners in New Zealand.

Keywords:
Circular economy, Construction, Offsite construction, Sustainability, Success factors

1 Introduction

In New Zealand, the number of building consent issued in 2021 was 47,715, which increased by 26% compared to October 2020 (StatsNZ, 2021). In the same year, the annual value of non-residential building work was $8 billion, which grew by 17% compared to October 2020 (StatsNZ, 2021). This suggests a strong demand for residential and commercial buildings, thus increasing resource consumption. In NZ, the waste produced by construction and demolition makes up 40%-50% of total waste going to landfills (BRANZ, 2022), and the study found that every house built will generate an average of 4 tonnes of waste (BRANZ, 2022). Therefore, it is time to rethink our economic activities because the traditional linear economy - take, make, dispose of, is not sustainable.

According to the Ellen MacArthur Foundation, by 2021, the Circular economy will need circular business models, including circular design, reverse logistics, enablers, and favourable circumstances (i.e., public policy). Circular designs and legislative enablers, on the other hand, have dominated industry debates and written material. Construction firms, practitioners, and customers in New Zealand and elsewhere have failed to transfer the concept of CE into reproducible practice in the circular economy without encountering cyclical business models and novel technical methodologies. There is no proven formula for success due to a lack of information on how to apply CE concepts in New Zealand's built environment and the fact that the circular economy is still relatively new in New Zealand and throughout the world. Consequently, the major success factors (CSFs) for employing a circular economy remain unclear, resulting in a significant research gap.

2 Literature Review

In construction, a circular building is a resulting product by adopting circular principles that the building is developed, used, and reused without resource depletion. It is environmentally and economically responsible, contributing to the well-being of humans and the biosphere (Kubbinga et al., 2018). Based on an intensive literature review, including journal articles, industry reports, and relevant governmental webpages, some commonalities have been found and summarised as critical factors for successfully adopting a circular economy in the built environment. The following chapters present the identified essential factors of success that can be explored for the NZ construction industry.

2.1 Identifying critical success factors

2.1.1 Design Inputs (6)

1) Design for deconstruction/disassembly: Disassembly/deconstruction at the end of life is the key to achieving circularity and completing the technical resource cycle. It allows construction components and materials to be reused or recycled for a new purpose. Additionally, products are designed to be repaired and refurbished, reducing the need for raw materials. Suppose all these design principles were considered and adopted by architects at the design stage. In that case, the used building products could be circulated back to the industry because it maintains the materials and components of the building for the highest practical purpose. This means assets are used more fully, and their lifecycles are extended and diversified (Arup, 2016).

2) Design for flexibility, adaptability, and resistance: A flexible and adaptable building design adapts to the changing market and societal demands. Building materials may be reused in the future if the market moves from commercial to residential. A flexible design allows structures to be disassembled for future use and provides room and shelter (Arup, 2016). Adapting building materials to unexpected shocks and persistent stress may boost future physical resilience. Buildings are not sustainable if they must be rebuilt before their expected lifespan. This includes how structures function and respond to natural disasters like earthquakes and hurricanes. A resilient design should withstand these harsh circumstances and continue to operate.

3) Reuse and recycling: In a circular built environment, reusing existing resources with a reasonable renovation can maintain the resource's value and avoid the consumption of new resources. Reusing materials and components through resale or redistribution can bring economic and social benefits (Arup, 2016). The mindset that materials, components, structures, and buildings will be reused and retrofitted where possible should be embedded in the design, allowing circularity in all system parts.

4) Modularity and prefabrication: There are outstanding benefits when using the prefabricating method in the built environment. Modular buildings are relocatable, designed for

deconstruction and made of high-quality materials (Acharya et al., 2020). They are also easier to reuse and repurpose as their structure can be easily changed. These features also facilitate the flexibility, adaptability, and durability of buildings.

5) Engagement of standardised components from upstream players: Manufacturers play a leading role in scaling up standardised building products. Relative instructions and specifications should be introduced into the construction industry, guiding building contractors with technical support. The provision for maintenance manual, guarantee and warrant should encompass every product delivery. Although the standardising and automatic way of manufacturing deskills labours in a factory setting, it upskills the industry and prepares the trades to deliver buildings efficiently

6) Early design with lifecycle-costing and renewable resources: Resource selection is critical in circular building design (Rahla et al., 2021). Aside from secondary materials, low-carbon, high-quality, and reversible resources should be preferred. A whole-life costing design technique maximises renewable resource utilisation, reduces demand, and achieves energy efficiency. A Passive House is an excellent example of how to save energy and help the building survive longer (Passive House Institute NZ, 2019).

2.1.2 Organisational Strategies (6)

1) The integration of circular economy principles into business design: Circular business models foster stakeholder collaboration (Carra & Magdani, n.d.). Circular business concepts come in three categories: design, usage, and recovery. These models can only be used at scale when business models shift. When planning and designing, the business model needs to plan and prepare for components, systems, and the actual asset that can be dismantled and rebuilt. The concept relies on take-back systems and collection services to recover usable items and recycle garbage.

2) Effective integration of circular economy procurement strategies: Contracts can be used to clarify collaborative boundaries and responsibilities at an early stage. There are some procurement strategies brought up and adopted in the industry. Suppliers can engage early with designers and manufacturers to identify opportunities for leasing services within the asset. Including supplier take-back schemes in contracts ensures reuse and recycling at the product's end of life.

3) Collaborative working and engagement with every stakeholder: Adopting a circular economy in the built environment requires a joint effort from the whole value chain. Early stakeholder engagement can help businesses identify circular economy opportunities. Cross-sector collaboration can provide a platform for information exchange and best experience practice. This is crucial when it comes to information sharing across sectors.

4) Innovative supply chain strategies: Reverse logistics is a closed supply loop that uses remanufacturing, refurbishment, repair, reuse and recycling to recover materials and products after consumption. However, this logistic route must be supported by stakeholders such as waste generators, waste collectors, transporters, processors, disposal operators and landfill owners (Ratnasabapathy et al., 2021). Therefore, an incentivised return policy should drive the flow of materials and components through a cyclic supply chain. Using reverse logistics can broadly provide cost savings on virgin materials and alleviate issues of resource depletion. Effective reverse logistics management should be well-planned, implemented and controlled by suppliers.

5) Inventory management and control: Inventory management and control refer to construction companies and suppliers making decisions about inventory, storage, and material handling to reduce economic, environmental, and social impacts. Each supplier is responsible for tracking the materials and components they provide to the construction work, whether raw or secondary. This information should be accessible by the whole supply chain, such as designers, manufacturers, contractors and building operators/users.

6) CE specialists: Companies across building sectors should train and up-skill their workforce to increase competencies and expertise to implement a circular economy in construction projects (Wuni & Shen, 2022). Companies can initiate training programmes and apprenticeships to educate practitioners about the CE principles and approaches. The professionalism gives designers, engineers, project managers and other team players tools to implement CE strategies in construction projects. More importantly, material extractors are essential to the circular practice, which have the technology to separate materials and components from each other and ensure their quality for reuse or remanufacture.

2.1.3 Information Management (3)

1) The big data system: In the circular built environment, buildings are seen as a material bank where each material used can be documented and tracked through a material passport (MP), which can provide accurate information for material recovery and reuse (Munaro and Tavares, 2021). This information can be identified, removed, and reused numerous times in the database, showing the input and output of each material. Tracking material flows helps stakeholders better understand resource inputs and outputs, making better resource allocation choices.

2) BIM supporting information management: BIM is an innovative digital tool that stores, shares, and visualises information relating to an asset's life cycle. It allows stakeholders to collaborate efficiently on the design, construction, and operation stages. BIM can also work as building stock that stores materials, so this can become a 'material bank' and identify the circular potential of materials. It is recommended to use digitalisation efficiently because it can increase resource and labour productivity as a source of added value to business decision-making (Rodríguez et al., 2020).

3) Online waste sharing platforms: Waste generated from the construction industry is considered to have a high potential to yield valuable resources to the economy through either recycling, reusing, repairing, or remanufacturing (Ratnasabapathy et al., 2021). Consequently, appropriate approaches are needed to transform waste into resources. The current approach available in NZ is the waste online sharing platform. For example, Civil Share and FLOOW2 are two online applications that create a new supply route for secondary construction materials. Hence, unwanted construction materials can be redirected from disposal to potential resources.

2.1.4 Governmental Support (5)

1) Awareness of circular economy: Since the concept of circular economy has not been widely accepted in the construction industry, governmental publicity plays a vital part in changing traditional thinking and behaviour. The social and economic benefits of implementing a circular economy should be taught to all construction industry stakeholders. Integrating circular economy thinking into school curricula is a way to embed concepts early on and may help circular economy adoption scale up in all possible sectors (Ellen MacArthur Foundation, 2021).

2) Certification for secondary materials: Policymakers can lead in encouraging a circular built environment by determining which materials and products are put and used on the market. The

government can create reclaimed and secondary materials certificates to support confidence and trust in trading. This ensures the quality and performance of recycled materials for new purposes. Customers are more willing to accept the use of second-hand materials certified as good as new materials.

3) Development of a practical circular construction framework: Currently, there is no standardised tool evaluating circular construction in place (Finch et al., 2021), so it is necessary to develop a systematic framework that has clear objectives, measurable targets, and strategies for a circular building (Circle Economy, 2018). The framework is meant to guide what and how to achieve circular requirements. By referring to a framework published by the Dutch government, it provides an insight for developing a general framework for circular buildings and proposing strategies and indicators for sustainable construction activities.

4) Flexible incentive policies to encourage the adoption of circular economy construction: Financial measures are needed to support the circular economy transition. Tax incentives for building products with CE principles have no or the lowest environmental impact. On the other hand, they restrict new construction and non-circular activities that do not include reused and recycled parts by adding a tax burden on developers and contractors. In addition, researchers suggested that shifting taxes from labour to non-renewable resources can support the transition to practices that are not as resource intensive (Ellen MacArthur Foundation, 2021).

5) A market for the circular economy: The government can be a leading market player who will direct the market to a more circular economy demand. Incorporating circular economy standards into procurement law and listing preferred suppliers and materials can increase business opportunities that meet circular economy goals. Policymakers setting regulatory incentives and disincentives can smoothly transit from the linear economy to the circular economy.

The focused literature analysis provided above demonstrates that existing research have done an excellent job of establishing the essential requirements for a circular economy in a built environment. The literature covers the years 2016 through 2021, enabling the hiring of a reliable group of CSFs for managing circular economy projects. However, none of the trials provided a clear evaluation and ranking of the CSFs for promoting of circular economy in New Zealand's built environment.

3 Research Methods

In New Zealand, the study used a quantitative research approach to establish CSFs for circular economy in NZ built environment. The research process involved a targeted literature study, interaction with subject matter experts, data collecting, statistical data pretesting, and data analysis. As part of the quantitative approach, questionnaires are employed to gather data. Researchers utilise questionnaires in Likert scales to learn more about a topic or to get comments from individual respondents. Using this approach, study outcomes are more dependable and objective, and data may be gathered and analysed more rapidly.

To develop viable critical success factors (CSFs) for implementing a circular economy in the New Zealand construction industry, targeted literature research was undertaken to extract possible CSFs for adopting a circular economy. We identified CSFs for circular economy in the built environment in NZ and sent them to two industry experts in the NZ construction industry. As described in the previous section, relevant publications were discovered using Scopus and Web of Science searches and analysed to identify probable CSFs. Table 2 outlined the essential

CSFs identified from the literature, refined via expert collaboration, and served as the foundation for this study's assessment.

This study uses purposeful sampling as a strategy to select respondents. The target respondents were construction experts and specialists with knowledge and skills in the circular economy. The study's target group includes registered contractors, suppliers, consultants, property developers, designers, subcontractors, manufacturers, and academics. Practitioners evaluate an organisation's multiple adjustments to boost productivity while lowering expenses. With the help of practitioners, we can identify challenges and devise solutions to successfully implement a circular economy in New Zealand's building sector. They may also aid with economic and legislative difficulties by knowing the whole building procedures and costs. Registered construction practitioners are from professional institutes such as NZIOB, NZIQS and experts with relevant experience implementing the circular economy in New Zealand's building sector. Consequently, their views on CSFs are representative and crucial for implementing New Zealand's circular economy in the construction industry. Twenty-three questionnaires were sent to the target respondents. 15 out of 23 have been received, representing over 65% of the response rate.

4 Findings

The demographic profile of the respondents is shown in Table 1. The practitioners worked at several NZ organisations delivering circular economy initiatives. Most responses were from consultants, principal contractors, subcontractors, developers, suppliers, and academic/research institutes (100%). Moreover, the respondents came from various backgrounds, providing an excellent opportunity to engage diverse perspectives in the CSF assessment. Directors (25%), project/operation managers (33%), and QS/estimators (42%) made up the remainder.

Table 1. The demographic distribution of the respondents

Category	Attribute	Percentage (N=100%)	Attribute	Percentage (N=100%)
Nature of organisation	Contractor	33%	Consultant	7%
	Developer	13%	Academic	7%
	Sub-contractor	20%	Supplier	13%
			Other	7%
Position of respondent	Senior management: director/general manager	25%	Middle management: project/operation manager	33%
			QS/Estimator	42%
Years of construction industry experience	Less than five years	60%	10-20 years	13%
	6-10 years	13%	Over 20 years	13%
Size of organisation	Less than ten employees	33%	50-99 employees	20%
	10-19 employees	0%	100 or more employees	27%
	20-49 employees	20%		

New Zealand now has over 26,000 small construction businesses, which employ around 90,000 people or 41% of the workforce. Only about 100 large enterprises employed more than 100 workers. SMEs (less than 19 workers) (33%), 20-99 employees (20%), and large enterprises (47%) staff the NZ construction industry. Though the study's sample size is small (15 respondents), the respondents' profile matches the national one. Nearly half of respondents (40%) had at least six years of building sector experience in NZ, assuring the study's conclusions are unbiased and reliable for future reference and research. Circular economy is a new concept, and its adoption in construction depends on these people and parties making an important decision.

Table 2: The identified list of critical success factors for implementing circular economy in NZ built environment

ID		RII	Mean Score
CSF16	Awareness of circular economy	0.76	3.78
CSF9	Collaborative working and engagement with every stakeholder	0.73	3.67
CSF5	Engagement of standard components from upstream players	0.71	3.56
CSF13	The extensive data system	0.71	3.56
CSF2	Design for flexibility, adaptability, and resistance	0.69	3.44
CSF8	Effective integration of circular economy procurement strategies	0.69	3.44
CSF14	BIM supporting information management	0.69	3.44
CSF3	Reuse and recycling	0.67	3.33
CSF7	Integration of circular economy principles into business model design	0.67	3.33
CSF10	Innovative supply chain strategies – e.g., reversed logistics	0.67	3.33
CSF1	Design for deconstruction/disassembly	0.64	3.22
CSF6	Early design with lifecycle-costing and renewable design – e.g., passive houses	0.64	3.22
CSF12	Circular economy specialists	0.64	3.22
CSF19	Flexible incentive policies to encourage adoption of circular economy construction	0.64	3.22
CSF20	A market for circular economy	0.64	3.22
CSF11	Inventory management and control	0.62	3.11
CSF4	Modularity and prefabrication	0.60	3.00
CSF17	Certification of secondary materials	0.60	3.00
CSF18	Development of a practical circular construction framework	0.60	3.00
CSF15	Online waste sharing platform	0.58	2.89

5 Discussion

In New Zealand, there are many critical success factors for CE implementation in the construction industry. The RII rankings of the 20 CSFs for implementing CE in New Zealand are summarised in Table 2.

All CSFs passed the Cronbach Alpha test, which gave 0.964, suggesting reliable data. The respondents' agreement and convergence of replies for the 20 CSFs gave us the statistical validity to look at the data as a whole for further analysis. Since all CSFs had a mean score of more than 2.5, 20 CSFs were considered significant in CE management in NZ. Furthermore, CSF16 (awareness of circular economy), CSF3 (Reuse and recycling), CSF5 (Engagement of standard components from upstream players) and CSF9 (Collaborative working and engagement with every stakeholder) are the top four most important CSFs for implementing CE in NZ construction projects, according to the RII and mean scores as shown in Table 2. These CSFs will be addressed after that.

Awareness of circular economy, which had the highest mean score of 3.73, is the most important CSF for implementing CE in NZ. Blismas (2007) showed that appropriate, relevant knowledge of project participants is an important CSF for adopting CE principles. The circular economy is co-created by many individuals in the project. These project partners provide interdependent duties and services at various supply chain stages in circular construction. Designers and quantity surveyors, in particular, should be familiar with the specification of materials allowing for the specific building components to be recycled or reused by the end of the project's economic life. Architects also need to ensure the information required at different stages of a project's lifecycle is available and apply the CE principles in the design. To contribute to module design and manufacturing to the project's circularity and modular construction aims, manufacturers' engineers must comprehend CE principles and apply them in formulating their manufacturing concepts.

The second most important CSF for implementing CE in NZ is reuse and recycling, with a mean score of 3.67. Circular economy changes how materials are selected, manufactured, and used in the built environment, so the building can perform better and serve longer. Decisions on new products that consume virgin materials should be carefully made, and the reusability of the existing asset is assessed. Reuse and recycling can be achieved with a closed technical resource cycle. The cycle allows materials and components from a product's end of life to be reused for a new purpose or recycled back to the manufacturer to make new products. The circularity of construction is also supported by integrating with other industries' resource and reuse cycles. It is not just about one manufacturer changing one product, but all the interconnecting suppliers that form our infrastructure and economy coming together (Ellen MacArthur Foundation, n.d.).

Engagement of standard components from upstream players, which had a mean score of 3.60, is the third most important CSF for adopting CE in NZ. Blismas (2007) identified early involvement as a critical CSF for circular economy adoption in Australia. According to Hwang et al. (2018), CE and modular construction are incompatible with some building projects. Consequently, it is vital to understand the relevance of circular modular construction for building projects based on relevant data. Early knowledge of the client or owner's circular and modular needs in a project permits comprehensive upfront planning and design for circularity and offsite construction. For example, to assure reuse beyond the planned economic life of the building, the customer or owner must realise that construction materials must be circular and recyclable (Kyröet al., 2019).

The fourth most important CSF for implementing CE in NZ was collaborative working and engagement with every stakeholder, with a mean score of 3.60. Collaboration, communication, and information sharing are the most well-documented CSFs for diverse creative construction endeavours (Wuni and Shen, 2022). Members of the project team located at various supply chain stages are always informed of crucial decisions and processes during the implementation of the circular economy due to collaborative working and information exchange (Norouzi et al., 2021). NZ construction accord 2020 also highlights the importance of building trust relationships by working collaboratively and inclusively.

Strategies: The top three strategies have been identified as integrated approaches for CE practice implementation with various stakeholders' engagement such as academia, government, and organisations.

Upskilling: To successfully conduct circular construction projects, construction firms need to upskill and supply appropriate workers with the necessary abilities and knowledge through higher education or on-the-job training. In an environment that supports thriving mental health and wellbeing, construction firms should actively participate in reshaping the business models which can support the development of trusted, competent professionals and review the whole value chain to accommodate new procedures for creating, delivering, and capturing value in CE projects while minimising waste and resource depletion.

An integrated delivery model for the reusing/recycling: The two powerful integrated data platforms developed by the NZ government, namely Integrated Data Infrastructure (IDI) and Longitudinal Business Database (LBD), can link all the stakeholders across the value chain (e.g., contractors, manufacturers, and suppliers), allowing for further collaboration and sharing information of standard component design/construction/delivery under an integrated delivery model. To promote early commitment, users can generate insights from integrated data such as project CE targets and goals to facilitate the reuse/recycling concept implementation.

Early involvement of stakeholders: Stakeholders like designers, consultants, contractors, and suppliers should work together early on. Customers, suppliers, and contractors should verify that materials are sustainably obtained, including eliminating hazardous substances and increasing the number of recycled materials.

6 Conclusion and Further Research

The research also highlighted strategies linked with the critical success factor, giving project stakeholders practical information when adopting a circular economy in New Zealand’s built environment. The results contribute significantly to the theoretical, empirical, and practical understanding of the circular construction economy in the New Zealand context and demonstrated the importance of planning and design in attaining circularity in building projects.

The research also gave critical information to project stakeholders for establishing circular building projects by identifying the exact stages linked with the most essential success criteria and developed the first set of important success factors for promoting a circular economy in the construction industry.

6.1 Limitations of the study

The highlighted critical success factors were prioritised according to expert opinion rather than case studies. The list may not be exhaustive, though due diligence was done. Next to the above contributions, this research has various limitations that are now detailed. First, the analytical sample includes industry practitioners, with QS accounting for close to half of the respondents, while architects and engineers who might affect circularity from the design stage are not clearly defined. Second, this study is a quantitative one with a limited sample size with no survey interviews. Future research can incorporate interviews to increase generalizability and give beneficial recommendations.

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A Review of Residential Construction Waste Reduction

Hadeel Albsoul [1*], Dat Tien Doan [1], Itohan Esther Aigwi[1] and Ali GhaffarianHoseini [1]

[1]School of Future Environments, Auckland University of Technology,
WZ Building, 34 St Paul Street, Auckland 1010, NEW ZEALAND

hadeel.albsoul@autuni.ac.nz; dat.doan@aut.ac.nz; esther.aigwi@aut.ac.nz, ali.ghaffarianhoseini@aut.ac.nz

* Corresponding author

Abstract:
The residential construction sector in New Zealand and worldwide is experiencing increased criticism about generating substantial waste that can cause significant environmental concerns. Accordingly, construction waste (CW) reduction strategies have been widely encouraged by researchers as a sustainable solution to managing CW. This paper provides a comprehensive overview of residential CW reduction (RCWR) concepts using keyword mapping analysis. The key objective of this paper is to understand the concepts of RCWR. Around 87 articles were extracted from the Scopus database and analysed using the VOSviewer software. Co-occurrence analysis of keywords resulted in three main themes for RCWR concepts: (1) CW estimation; (2) Environmental assessment based on the two primary concepts of environmental benefit and impact; (3) Design decisions for RCWR. The results indicate that informed design decisions regarding methods and building materials is the most critical concept acknowledged by researchers for effective RCWR. Furthermore, future research areas highlighted the need to explore the contribution of energy-efficient building materials to RCWR. These results provide valuable information to support RCWR's future policy formulation and deeper insights into research direction.

Keywords:
Construction waste, Residential construction, Keyword mapping, Waste reduction.

1 Introduction

Residential construction has a fundamental role in boosting employment, economy, and social development (Arestis and González-Martínez, 2015). The construction of buildings facilitates the consumption of total global natural resources (Horvath, 2004). Along with resource consumption, construction activities generate significant waste (Wuyts et al., 2019).

The demand for residential construction is following worldwide trends in urbanisation and population growth, which is forecasted to proceed until 2050 (Marinova et al., 2020). In particular, New Zealand's residential construction sector contributed around 60% of the total construction value in 2020 (Ministry of Business, Innovation and Employment – MBIE, 2021). The Building Research Association of New Zealand- BRANZ (2020) estimated that CW contributes up to 50% of total waste in landfills. From this perspective, the principle of CW reduction has been proposed as a critical element for sustainable construction (Lu et al., 2016). Moreover, CW reduction is prevalent in the residential construction sector due to its significant share of economic contribution and waste generation (Hossain and Poon, 2018).

Existing research lack comprehensive reviews specifically focused on waste reduction in the residential sector. Therefore, this study aims to provide a review of the concepts in residential construction waste reduction systematically. Furthermore, this review focuses on reducing waste from new residential construction activities; hence, demolition or renovation waste is out of the review scope. Accordingly, the term residential construction waste reduction (RCWR) will reflect the focus of this review. The findings are expected to provide valuable information to support RCWR's future policy formulation and offer insights into the research direction.

2 Methodology

This paper combines keywords mapping and critical review analysis methods to provide a comprehensive review of literature. Methodology steps are illustrated in Figure 1.

2.1 Data Collection

Data collection follows a systematic search strategy that is restricted to Scopus database, identified keywords, and an inclusion criteria. Scopus is the only database with large-scale peer-reviewed articles in all disciplines (Schotten et al., 2017). Peer-reviewed articles establishes the credibility to research findings and reduces bias (Soderberg et al., 2021).

Keywords search is the most critical step in bibliometric analysis because it has major impacts on the results of the study. This paper used generic literal concepts, Boolean operators, and truncation technique to identify the optimal search criteria. Initially, a fundamental literature review was conducted to find related generic literal terms. First, while this research focuses only on construction waste, literature tends to group the waste products from demolition and construction activities together (Park and Tucker, 2017). Hence, the term 'construction and demolition waste' will be used.

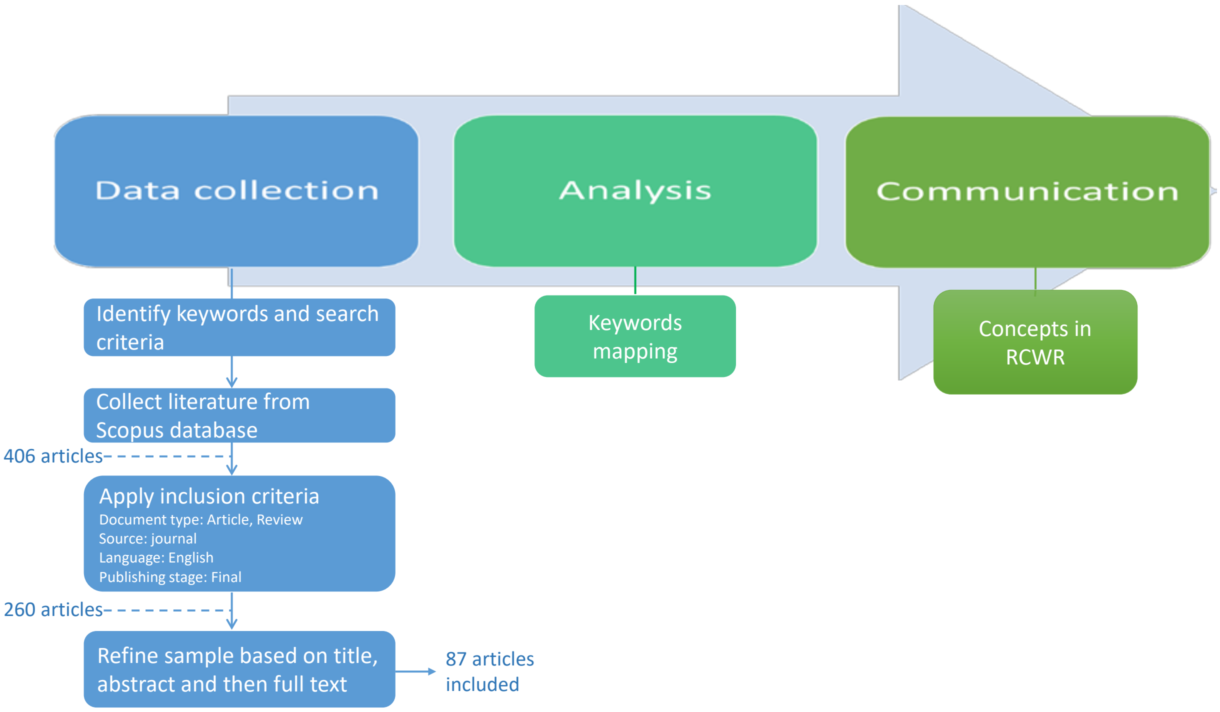

Figure 1. Methodology steps

Moreover, the publication related to waste reduction would alternatively use a different expression to refer to its fundamental concepts in their work aspect. For example, Ajayi et al. (2014) mentioned that waste reduction is a strategy in construction waste management that minimises waste at the source. Additionally, waste reduction is the optimal approach in the waste hierarchy following the 3Rs principle (reduce, reuse, recycle) (Kabirifar et al., 2020). Some literature suggested prevention and minimisation strategies (Esin and Cosgun, 2007;

Laovisutthichai et al., 2020) and the “zero waste” principle (Umar et al., 2017) as powerful tools in construction waste reduction. Other literature highlighted waste reduction as one of the objectives of a “circular economy” (Organisation for Economic Co-operation and Development-OECD, 2020).

In addition, keywords such as: “sustainable construction” and “sustainable built environment” have been increasingly regarded for promoting sustainable waste management practices including waste reduction (del Río Merino et al., 2010; Dahiru et al., 2012). Hence, the final keywords combination applied for the search criteria is: (((“Construction waste” OR “construction waste management” OR “construction waste minimi*” OR “waste prevent*” OR “source reduc” OR “construction and demolition waste” OR “construction and demolition waste management” OR “waste reduc*” OR “material* waste” OR “waste minimi*” OR “3Rs principle” OR “zero waste” OR reduc* waste”) OR (“sustainable built environment” OR “circular economy” OR “sustainable construction”) AND (“residential build*” OR “hous* construction” OR “residential construction” OR “residential project*” OR “residential build* construction”))).

The keywords-based search in Scopus returned 406 related publications. An initial filter criterion was created with limitations to include only fully published papers, document type of review and article, and document source of journals. After applying the initial filter criteria, a total of 260 papers were retrieved.

Further reading the title and abstract, and then full text to refine the resulting articles based on the research objectives, 87 articles were included. Only papers focused on residential construction and related waste reduction were included. Articles related to waste reduction of demolition or renovation in residential construction projects were excluded.

2.2 Keywords Mapping

The keywords co-occurrence map is a valuable tool that effectively support data mining and illustrates the main topics within selected research area (X. Wang et al., 2020). The visual mapping of keywords and their relationship displays the rationale of research themes (Jin et al., 2019). To create the keywords co-occurrence map, the unit of analysis is set to ‘all keywords’ and ‘full counting’ method. A minimum of 3 is set for the occurrence of the keyword. Of the 909 keywords, 108 met the threshold. For each of the 108 keywords, the total strength of co-occurrence links with other keywords are calculated by VOSviewer.

Next step is data cleaning to verify selected keywords, remove duplicates, and provide more comprehensible and defined keywords analysis. As a result, 37 keywords in total were included. Included keywords are visualised, in Figure 2, based on the number of keyword occurrences using the VOSviewer.

3 Analysis of Keyword Map

Researchers have formulated different estimation methods to examine CW generation and understand the effects on CW management performance. The variation in estimation methods is because of identifying different indicators to waste generation. For example, the floor area is the most widely used indicator for estimating CW generation in RCWR literature (Sáez et al., 2014; Li et al., 2013). However, an estimate of CW generation supports informed design decisions that establish benchmarks for a suitable selection of residential building materials (Cherian et al., 2020).

Furthermore, Quiñones et al. (2021) revealed that forecasting CW generation is a key requirement of the project waste management plan. In addition, RCWR could be optimised by creating a project-specific waste management plan that includes all construction phases (Ratnasabapathy et al., 2020; C. S. Poon et al., 2004).

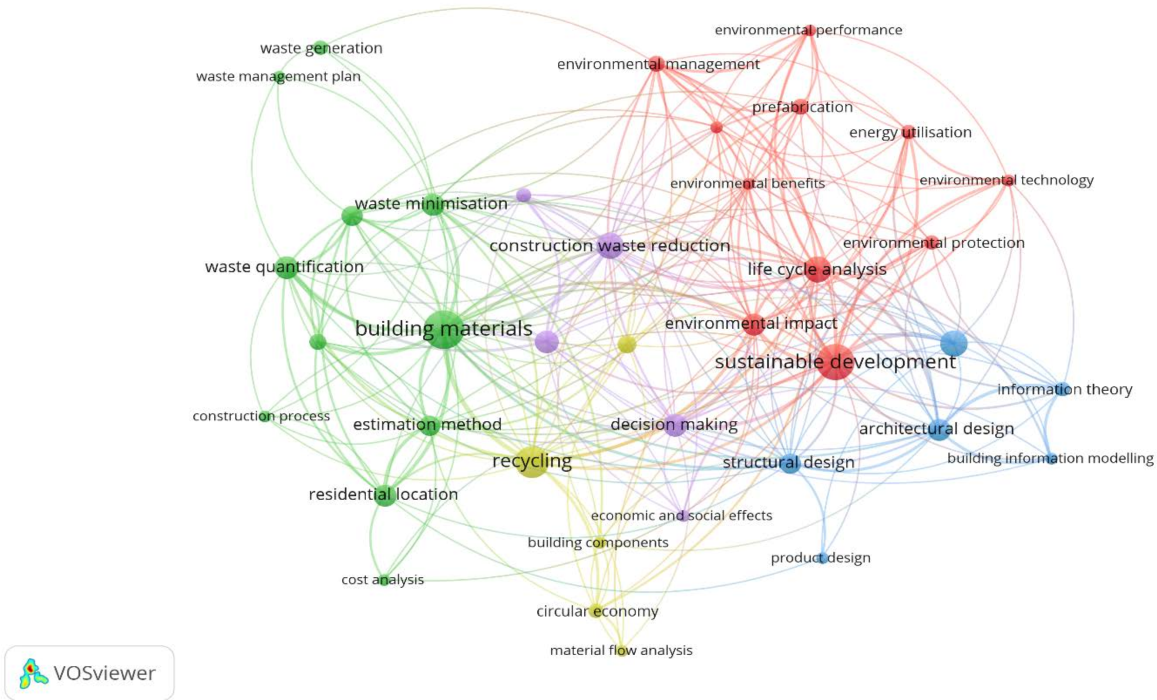

Figure 2. Keyword occurrences map.

Current conventional methods and building materials in residential construction are causing considerably severe environmental impacts (Q. Wang et al., 2020). Therefore, prefabrication is receiving growing interest as a residential construction method that supports waste reduction at the source (Jiang et al., 2019; Zhai et al., 2014). Hence, Nan and Jie (2020) and Hao et al. (2021) suggested that prefabrication enhances achieving effective RCWR, cost reduction in CW management, and minimises the environmental impacts of CW.

Likewise, Kedir and Hall (2021) suggested that materials designed through prefabrication improve the overall residential project lifecycle by contributing to RCWR and materials consumption. Cherian et al. (2020) and Aye et al. (2012) indicated that prefabricated materials in residential construction showed a significant reduction in materials use and contributed to low energy consumption.

Moreover, the concept of life cycle analysis (LCA) emerged recently as an environmental assessment tool. LCA is generally employed to evaluate the environmental impacts or benefits of residential construction methods and materials. For example, Kakkos et al. (2020) employed LCA to evaluate the potential of utilising waste materials as secondary resources in residential construction. On the one hand, contributing to RCWR, on the other hand, maximising environmental protection and energy efficiency. Maximising the environmental benefits contribute to achieving sustainable construction.

The concept of information theory is a design approach observed in studies that incorporated mathematical algorithms to optimise waste reduction in design. For example, Manrique et al. (2011) applied such an approach in frame design and endorsed a wood waste reduction result. The study concluded that material waste reduction contributes to economic and environmental benefits, which promotes sustainable construction. Another application in information theory is the barcode approach by Li et al. (2003) to control and reduce on-site construction wastes through incentives.

H. Liu et al. (2018) suggested building information modelling (BIM) to optimise design planning and reduce material waste. For instance, developing material passport tools with BIM to optimise waste material reduction strategies (Honic et al., 2019). Atta et al. (2021) described a material passport as a tool that details building material installation, during construction, and recovery alternatives at the end-of-life stage. Software tools such as BIM enhance the design process and RCWR performance. For example, Quiñones et al. (2021) proposed that BIM is a valuable tool to estimate CW during the early stages of design.

Further, Seeboo (2022) states that poor design decisions contribute 30% of generated construction waste. Lekan and Segunfunmi (2018) supported this view and indicated that efficient designs requiring no alteration or rework significantly reduce CW. Georgiadou (2019) revealed that BIM is an assessment tool helpful in managing digitised data across the project lifecycle and guiding design decision-making. Residential design approaches that adopt information modelling enables designers to visualise complex design and construction processes, which increases design efficiency (Baldwin et al., 2009). In addition, Baldwin et al. (2008) suggested that considering lifecycle assessment in terms of cost, environmental, and social impacts support informed decision-making by designers.

Another efficient design approach is three-dimensional printing (3DP) technology. Zhang et al. (2019) have endorsed the implementation of 3DP in obtaining sustainable residential construction design. However, Zhang et al. (2019) pointed out that the 3DP could have limitations to the quality and functionality of the required material. Tahmasebinia et al. (2018) described 3DP as a sustainable residential construction practice for the benefits of waste reduction and the capability to produce materials of high precision design characteristics, which reduce construction costs and boost efficiency.

In the design phase, performing efficient recycling and reduction strategies starts with a CW management plan that includes incentives to promote implementation (Kakkos et al., 2020). Sáez et al. (2014) noted that on-site CW sorting is the best way to optimise the number of recycled materials. The study suggested that allocating an adequate number and size of bins in working site areas is significant to recycling practice. Lau et al. (2008) found that poor site management practices hindered efficient waste data collection and recycling decisions are cost-driven instead of environmental benefits. Further suggestion by Boser and El-Gafy (2011) is to identify and prioritise materials for recycling in the waste management plan.

Lehmann (2012) and Arora et al. (2019) focused on facilitating the reusing of building components and materials to reduce CW and allow for recycling to enhance the potential of circularity. Material flow analysis is described by Tazi et al. (2021) as an assessment method to understand the stock and flow of building materials, CW generation, and material recyclability in residential construction. In addition, Tazi et al. (2021) highlighted that information collected about the consumption, use, and landfilled residential building materials offers new perspectives in evaluating the construction processes and improving source reduction strategies.

Improving decision-making in designing and selecting building components enhances sustainability performance and RCWR. Gilani et al. (2022) developed an assessment tool to support the sustainability of, design and selection, decision-making in facade systems. In terms of decision-making, Shooshtarian et al. (2021) highlighted the lack of knowledge of requirements in residential construction decision-making and sustainable planning.

Sustainable decision-making in residential construction practices is necessitated by the rise in environmental awareness and costs associated with CW management (Gavilan and Bernold, 1994). The study suggested that decision-makers need information about sources of CW to assess efficient planning for waste reduction at the source. Furthermore, Gavilan and Bernold (1994) argued that indicators representing environmental criteria have limited effect in most decision-making models because of the challenging environmental impact quantification. Current environmental assessment tools have limited performance due to the difference in terms of issues, criteria and weighting (Wallhagen and Glaumann, 2011). For example, Yan et al. (2012) challenged the decision-making assessment criteria in green residential buildings for allocating higher weight to energy efficiency than waste reduction.

RCWR is one of the environmental benefits of applying innovation in residential construction (Sitek and Tvaronavičienė, 2021). Umar et al. (2018) and Sun et al. (2019) revealed that cost could hinder the implementation of RCWR practices; hence it is vital to budget the CW management cost earlier in project planning (Jingkuang et al., 2012). For example, J. Liu et al. (2019) indicated that integrating budgeting for CW reduction in bidding is valuable in informed decision-making.

Sufficient RCWR can be enhanced through adequate project management strategies such as efficient material time delivery and storage and sustainable procurement to prevent loss and enhance material reuse (Umar et al., 2018). In addition, improvement in waste management practices requires support in regulation, policy formulation and innovative technology. An earlier study by Jaillon and Poon (2008) aimed to assess the sustainable aspects (economic, environmental and social) of prefabrication. Results indicated that an associated increase in cost when adopting a sustainable construction method is balanced by reducing waste, time, and site activities resulting in improved quality and environmental performances.

4 RCWR Concepts and Future Research Direction

It is observed that residential CW varies in weight and composition. The differences in residential design features, construction methods, and building materials explain the variations. The review's findings suggest that informed design decisions, sustainable construction methods, and early waste management planning are the key strategies to achieving sufficient RCWR. CW estimation is a necessarily preceding design step because valuable information about the material waste composition and weight are critical in featuring residential designs and benchmarking for RCWR. Thus, an actual estimation for CW is a key concepts in RCWR.

Moreover, residential design decision concepts are categorised into construction methods and building materials, and both need to be assessed based on economic, environmental and social principles, which comprise the concept of sustainable construction. It can be observed that waste management planning contributes to effective performance in RCWR.

The environmental assessment based on the two primary concepts of environmental benefit and impact is critical to decision-making. LCA is the most sustainable and effective practice for pursuing environmental assessment. However, the findings suggest that the environmental assessment should be through the project lifecycle and against unique criteria for RCWR. The significance of LCA in RCWR is the capability to examine the environmental impact of sustainable vs. conventional construction methods or materials.

For future research direction, innovation manufacturing of building materials and sustainable construction practices such as prefabrication has been approved to contribute to RCWR and energy efficiency. However, there is still a gap in the literature that addresses the benefits and impacts of innovative manufacturing and sustainable construction practices on RCWR. Integrating the principles of sustainable construction and energy-efficient building materials in the design maximises the environmental, social, and economic benefits for RCWR. Additionally, the relationship between energy-efficient building materials and RCWR has not been fully explored yet but is receiving growing interest in this research area.

5 Conclusion

The review highlighted three key concepts in RCWR that are: (1) CW estimation; (2) Environmental assessment based on the two primary concepts of environmental benefit and impact; (3) Design decisions for RCWR. Estimating CW generation is valuable in benchmarking RCWR strategies and supporting design for RCWR decision-making. The environmental assessment for methods and materials in residential construction to understand the associated benefits and impacts is valuable in making informed design-decisions. Design-decisions are critical to achieving effective RCWR and could be enhance through efficient CW management planning.

Future research could be directed into evaluating building materials manufacturing and sustainable construction practices on RCWR. Another research area is exploring the opportunities for achieving RCWR using energy-efficient building materials.

Despite the systematic analysis of current RCWR research, various limitations exist. First, sourced publications were only from the Scopus database, which may have limited the broadness of collected data. Second, there is a possible mis-formatting of data in the data cleaning step because of the similarity in idiomatic expressions.

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Challenges to Zero Carbon Refurbishment of Existing Buildings in New Zealand: An Exploratory Study

Thao Thi Phuong Bui[1*] Niluka Domingo[1] Suzanne Wilkinson[1] and Casimir MacGregor[2]

[1]School of Built Environment, Massey University, Auckland, 0632, New Zealand
[2]Building Research Association of New Zealand, Judgeford, Porirua, 5240, NEW ZEALAND

T.Bui@massey.ac.nz; N.D.Domingo@massey.ac.nz; casimir.macgregor@branz.co.nz; S.Wilkinson@massey.ac.nz

* Corresponding author

Abstract:
The construction sector has a key part to play in alleviating climate change and achieving net-zero greenhouse gas (GHG) emissions by 2050. Building refurbishment is crucial as the majority of the existing building stock will still be in use in 2050. Over the past two decades, studies on zero carbon refurbishment have provided important technical information but given little attention to other aspects, such as the current industry practices on carbon-reduction refurbishment and building stakeholders' decision-making on reducing carbon emissions in refurbishment projects. In response to this important issue, we investigate opportunities and challenges in reducing carbon emissions in the refurbishment process by undertaking an exploratory study using seventeen semi-structured interviews with construction experts within Aotearoa New Zealand. Even though refurbishing existing buildings presents a significant opportunity to reduce embodied carbon emissions by reusing existing buildings' components, it must still carefully consider embodied carbon emissions of newly-added construction materials and products. Our research indicates several challenges to reducing carbon emissions in the refurbishment process, including (1) inexplicit carbon goal setting, (2) ineffective building condition assessment, (3) deficient and incomprehensive relevant whole-of-life carbon information to support the decision-making, and (4) inconsistent and ambiguous carbon-calculation guidelines and benchmark. A comprehensive decision support framework incorporating carbon-reduction initiatives for building refurbishment is suggested for future work. This research contributes to theoretical and practical knowledge by providing recommendations to enhance industry practices in reducing whole-of-life carbon emissions for building refurbishment.

Keywords:
carbon emissions, carbon reduction, existing building, refurbishment, zero carbon

1 Introduction

In the light of climate change, the world wrestles with reducing global warming to no more than 1.5 degree and achieve net-zero greenhouse gas emissions by 2050. Having responsibility for more than 40% of international energy use and one-third of global GHG emissions, buildings contribute significantly to global GHG emissions (United Nations, 2009). In New Zealand, research has highlighted that the construction sector contributes roughly 16% of New Zealand's GHG emissions (MBIE, 2020). To meet targets of reducing emissions by 2050, there is a need to maximise carbon reduction in the design and construction of buildings. Moreover, implementing zero carbon strategies for refurbishing existing buildings should be prioritised as refurbishment is a better carbon mitigation measure than constructing a new build (Hasik *et al.*, 2019). For instance, a life cycle assessment of an office building in Wellington, New Zealand, showed that the refurbishment building saved approximately 3100 tonnes of carbon emissions compared to a new building (BRANZ, 2018). Thus, this study focuses on understanding the opportunities and challenges of undertaking zero carbon refurbishment (ZCR). The term “refurbishment”, which represents a “modification and improvement to an existing building to bring it up to an acceptable condition” (ISO 2010; BS_EN 15978 2011). In this study, refurbishing existing buildings to reduce the highest level of carbon reduction is called “zero carbon refurbishment”.

Several opportunities exist for reducing carbon emissions in building refurbishment, such as improving building energy performance and using low-carbon materials and products (Giesekam *et al.*, 2016, Luo *et al.*, 2019). However, implementing ZCR also faces challenges in mitigating carbon emissions, such as enabling building regulations, financial barriers, and expected user comfort (Bui *et al.*, 2021a). These challenges can be critical for making carbon-reduction decisions in the refurbishment process. In reviewing the literature, there is little consideration for the opportunities and challenges regarding integrating whole-of-life carbon reduction in refurbishment decision-making practices. This paper examines opportunities and challenges in reducing carbon emissions in the refurbishment process in New Zealand. The remaining part of the paper proceeds as follows: (1) review the literature, (2) describe the methodology used in the study, (3) report findings and discussion, and (4) outline the conclusion and recommendations for further research.

2 Literature Review

Two main opportunities for reducing carbon emissions in building refurbishment include operational and embodied carbon emissions. Improving building energy performance may be the most effective and common measure to reduce operational carbon emissions in building refurbishment. It can be achieved mostly via upgrading energy-efficient systems, implementing passive design, and installing renewable energy technologies (Pan and Li, 2016, Luo *et al.*, 2019). However, improving building energy performance requires extra materials and systems that increase the embodied carbon of the whole building (Asdrubali *et al.*, 2019). Therefore, it is argued that using alternative materials with lower embodied carbon, such as reusing existing building elements and utilising recycled materials, is also critical for refurbished buildings (Giesekam *et al.*, 2016, Moncaster *et al.*, 2019). Although debate continues about prioritising operational or embodied carbon reduction strategies for building refurbishment, the building stakeholders’ perspectives on this matter have received little attention in the research literature.

Many studies have examined the barriers and challenges to zero carbon buildings, including new buildings and refurbishing existing buildings that focus on improving energy efficiency and carbon reduction worldwide (Osmani and O’Reilly, 2009; Pan and Pan, 2021; Bui *et al.*, 2022a). Particularly for the refurbishment, Davies and Osmani (2011) investigated the key challenges for achieving low carbon housing refurbishment in England from architects’ perspectives. It is concluded that high capital costs for micro-generation technologies and energy-efficient materials, the disparity in tax between new build and refurbishment, and the complexity of the United Kingdom (UK)’s existing housing stock are the most considerable challenges. But Mokhtar (2019) was more interested in identifying both the technical and the financial difficulties when developing refurbishment guidelines within the context of The United Arab Emirates (UAE). The technical challenges include the variation in construction systems, the quality of construction, and energy modelling challenges. The financial challenges include the subsidised price for electricity, the cost estimation for various energy conservation methods, and the payback for installing local renewable energy sources. However, these studies pay attention to the common challenges of adopting zero carbon initiatives within the construction sector. Few studies have investigated carbon-reduction refurbishment practices and building stakeholders’ decision-making on balancing the carbon-reduction factor with others in their decision-making for refurbishment. Not to mention, various constraints and limitations influence the refurbishment process that focuses on zero-carbon strategies (e.g. project objectives, budget, and available refurbishment techniques, approaches, and expertise). This paper contributes by identifying carbon-related opportunities and challenges found in different areas of the pre-design and design stages of the refurbishment process, specifically in the New Zealand case.

3 Research Methodology

The exploratory study employed a qualitative research method, using semi-structured interviews with the building experts to examine opportunities for and challenges in reducing carbon emissions in building refurbishment in New Zealand. The qualitative research method was chosen because it is particularly useful for exploring and seeking new insight into the research topic and providing reliable and comparable qualitative data when working with a complex issue such as carbon reduction for building refurbishment (Saunders et al., 2016; Gray, 2018).

We purposively recruited participants from various parts of the construction sector to provide a comprehensive view, covering government agencies and multiple-sized construction companies. Participants were also required to have knowledge and expertise in carbon reduction and sustainable construction. Eventually, 11 online and 6 in-person interviews were conducted with construction experts between December 2020 and August 2021, ranging from 30 to 75 minutes. Participants received an invitation via email then asked to carefully read the project information and sign the written participant consent form following standard ethics protocols. Oral consent was also obtained during the interview. The interviews included questions about: (1) participants' background, and (2) participants' perspectives on opportunities and challenges to reducing carbon emissions in building refurbishment. The sample size is consistent with qualitative research sampling procedures (Galvin, 2015; Creswell and Poth, 2016), confirming that 12-15 interviews are appropriate for data saturation. Table 1 illustrates an overview of the participants, including the codes used later in the paper to report the findings.

Table 1. Overview of the respondent type and codes (Source: authors)

Respondent type	Codes
Client presentative (public sector)	LG1, LG2, LG3, HA1
Client presentative (private sector)	RE1, RE2
Architect	AD1, AD2, AD3, AD4
Contractor	C1, C2
Manufacturer/Developer	M3, M4
Project manager	PM1
Engineer	EC1
Non-profit building organisation presentative	NGO1

Thematic analysis was utilised for data analysis. Thematic analysis is a foundational method for qualitative analysis. It is often used to identify, analyse, organise, describe, and report themes within the interview data set. To conduct a trustworthy thematic analysis, we followed a step-by-step approach demonstrated by Nowell *et al.,* (2017). Interviews were audio-recorded with permission from the participants and then transcribed. Transcripts and notes were logged and coded using NVivo 12. The themes from data analysis include opportunities and challenges in reducing carbon emissions in building refurbishment in New Zealand.

4 Findings and Discussion

4.1 Opportunities for reducing carbon emissions in building refurbishment

The first set of analyses examined the participants' perspectives on the opportunities for reducing carbon emissions in building refurbishment. When the participants were asked to elaborate on design opportunities to reduce carbon emissions in building refurbishment, most answers focused on lowering operational carbon emissions rather than considering whole-of-life embodied carbon emissions. A common view amongst interviewees was that reusing the existing building, such as keeping the structure and other building components, like the glazing system, was the best way to lower embodied carbon emissions. Thus, for our participants, the primary focus for building refurbishment was maximising operational carbon reduction by improving energy efficiency. Another way our participants sought to reduce carbon emissions was by using environmentally sustainable products, which a minority of the participants reported. Table 2 demonstrated several participants' views on design opportunities to reduce carbon emissions in building refurbishment.

Table 2. Examples of participants' views on design opportunities to reduce carbon emissions in building refurbishment (Source: authors)

Design opportunities	Illustrative quotes
Reusing existing buildings (e.g. building structure, envelope, services, etc.)	"The first thing is that we try to reuse the building where we can. That is the lowest carbon development in practice so far. We've refurbished existing buildings with keeping the structure, and we keep the glazing systems" (RE1).
Improving energy efficiency	"Historically, the buildings haven't been well insulated. They lose a lot of heat, which is hard to heat and cool. Thus, you would consider where the thermal envelope will go throughout refurbishment for low-carbon" (EC1).

While preliminary, these findings help us to understand the current practices in selecting refurbishment design opportunities to lower carbon emissions of building refurbishment in New Zealand. However, one of the issues that emerged from these findings was the existing priority on reducing operational carbon emissions. This finding is consistent with that of (Moncaster *et al.*, 2019, Röck *et al.*, 2020), confirming that the global construction sector currently focuses on optimising 'operational' energy use of buildings and the associated carbon emissions rather than assessing the whole-of-life carbon emissions. Moreover, deep energy refurbishment is associated with significant carbon emissions, mainly due to the use of energy-intensive construction materials. Measures to promote energy efficiency refurbishment may not reduce overall environmental impacts. This appears to be not only the case of New Zealand (Ghose *et al.*, 2017, Ghose *et al.*, 2019, Ghose *et al.*, 2020), but also other advance economies such as the UK (Pomponi *et al.*, 2015), Sweden (Wallhagen *et al.*, 2011) and Italy (Ardente *et al.*, 2011). Therefore, building refurbishment towards zero carbon must consider whole-of-life embodied carbon reduction of newly-added construction materials and products, alongside operational carbon reduction associated with energy use and the reuse of existing building components.

4.2 Challenges to reducing carbon emissions in building refurbishment

Issues related to ineffective decision-making in the refurbishment process were particularly prominent in the interview data. Four broad sub-themes emerged from the analysis: (1) inexplicit goal setting, (2) ineffective building condition assessment, (3) inadequate design information and consideration of whole-of-life carbon reduction, and (4) inconsistency in calculating and accounting carbon emissions for building refurbishment.

4.2.1 Inexplicit goal setting

A common view amongst interviewees was that the building refurbishment practices generally lacked clear goals and objectives in the initial planning stage. Setting a carbon-reduction goal was necessary for a successful building refurbishment that focused on reducing carbon emissions. It was also important to note that specific carbon goals should be established at the earliest stage of the refurbishment process. Table 3 shows participants' perceptions on goal setting to reducing carbon emissions in building refurbishment.

Table 3. Examples of participants' perceptions on goal setting to reducing carbon emissions in building refurbishment (Source: authors)

Perceptions	Illustrative quotes
There is a requirement for setting embodied carbon emissions targets	"The first thing to do is to set some goals and targets, saying that a 20% reduction in embodied carbon emissions must be achieved. You must set an energy goal, a water goal, or a carbon goal for embodied and operational, a percentage reduction over a benchmark" (AD1).
Specific carbon goals should be established in the design brief at the earliest stage of the refurbishment process	"First is clarifying the briefing, ensuring all design aspects stated in brief are being worked. What rating system are you going to use? What are the pros and cons, or the benefits or costs associated with making design decisions? How do those decisions align with the client's values?" (EC1).

This finding confirms the importance of setting the right goal in the early stages of the refurbishment process, which is in line with previous studies found in the literature (Ferreira *et al.*, 2013, Bui *et al.*, 2021b). Goal setting, where refurbishment objectives and criteria are defined, is the most critical stage because all subsequent stages during the refurbishment process are about implementing the set goal. However, our present research strongly emphasises the inexplicit carbon goal setting in the current New Zealand industry practices can lead to several barriers affecting the design decisions about carbon benchmarking, such as the trade-off between cost and carbon performance and identification and performance assessment of refurbishment solutions.

4.2.2 Ineffective building condition assessment

Several problems were identified regarding ineffective building condition assessment of existing buildings, which resulted in uncertainty in the design and implementation of building refurbishment. First, the current building condition was assessed mostly against the performance requirements of the New Zealand Building Code, which did not include carbon performance metrics and benchmarks. The historical data regarding building performance, such as energy bills, water bills and maintenance costs, was often inadequate due to poor building management practices. These practices led to insufficient and inconsistent performance assessments for existing buildings before and after refurbishment. An interviewee said about this issue:

> *We don't develop a brief that addresses performance issues. There was one upgrade where we put an installation, but we didn't do any calculations on what the consumption reduction would be or anything quantifiable (LG2).*

Another reported issue was the lack of a comprehensive existing building condition assessment. As opposed to constructing new buildings, most participants agreed that the constructability of building refurbishment was one of the most significant factors. Especially for the major refurbishment involving the upgrade of existing features and the construction of newly-added components, deficient existing building data collection and assessment caused the selection of inappropriate refurbishment solutions and unforeseen constructability problems in the construction process. These characteristics were described in the following evidence:

> *The challenges we had with stripping the building back to its structural frame and building back up from there are many unknowns. There's not only so much that designers, engineers and quantity surveyors can also see in designing solutions for an existing building (PM1).*

In general, these findings suggest that ineffective building condition assessment is mainly due to: (1) the inadequate existing building data and (2) the lack of guidelines and methods for building condition assessment. Regarding the refurbishment focusing on carbon reduction, it is important to benchmark energy use and associated operational carbon emissions. Building assessment methods such as Greenstar, LEED, BREEAM, etc. and other multi-criteria assessment approaches may provide a direction for building condition assessment as they offer a structured framework to evaluate building energy and environmental performance (Ma *et al.*, 2012, Nielsen *et al.*, 2016). However, our research has been unable to demonstrate this aspect. Furthermore, the question about how effective building condition assessment could help reduce embodied carbon emissions in building refurbishment remains unanswered and should be a focus for future research.

4.2.3 Inadequate design information and consideration of whole-of-life cycle carbon reduction

Concerns about the lack of design information and consideration for whole-of-life carbon reduction when making design decisions for refurbished buildings were expressed. First, design decisions were often made without considering complete information regarding refurbishment options such as whole-of-life carbon savings, whole-of-life cost, client expectations, stakeholder values (e.g. co-benefit for users), and constructability risks. This practice resulted in a delay in the design and construction processes for refurbished buildings. In one case, the participant commented:

That's the risk of not getting the design brief right at the beginning and giving enough thought to the design decisions and some information, such as benchmarking (EC1).

From clients' perspectives, one participant claimed that there was insufficient information about whole-of-life carbon emissions to support their decision-making. For example, concerning embodied carbon information and the possibility of integrating long-term refurbishment strategies, the participant stated:

> *There's one wall that's entirely single-glazed windows. If we replace it, is that a lot of embodied carbon emissions? How do you get the building to perform better unless you replace those? What are the different options that we have? If you can't afford to do everything at once and look toward the future, what are*

> *the things you can line up in the building? So that, ten years down the track, you can start adding those things (LG2).*

A recurrent observation in the research was that energy modelling and LCA were not generally applied in the early design stages of the refurbishment process to estimate carbon performance. Particularly for small to medium refurbishment projects, the discussions around energy modelling and whole-of-life carbon reduction initiatives were not usually involved, even though there were always opportunities to identify and implement carbon-reduction refurbishment solutions.

These findings are consistent with that of (Bui *et al.*, 2022b), suggesting that a holistic multi-objective approach considering whole-of-life carbon, economic factors, co-benefits, and other impacts is necessary for making carbon-reduction decisions in building refurbishment. However, the reported results identify insufficient and incomprehensive relevant information to support the decision-making in the refurbishment process in the New Zealand context. In contrast to earlier findings in other developed economies (e.g. European nations), where multi-objective optimisation processes integrating advanced building energy simulation, LCA and LCC methods are applied to identify the most carbon-and cost-effective refurbishment alternatives in the early design stages (Kamari *et al.*, 2021, Serrano-Jiménez *et al.*, 2021). But this does not appear to be the case in this study. This observation may support the hypothesis that refurbishing towards zero carbon in New Zealand is in its infancy.

4.2.4 Inconsistency in accounting and calculating carbon emissions for building refurbishment

Turning to the evidence of the inconsistency in calculating carbon emissions for building refurbishment, most participants believed there were no consistent carbon calculation guidelines, standards and benchmarks within the New Zealand construction sector. More importantly, the participants mentioned that they were not fully aware of how life cycle carbon assessment was reported in the current building refurbishment projects. These aspects have led to many debates concerning methods and scope of work for calculating carbon emissions; as one participant described:

> *There is no standard in New Zealand for carbon design. Only a couple of companies report carbon emissions in their projects, but it's not clear what they're recording and how they're counting their carbon calculations (RE1).*

Two divergent and often conflicting discourses emerged in the findings related to life cycle carbon accounting for building refurbishment. Opinions differed on whether embodied carbon emissions of existing building components were accounted for when conducting LCA for refurbished buildings. Some participants thought that the boundaries of LCA for refurbished buildings only included embodied carbon emissions of newly-added materials and products. In contrast, others argued that embodied carbon emissions of all existing building components should be considered as one individual stated:

> *If it is a refurbishment, how do you count for existing components, and how are you adding other things? For refurbishing a commercial building's fit-out, how will the concrete that has been there for 20 years be accounted for in LCA analysis? (M4).*

These results reflect those of (Vilches *et al.*, 2017, Hasik *et al.*, 2019). They also found various carbon calculation assumptions and scope of work for refurbished buildings in the literature and current industry practices within the global construction sector. More importantly, this variation challenges New Zealand's construction stakeholders in calculating life cycle carbon emissions for refurbished buildings as the sector is in its early transition to a zero-carbon future. This study suggests that an appropriate calculation method for estimating the LCA of building refurbishment may help prevent inconsistent and ambiguous knowledge and understanding within the construction sector.

5 Conclusion and Further Research

This investigation aimed to investigate opportunities and challenges to reducing carbon emissions in building refurbishment in the New Zealand context. This study has found that whole-of-life embodied carbon reduction of newly-added construction materials and products should be considered alongside operational carbon reduction and the reuse of existing building components in the planning and implementation building refurbishment. The more significant findings are challenges to reducing carbon emissions in different areas of the pre-design and design stages of the refurbishment process, including (1) inexplicit carbon goal setting leading to several barriers affecting the design decisions regarding carbon benchmarking, trade-off between cost and carbon performance, identification and performance assessment of refurbishment solutions; (2) ineffective building condition assessment due to the inadequate existing building data and the lack of user guidelines and methods for building condition assessment; (3) deficient and incomprehensive relevant whole-of-life carbon information to support the decision making, and (4) inconsistent and ambiguous carbon-calculation guidelines and benchmark. The insights from this study may assist in enhancing the current industry practices in reducing whole-of-life carbon emissions in the refurbishment process. What is now needed is a comprehensive decision support framework that incorporates carbon-reduction initiatives for building refurbishment in New Zealand. A further in-depth investigation into the decision-making process of real-life building refurbishment case studies considering whole-of-life carbon reduction is strongly recommended to validate this study's findings and assist in developing the guideline for better-delivering building refurbishment towards zero carbon.

6 Acknowledgement

This work is a part of a Ph.D. research project funded by Massey University, New Zealand. The authors gratefully acknowledge Massey University and the Building Research Association of New Zealand (BRANZ) for their support.

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Incentivization of Sustainable Waste Management Solutions for Commercial Construction in Australia

Pieter van der Lans[1*], Christopher Jensen[1] and Mehran Oraee[1]

[1] Faculty of Architecture, Building and Planning, The University of Melbourne, Parkville, VIC 3010, Australia

pvanderlans@student.unimelb.edu.au; cjensen@unimelb.edu.au; mehran.oraee@unimelb.edu.au
* Corresponding author

Abstract:
The construction industry has one of the highest waste intensities in Australia. While currently there are barriers to the implementation of sustainable waste management (WM) practices, there is a lack of viable solutions to overcome these barriers. This research aims at examining the main barriers and issues to the implementation of sustainable WM in the Australian commercial construction industry with a focus on incentivization as a possible solution. To this end, a qualitative approach through interviewing experts in the field is adopted to explore new ideas around possible solutions to the issue. Thus, 13 online semi-structured interviews were conducted with experts in the Australian construction industry and the findings show that participants are willing to use more sustainable WM practices, however, the barriers are too substantial. The findings also indicate solutions such as influencing WM practices by stakeholders (client, government, and industry regulators) through financial incentives, mandating measurable and relevant KPIs, amending existing legislations, implementing stewardship programs, conducting audits on waste contractors to improve the waste reporting reliability, and creating separate waste streams to foster a Circular Economy. This study benefits researchers and practitioners by shifting their focus more towards solutions around the incentivization of head contractors (HC) towards sustainable WM practices.

Keywords:
Construction, Incentivization, Resource Recovery, Sustainable, Waste Management

1 Introduction

The value of the Australian commercial building activity has risen from $38 billion in 2015 to an all-time height of $49 billion in 2019-20 (Master Builders Australia, 2021), while the construction industry has one of the highest waste intensities in Australia (Pickin *et al*., 2020). Globally, around 800 billion tons of natural resources have been captured by the construction industry (Ratnasabapathy *et al*., 2021b), which is among the leading industries contributing to the largest carbon footprint (Sizirici *et al.*, 2021). The current waste management (WM) practices in the Australian commercial construction industry present issues that impact the Australian economy, the society, and the environment, including the health and wellbeing of communities (Maqsood *et al*., 2022). In Australia, 43% of the total waste is generated by the construction and demolition (C&D) waste stream, which accounts for 20.4Mt annually. Circa 6.7Mt of the C&D waste stream goes to landfill every year (Shooshtarian *et al*., 2020a). Although the present issues emphasize the urgent need for sustainable WM solutions, the WM practices in the Australian commercial construction industry are currently not sustainable. Attempts for waste resource recovery are limited in the industry, which leads to useful waste ending up in landfill sites (Caldera *et al*., 2020). Population growth and migration accelerate the issues, as they increase construction activities, as well as the C&D waste generation (Shooshtarian *et al*., 2020b).

It is evident that the implementation of sustainable WM solutions in the industry is significantly impeded by various barriers, such as cost, legislation, and poor quality of waste data (Ratnasabapathy *et al*., 2021b), while there are no viable solutions to overcome them yet. There is a lack of viable government incentives and regulations to support the quality and use of recycled products, which could ultimately lead to a reduction in waste levels in the Australian construction industry (Shooshtarian *et al*., 2020a). Compounding the problem there is a lack of education and awareness about the nature and size of the problem, to reduce waste and understand how to take advantage of the incentives that could be offered in the construction industry (Ratnasabapathy *et al*., 2021b). Wide implementation of sustainable WM practices in the Australian commercial construction industry would foster reduction, recycling, and reusing of waste, which is an opportunity to improve the efficiency of the industry, the environment, the economy, and society. This issue of how Australian head contractors (HCs) in the Australian commercial construction industry can be successfully incentivized to overcome the barriers is under-explored in research, as viable solutions and answers are not yet available. Incentivization of the industry is an important area, as it has been shown to be successful in other areas. The head contractor (HC) holds the initial contract with the client, leads the project, obtains the required resources, and is responsible for performing the works according to the agreed terms and standards in the contract, in compliance with regulations such as waste disposal (EPA, 2021) and industry standards (MRKTS, 2022). The HC also manages the subcontractors (SCs), and each SC is contractually obligated to the HC (Karim *et al*., 2006). This explains the significance of HCs as decision makers in construction projects, including WM practices and the potential for a reduction in construction waste from commercial construction projects.

The scope of this study is limited to the Australian context, with a focus on the incentivization of commercial construction HCs. The findings of this research are based on the analysis of the responses from semi-structured interviews with experts in commercial construction companies. The aim of this research is twofold. At first, it explores the main barriers and motivators of commercial construction HCs for implementing sustainable WM practices. This will lead to examining how to overcome the barriers, with a focus on incentivizing sustainable WM practices, which is the "action" side of the research. Second, this research evaluates the willingness of commercial construction HCs to change towards sustainable WM solutions.

2 Literature Review

Construction activities are globally one of the major generators of waste. Construction and demolition waste may include metal, masonry, concrete, lumber, plaster, glass, asphalt, carpet, and dirt (Kabirifar *et al*., 2020). The Australian C&D sector generated 27Mt (millions of tons) of C&D waste in 2018-2019, which is waste managed within the waste and resource recovery sector. This is significant because it represents 44% of Australia's total core waste (Pickin *et al*., 2020). In general, C&D waste goes to landfill sites and attempts for resource recovery are limited (Caldera *et al*., 2020), which shows the need for a wide application of sustainable waste management (WM) solutions in the industry.

There are several benefits to sustainable WM solutions, which include increased recycling and utilizing more secondary materials. This leads to more recycled content in construction projects, reduced waste generation, less pollution, lower consumption levels, and decreased pressure on landfill capacities and natural products (Ratnasabapathy *et al*., 2021a). Moreover, reusing and recycling avoid illegal dumping (Shooshtarian *et al*., 2020a). Consequently, sustainable WM reduces the burning of fossil fuels and emissions of carbon dioxide, which leads to a more sustainable environment. Furthermore, sustainable WM might improve public health and safety. For instance, minimizing plastic in landfills to reduce the risks of a potential fire in landfill (Li and Du, 2015). As discussed by Shooshtarian *et al*. (2020a), utilizing recycled C&D waste products lead to a reduction in construction costs and energy consumption, and it avoids landfill tax. Moreover, the implementation of sustainable WM practices is an opportunity to create niche markets, as well as new job opportunities in the local markets (Shooshtarian *et al*., 2020a), which can incentivize several stakeholders in the industry, as well as politicians. According to the study conducted by Li and Du (2015), engaging in sustainable construction activities can lead to corporate social responsibility. For instance, the use of secondary materials in construction projects to play a positive role for the community.

However, the implementation of sustainable WM solutions is significantly impeded by various barriers. The study by Maqsood *et al*. (2022) found that there is limited knowledge in the industry about the possibilities of using recycled materials. This finding is strengthened by Shooshtarian *et al*. (2020a), who argued that there is a lack of competent staff and awareness about managing construction waste, which leads to a negative demand in the market for recycled materials. In addition, O'Farrell *et al*. (2013) summarized that there is limited awareness about the financial benefits of minimizing and avoiding waste, while Shooshtarian *et al*. (2020a) argued that the additional time and costs associated with separating, transporting, and reprocessing of waste, keeps builders from implementing sustainable WM practices. This shows the potential to make better use of the benefits through WM solutions. Moreover, there are space constraints for the segregation, handling, and storage of materials (O'Farrell *et al*., 2013). This finding is confirmed by Ratnasabapathy *et al*., (2021b), who stated that on-site space does not always allow for proper separation of waste, which limits the quality and demand of secondary materials. Another important barrier is the shortage of accessible (web-based) technologies and market platforms for waste information, as well as the lack of reporting and waste data systems (Ratnasabapathy *et al*., 2021b), which are critical tools for HCs to buy products of the required quality. The Office of the Chief Economics report (2018) confirms this finding, which shows that the construction industry is slow in implementing new innovations and web-based technologies. Additionally, Maqsood *et al*. (2022) found that there is a lack of incentives and investment for innovation in the recycling sector. Another issue, discussed by Shooshtarian *et al*. (2020b), is the fact that waste strategy documents are developed by individual states and territories. The different strategies can lead to inconsistencies. To clarify, the resource recovery and recycling measures vary significantly between Australian states and territories. This points to an opportunity to learn from each other and improve, by paralleling back the methods used in the best practices, throughout the remaining states and territories.

2.1 Existing incentives for improving waste management practices

Incentivization strategies are based on overcoming barriers and include programs, tools, and accessible systems to encourage the utilization of recycled products, application of material testing and product certification to increase sustainable WM practices. For instance, the Green Building Council of Australia (GBCA) rates the sustainability of building projects through a rating system, named Green Star, which encourages the efficient use of construction materials. Green Star also focuses on C&D waste minimization through credits, to encourage construction projects to design and construct in a way that fosters the best WM practices. These credits aim to incentivize and reward WM practices that minimize the amount of C&D waste from construction activities that are going to landfills (GBCA, 2022). Construction projects can obtain credit points for waste-related practices which include: the use of recycled materials, waste storage that promotes recycling, and recycling C&D waste from the project. Therefore, the Green Star credit points act as an incentive for companies to develop and maintain sustainable WM practices. GBCA claims that Green Star certified buildings recycle 96% of their generated waste. However, as argued by Shooshtarian *et al*. (2019), Green Star's waste requirements are not mandatory, which indicates the potential for further improvement around the encouragement of WM practices in the industry. Clients must incur significant costs to receive a Green Star certificate. This points to a lack of incentives for the widespread adoption of such programs. Another existing incentive to reduce waste is penalizing through waste levies. For instance, waste levies must be paid for all wastes received at licenced landfills. The main purpose of the waste levy is to help reduce waste by incentivizing waste generators to look for alternatives to avoid waste and minimize the waste they create and send to landfill. From 2020-2021 to 2021-2022, the landfill levy has been increased by circa 61% (EPA, 2022). Moreover, Sustainability Victoria works closely with the EPA and the tyre industry to develop sustainable tyre markets, which satisfies the Circular Economy (CE) principle. The funding for the development program includes the source of income from levies on car tyres. The product stewardship supports a new regulatory framework for end-of-life tyres, which prevents stockpiling and illegal dumping, and fosters market growth for tyre-derived products (Sustainability Victoria, 2022). Since there are existing programs to develop sustainable markets for tyres in Australia, it is an opportunity to develop similar programs for key C&D (waste) materials.

2.2 Circular Economy

CE is a principle that supports the circulation of materials to ensure natural resources remain in the supply chain by maximising the recycling and reusing of materials through innovation of the entire chain of consumption, production, recovery, and distribution of materials (Ghisellini *et al*., 2018). Managing construction waste is therefore a critical part of this cycle. CE principles are widely implemented around the world (including Japan, China and Europe) as a political objective to encourage sustainable WM through government programs (James and Mitchell, 2021). CE reduces material demand and greenhouse gas emissions, while it contributes to an increase in the use of secondary materials, consequently increasing the value and reuse of construction waste, which in turn broadens their activities. According to Ferdous *et al*. (2021), every 10,000 tons of waste recycling is estimated to create 9.2 jobs, while this is 2.8 jobs for landfill disposal, which shows the significance of encouraging a CE.

3 Research Methodology

In this study, a 'qualitative' approach was selected which facilitated exploring insights into individual participants, including their opinions, understandings, and attitudes (Nassaji, 2015). To explore how Australian HCs can be incentivized to implement sustainable WM solutions, semi-structured interviews were used as the mean of qualitative data collection.

3.1 Sampling

The target population for semi-structured interviews of this research project include the decision makers around sustainable WM practices within the Australian commercial construction companies. Within the companies, the Sustainable Development Managers are most relevant for the data collection of this research project. However, different views, from professionals with different skills and positions in the industry, need to be obtained. Therefore, more professions with decision making responsibilities were included as well. Sampling was based on snowballing, which is suitable when participants are harder to reach (Parker et al. 2019). In total, 13 online interviews were conducted through the Zoom application, and the list of participants and their profiles, who are mainly in Victoria State, are illustrated in Table 1.

Table 1. Interviewees' profiles

No.	ID	Role	Experience (year)	Organization type
1	A	Director	17	Demolition & Salvage
2	B	Sustainability Manager	22	Construction
3	C	Contract Manager	20	Construction
4	D	Director	11	Building Surveyor
5	E	Sustainability Manager	15	Construction
6	F	Sustainability Manager	7	Construction
7	G	Project Manager	15	Construction
8	H	Sustainability Manager	17	Waste Contractor
9	I	Sustainability Manager	16	Construction
10	J	Sustainability Manager	26	Construction
11	K	Sustainability Manager	16	Supplier
12	L	Design Manager	11	Construction
13	M	Sustainability Manager	10	Construction

3.2 Analysis

In the present study, to analyze the collected data, the Nvivo software was used as the qualitative data analysis tool. The analysis process started with transcribing the audio-recorded interviews into text documents to generate clear information from recordings as well as minimising misunderstanding and errors (Creswell and Creswell, 2018). In the next stage, category coding and thematic analysis were applied. As stated by Punch (2013), the qualitative analysis starts with coding, which is significant in discovering regularities in the data. Coding is the process of assigning labels (names) to the collected pieces of data, which can be used to identify patterns, and summarize data into themes (Punch, 2013). In this research, the codes were created based on the existing literature, as well as the collected qualitative data from semi-structured interviews. Preliminary codes from the existing literature include barriers, motivators, and incentives to sustainable waste management. Moreover, analysis of the interview data resulted in identifying new codes that were added to the preliminary list.

4 Findings and Discussion

4.1 Willingness

The interview participants are very willing to use more sustainable WM practices and contribute to a more sustainable environment. As explained by participant E: "*Especially at corporate level, everyone knows that we don't want to send loads of waste to landfill, that we need to recycle waste, and that waste is harmful to the environment. The level of knowledge is pretty good around that, but the challenge is how to translate that desire to do the right thing into reality, and into getting the right outcomes on site. This comes back to the client, the cost, and the program. We do what our client tells us to do and if we do anything beyond that we lose money, so where is the incentive?*". Participant B highlighted that their company is very willing to improve WM practices, and that they see the investor and the stakeholder benefit of being sustainable, as well as the internal benefits. Participant C and L also mentioned to be very willing and stated that their company focusses a lot on Green Star, passive house, and sustainable design. Participant C also added: "*Similar to a lot of other improvements in construction techniques and site management, it will take some time, but then it just becomes* *part of normal operations"*. However, most participants mentioned that WM is competing with other important aspects. Most participants put sustainable WM as the last priority, when asked to put the following aspects in order of priority: safety, cost, time, quality, and sustainable WM. However, Participant E explained that when you are sustainable, it does not have to be an order of priority: *"Take carbon, for example, if you seek to remove carbon from your design you will reduce your cost, as you are reducing energy. Therefore, it doesn't have to be one or the other, it can go hand in hand. Thus, if we want to focus on cost, we must focus on carbon as well. And when you reuse waste, instead of using virgin materials, it is usually going to have a lower carbon footprint"*. Most participants in this study believe that the level of awareness around WM issues in the industry is good, whereas the existing literature shows that the level of awareness in the industry was found poor (Shooshtarian *et al*., 2020a).

4.2 Key motivators

In the perception of the interviewees, the key motivators for implementing sustainable WM practices are based on the following factors.

4.2.1 Opportunities to create new markets, sectors, and job growth

The opportunity to create new markets and job growth was most mentioned by participants. Participant C stressed that sustainable WM is a great opportunity to create small scale industries in the resource recovery sector. Participant D had the same opinion and added that it would lead to innovations in the recycling industry, which create economic benefits. Participant E mentioned that besides new jobs, it can foster a (local) CE.

4.2.2 Reduced construction costs

Most participants mentioned that the construction industry is mainly cost driven. A key motivator for implementing sustainable WM solutions is to reduce the construction costs. For instance, Participant B emphasized that cost benefits can be achieved by implementing prefabricated and standardized construction components to the design, which reduces waste generation, saves time, and reduces the costs (mass production, economy of scale, etc.). Participant E had a similar view, stating that "*it is in our interest to implement the waste hierarchy and reduce the amount of waste that we sent to landfill, because we save money*".

4.2.3 Circular Economy and reduced embodied carbon

The participants are keen to contribute to a CE and reduce the embodied carbon, for a more sustainable environment. Participant E acknowledged the advantages of making new products from waste materials, while fostering an ongoing loop that can occur: *"that is what we need to get to right, that is the definition of human sustainability".* Participant B had similar views and stated that environmental (and cost) benefits can be achieved by using more recycled content in the construction of buildings, as well as by getting those recycled materials back into the CE again. For example, the use of more sustainable concrete, with higher recycled content in it. Participant C confirmed this, stating that recovering resources has significant energy and carbon benefits. Participant D had a similar opinion and stressed that it is important for our environment to decrease the use of raw materials and the embodied energy that is used to create materials. The participants' awareness of the CE and its link to sustainable WM is encouraging. However, it is also clear that the CE remains as a concept and the operational task to hand of improving WM practices, including material recycling are not connected.

4.3 Key barriers

Despite the willingness in the industry and the key motivators for implementing sustainable WM solutions, various inherent barriers were mentioned by interviewees, which are challenging to solve. The key barriers mentioned by participants are in alignment with the findings in the literature review, except for the reporting reliability of waste contractors, which is a new finding in this research. The key barriers are outlined below.

4.3.1 Reporting reliability of construction waste

During the interview discussions, it was found that interview participants have no confidence in the reporting system of waste contractors, because they find the WM reports (provided by the waste contractors) unreliable. Participant F mentioned that there is a lack of transparency on how their waste is managed at waste facilities. Participant E emphasized that waste contractors who pick up the waste from construction sites, mostly conduct visual estimations at their waste facilities to determine the percentage of different waste types, rather than automatic checks, which makes the system unreliable. Furthermore, participant J mentioned that the reporting system is based on percentages, which often shows satisfactorily high recycling percentages, while it is unsure how valid those outcomes are, making the system a waste of time. Most participants mentioned that there is a lack of incentives to improve reporting reliability. Participant B strengthened this argument, by saying: *"People got so used to seeing reports that have a 90% plus recycling rate, that government contracts and requirements are framed around that. But those are made up by the waste contractor companies and will realistically be lower. Therefore, there are external drivers that require a high recycling rate, rather than the best actual recycling rate, or the best environmental outcome"*. Participant E admitted that it saves time and cost for their company to use a waste contractor, because they use one bin for all the waste, and the waste gets sorted by the waste contractor (off-site), however, they rely on the sorting system of the waste contractor. Participant B had a similar opinion, stating that it would be cost-prohibitive for HCs to sort and weigh the waste on the construction site. Additionally, participant B pointed out that there is a lack of audits on waste contractors, and waste facilities are not mandated to publish their average recycling rate. Participant E strengthened this argument, by saying: "*Waste contractors do not have an incentive from a regulator point of view to give construction HCs 100% accurate waste reports*". Most participants pointed out their concern about reporting reliability, which is the main barrier that was found in this research. When it comes to waste reporting, the interviewees believe that we are fooling ourselves in the industry with waste management reports that show great recycling rates, while people strongly suspect that the reality is different. This takes away the incentive in the industry to perform better in sustainable WM, as construction companies are confronted with recycling rates that they perceive as inaccurate and unreliable. The participants feel powerless to change this issue, which indicates that solutions from other stakeholders are required to solve this issue.

4.3.2 Site constraints

Responses show that HCs are often dealing with limited on-site space, which is found to be a key barrier for separating different waste materials on-site. As a result, a single waste bin is used on the construction site and waste gets contaminated. Interviewees B, C and D mentioned that it is unrealistic to have several waste bins on site, especially in urban areas, where there is not enough space on site. Participants E, H, and M had similar opinions and emphasized that limited space on site is the main barrier, which restricts the opportunity to separate waste materials. Participant B pointed out that the single-bin solution on-site, which gets sorted off-site by waste contractors, is not ideal because it increases the contamination of different waste materials, and it reduces the accuracy of waste reporting.

4.3.3 Additional costs, time, and resources for separating C&D waste on-site

Most participants mentioned that important barriers are the additional time and costs to sort the different waste materials on-site, including the required effort to transform towards sustainable WM practices in the daily workplace. For instance, participants B, D and E mentioned that there is averseness and lack of care from labour. It was clarified by most participants that waste is a significant cost item for construction projects both, for the disposal of waste, as well as transportation of waste. Participant E mentioned: *"Five years ago we used to sort all waste on our sites ourselves. That has its own challenge. It takes up space, it is time consuming, it requires extra resources to separate waste on-site, and often people do not put the right waste materials in the right bins, and you need to manage this process"*. Participants C and D pointed out that cost is the biggest challenge that a construction company will encounter when separating, sorting, and transporting the waste by themselves.

4.3.4 Lack of (financial) incentives around sustainable WM

A key barrier is the lack of financial incentives from the government to encourage sustainable WM practices, including a lack of penalties for unsustainable WM practices, low landfill levies, poor communication around environmental impact, and limited communication around the economic benefits of sustainable WM practices. Interviewee I pointed out that "*the waste levies are not high enough to keep people from going to landfill*".

4.4 Incentivization

Results show that the reason for not improving towards sustainable WM practices is the fact that the barriers are too substantial. Removing the existing key barriers would incentivize HCs to implement sustainable WM practices. However, as mentioned in the previous paragraph, the barriers are challenging to solve. While most participants talked about their willingness and desire to help improve the environment with better WM practices, most participants also talked about the significant amount of work to do, before sustainable WM practices can be achieved. This is mainly because participants do not want to compensate for other important aspects in construction projects (including cost, time, and quality), which are essential to keep ahead of the competition in the market. Most interviewees believe that implementing sustainable WM solutions will only happen if the government, clients, or industry regulators come up with viable programs, incentives, or enforcement. As clarified by Participant E, "*We are driven and motivated by what our client and the Government asks us to do. If they allow us to do something and it's the cheapest way to do something, then market forces prevail*". The key incentives, as solutions to overcome the barriers towards implementing sustainable WM are outlined below.

4.5 Incentivization through influence from client and design team

4.5.1 Selection of building materials, prefabrication, and WM KPIs

Most interview participants pointed out that the client has a significant influence on the selection of building materials from a design perspective. Participants B and J emphasized that the client is decisive in the choice between conventional construction and prefabrication. For instance, the client can influence the design of standard column sizes, which enables for precast columns. This avoids the need for formwork and in situ concrete pores, which reduces waste (and costs). Another example mentioned by Participant B is *"trying not to have 100 different bathroom types, but rather the same types, which allows to have modular units built off site"*.

Participant B strongly believes that waste reduction has a significant opportunity in Australia, because *"in Europe landfill space is really scarce and they are more efficient with materials that you bring to site".* This is an opportunity, which can be utilized in the early planning stages, and controlled and incentivized by the client. Participant C also stated that clients should consider the life cycle of the main materials that will be used in construction and have that as a major consideration for the selection of materials in design, as *"this can flow through to the types of waste that get generated as well*". Participant E has a similar view, but also pointed out that prefabrication is not something that develops quickly in Australia, due to the more risk averse culture, with more hesitance for new innovations, compared to Europe. Participant D clarified that if you get the design stage right, including the right material selection, the rest will take care of itself. Participant D mentioned that KPIs for WM should be included in the tender request, which is controlled by the client. Participant B had the same view and added that HCs should be assessed against KPIs, and the measures of KPIs should be based on volumes, for instance, the average of waste generated per apartment. "*That would incentivize efficient use of materials on site, especially if you know that that is something that is going to be assessed and possibly, somehow linked financially*". Participant M had a similar opinion and stressed that a WM shift in the construction space needs to come from the client and the architect.

4.6 Incentivization through influence from government and regulators

4.6.1 Financial incentives on materials and waste

Most interview participants stressed that HCs can be successfully incentivized by applying more financial incentives, which can either be penalizing poor WM practices, or providing credits for more sustainable WM practices. Participant E emphasized: *"put it in our contract, and either incentivize us with money, or take money away from us".* Participant C pointed out that the biggest overriding challenge is the low cost to get rid of waste, whereas in Europe, they are constrained with limited space, making the cost of waste disposal very high. *"When it becomes very expensive to dispose waste you would come up with innovative ways of doing other things, for instance, recovering resources".* Participant B had the same opinion and stated: *"the more landfill rates go up the better".* Participant B also mentioned that independent rating systems, including Green Star, should focus more on construction waste credits, to incentivize sustainable WM solutions. Participant E argued that if materials cannot be disposed sustainably, companies should not be making things from these materials. To avoid this, the industry needs a stewardship program imposed by the government that holds the manufacturers of such materials to account. Participants C and L had the same view and mentioned that industries experienced positive effects from penalizing materials that you do not want people to use, including materials that are harder to recycle.

4.6.2 Programs initiated by the government and industry regulators

Interviewee C stressed that the majority of the paid landfill levy goes back to state governments for resource recovery, recycling, and WM programs. However, not a lot of the landfill funds focus on the construction sector. Interviewee C mentioned that this levy can be used to incentivize construction HCs towards more sustainable WM practices, for instance, for trying out new initiatives. Participant D clarified that "*programs should also focus on providing site facilities that are easy to understand, to incentivize sustainable WM practices on site, for instance, separate waste bins that are clearly labelled, separately for timber, concrete, and so forth*". Participant B had the same view and mentioned that separate waste bins on site would incentivize better WM practices, as long as people are trained to use the bins properly, and a waste monitor is present on site to monitor whether the bins are correctly used. Moreover, waste bins should also be structurally easy, for instance, slots that only allow specific materials to fit through. Participant C stressed that the government and regulators in the industry should create separate waste streams, and places for people to dispose them, manage them, and recover resources from, adding that "*once the pathways are created, you can start to work with the generators of waste to load it all up*". Participant I had a similar view and stated that the best way to achieve the sustainable outcomes is to invest more in waste infrastructure, which enables to achieve more sustainable WM outcomes.

4.6.3 More audits and government control

Participant E stressed that real-time tracking of the waste contractor trucks should be enabled, to provide transparency around transportation of waste, while Participant D mentioned that the issue of waste reporting reliability should be completely controlled by the government, to overcome this barrier. This can be achieved by making the council responsible for picking up the waste, processing the waste, and reporting of the waste, which also provides transparency about the transportation, sorting, and recycling of the waste. Participant K stated that the government should make suppliers and subcontractors responsible for managing their own waste. Participant E had a similar view and pointed out that the government should come up with legislation that enables HCs to send waste (including packaging) back to the suppliers.

5 Conclusion and Further Research

From the findings in this research, it can be concluded that HCs have a positive perception towards the implementation of more sustainable WM solutions. The identified key motivators include the contribution to a CE, and the opportunities to reduce construction costs, create new markets, and foster job growth. However, it was identified that the barriers to sustainable WM practices are too substantial, including reporting reliability of construction waste, site constraints, lack of financial incentives, and efforts to separate C&D waste on-site. Removing the key barriers would incentivize HCs to implement sustainable WM practices.

This research shows that incentivization of HCs towards sustainable WM practices requires several stakeholders to be involved. The influences from clients and the government are most crucial to overcome the barriers. The key incentives that were identified include financial incentives and programs imposed by the government, including the creation of separate waste streams, higher waste levies, and stewardship programs, aiming to increase the proportions of recyclable materials used in construction and encourage a CE. Participation from clients is required to become effective, especially in the early stages, since they have influence in the design and the way materials are used, including the option for prefabrication as a sustainable solution to reduce waste generation. Additionally, the results reveal that action from the government is required to improve the reliability of waste reporting, either by conducting more audits on waste contractors, or by taking over the responsibility and managing waste and recovery facilities by themselves. This in turn improves trust in WM reports and can encourage HCs to achieve higher actual outcomes. Thus, the findings in this study are significant for the government, property developers, clients, design teams, and regulators in the industry to help develop strategies to improve WM practices for commercial construction companies in Australia, which benefit the environment, the economy, and the society. Of specific value to the industry is the understanding that HCs are generally very willing to improve WM practices, but see regulatory and client side cost barriers to change. Potential actions include communicating the opportunities and benefits of pursuing sustainable WM for both the project and the environment.

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Revealing the Value of the Circular Economy as a Solution for Mitigating Waste Implications within the Construction Industry

Nathan Johns[1*], Saeed Talebi[1], David Edwards[1], Chris Roberts[1], and Mark Shelborne[1]

[1] School of Engineering & Built Environment, Birmingham City University,
Millennium Point, Curzon Street, Birmingham, B4 7XG, UNITED KINGDOM

* Nathan.Johns@BCU.ac.uk; Saeed.Talebi@BCU.ac.uk; David.Edwards@BCU.ac.uk;
Chris.Roberts@BCU.ac.uk; Mark.Shelborne@BCU.ac.uk

* Corresponding author

Abstract:
This paper critically reviews the inherent value of the circular economy (CE) as a systems solution framework for mitigating anthropogenic pollution associated with linear consumption and waste within the construction industry. Although the CE has been identified as a key innovation for mitigating the concomitant environmental implications of consumption and waste, within construction activities, it requires further development and application for widescale application. Such development is currently hindered by the industry's failure to collect pertinent practical data on the inherent value of the CE strategy within the sector. Therefore, to achieve the next stage of development, the inherent value of the CE must be explicitly elucidated upon to incentivise industry application. To explore this phenomenon, a review of core literature and government documents on CE applications in the construction industry were undertaken. The research findings revealed that stakeholders within the industry (e.g., the client, designers and contractors) have a lack of knowledge of the innate value of the CE strategy. This paper's contribution to knowledge is threefold viz.: (i) it identifies the value driving the CE within the construction industry as a solution to consumption and waste; (ii) it analyses the barriers to wider CE implementation and provides insight into the reasons hindering CE development, and (iii) it provides researchers and practitioners with a pivotal basis for the development of the CE. Future research elucidated upon includes informing and incentivising construction industry stakeholders to gain further practical data collection on the value of the CE strategy within construction.

Keywords:
Circular Economy, Closed-loop, Construction Industry, Environmental Implications, Value

1 Introduction

The Anthropocene's capitalistic use of linear economic consumption (Take-make-waste), coupled with the thermodynamic finality of the Earth's resources, has created an unsustainable future for humankind (Crutzen, 2006; Steffen *et al.,* 2007; Rockström, 2009; Working Group II, 2022). The International Panel on Climate Change (IPCC) has painted a stark future for humanity within their sixth assessment report; specifically, the worst-case scenario predicted in the fifth report has now become the current trajectory in the updated sixth assessment (Working Group II, 2022). Premised upon these reports: governments worldwide are implementing Sustainable Development Goals (SDGs) and mitigation strategies for climate change (cf. Schroeder *et al.*, 2019; EC, 2020; NDRC, 2021; USEPA, 2021); consumers are demanding economic systems that are less damaging to the environment and biological life (e.g., clean energy) (Kanchanapibul *et al.,* 2014); and organisations are facing changing demands from both governing policymakers and consumers, in legal and moral capacities (Murray *et al.,* 2017; Ogunmakinde *et al.,* 2022). However, the rapid requirement for action is outpacing the development of theory causing misdirection in the application of a sustainable solution. Within sustainable development goals, a clear strategy is visibly consistent across governments and policymakers called the Circular Economy (CE) (Schroeder *et al.*, 2019). The CE is a systems solution framework that has become inextricably linked with industrial and environmental symbiosis. This is due to the 3Rs, the reduction, recovery, and reuse of waste, ultimately avoiding a linear exchange with the environment in a closedloop flow as opposed to linear take-make-waste (Ghisellini *et al.,* 2016; Geissdoerfer *et al.,* 2017). By recovering resources from industrial waste, new resources and products can be created increasing the value of the original input into the system (MacArthur, 2013). Resource efficiency within the industrial system has a multitude of values beyond material recovery, for example, generating new business income streams and a reduced strain on the environment (Geissdoerfer *et al.,* 2017). A fundamental objective in the effort to embed a CE strategy is the promotion of its defining characteristics and value for governments, organisations, and consumers which is gained from the closed-loop economic structure of the strategy (Adams *et al.,* 2017; Govindan and Hasanagic, 2018). This suggests that the value of the CE strategy is largely unknown to researchers and practitioners, ultimately hindering the level of application within industrial activities and the possible value gained from resources.

To reduce the omnipresent Gordian knot of linear consumption and waste, the most impactful industries are of the highest priority for CE innovation (cf. EC, 2020; USEPA, 2021). Agriculture, energy production and construction are prioritised as being the top industries contributing to the problem domain (MacArthur, 2013), of which construction contributes 20-35% of the total waste produced (EC, 2020; USEPA, 2021). However, so far, the construction sector has witnessed limited innovation within the application of CE practices, and academic discourse in the extant literature is a relatively recent phenomenon – beginning to flourish from 2018 onwards (Benachio *et al.,* 2020; Munaro *et al.,* 2020; Çetin *et al.,* 2021). Yet, papers investigating the barriers to CE adoption within the industry commonly identify a lack of incentives as a leading barrier to CE innovation (Adams *et al.,* 2017; Ghisellini *et al.,* 2018; Bilal *et al.,* 2020). Another barrier commonly identified is the lack of knowledge and education within the industry on the palpable benefits associated with the CE strategy (Hart *et al.,* 2019; Bilal *et al.,* 2020; Kanters, 2020; Çetin *et al.,* 2021; Giorgi *et al.,* 2022). The lack of incentive and education suggests that the value of the CE is not clear within the literature to novice researchers and practitioners looking for system-based innovation. Thus, this research aims to investigate and elucidate upon the inherent value of the CE within the construction industry and explore the barriers to achieving said value for researchers, practitioners and wider society. The primary objective being to review the extant literature on the CE strategy to engender new theory on achieving value in the sector. This is achieved by generating polemic debate on the current state of literature and barriers to achieving value from the CE strategy in the construction industry.

2 Research Methodology

The research conducted was in the form of a critical literature review, in which data was collected using Scopus, Web of Science, and Google Scholar by using keywords to search within the title of extant literature. Consequently, an interpretivist philosophy and inductive reasoning guided this study to develop new theories and insights. Initially using "Circular Economy" as a keyword to identify core papers in the broader subject area, the search was subsequently further refined based on the research focus of the CE's value, drivers, and barriers using the following keyword strings; **String 1 (CE):** "Circular Econom*" OR "Circular Business" OR "closed-loop" OR "circular suppl*" OR "circular manage*"; **String 2 (Construction):** "construction industry" OR "construction" OR "built environment"; **String 3 (Specific):** "value" OR "enabler" OR "driver" OR "barrier". Finally, the papers were manually reviewed and excluded if deemed irrelevant to the desired focus of the research, or of low quality. The initial search identified approx. 1500 sources that met the criteria, this was refined to the top 200 cited documents, of which 25 directly matched the search requirement for value, drivers, and barriers. Once coalesced, the literature was analysed thematically into the values and barriers of the CE in construction. Finally, the research offers a simplified thematic table to summarise and guide researchers and practitioners in future research, development, and application of the CE in the sector.

3 The Drivers and Value of the Circular Economy

The CE was initially designed to increase resource value within a system (Leontief, 1991; MacArthur, 2013). The main principles of the CE are known as the 3Rs, to reduce, reuse, and recycle waste within the lifecycle, this has been expanded to 6Rs and 12Rs that further reduce linear waste in more detail. It has since become a versatile strategy with multiple benefits both internal and external to the industrial system (Geissdoerfer *et al.,* 2017). For developed countries, the CE is a source of new raw resources to alleviate their increasing imports of resources (USEPA, 2021). The finality of resources is more apparent within developed economies that have exhausted their supply of raw materials, resorting to costly imported resources (Webster, 2017). Moreover, the level of resources consumed and wasted in developed economies highlights the damage caused to the natural environment when developing using a linear system like capitalism, posing a motive for a complete worldwide transition towards the adoption of the CE strategy (EC, 2020). Similarly in developing economies, high levels of consumption and waste are present, making a CE an attractive strategy to reduce consumption of raw resources and costs required to develop (Yuan *et al.,* 2006; Xinan and Yanfu, 2011). Furthermore, for undeveloped economies, the acceptance of waste imports from developed economies has created an overflow of waste resources without the necessary infrastructure for processing (Bai and Givens, 2021; Browning *et al.,* 2021) - a scenario that pushed China to implement an import ban on waste (Wang *et al.,* 2020). For developed and developing economies alike, the CE provides a valuable output for waste.

Within the construction sector, the transition to a CE has been less impactful even though the industry is of the upmost priority due to its massive contribution to economic waste (Hart *et al.*, 2019; Bilal *et al.*, 2020; Çetin *et al.*, 2021; Giorgi *et al.*, 2022). Recent drivers for the CE within the sector have originated from: new laws and legislation for managing waste; frameworks and business models conceptualising the strategy for application; technological advancements for design, management and analysis of the supply chain's lifecycle; and the overall value of reduced material consumption and waste within the supply chain producing economic, environmental , and social value (Angrisano *et al.*, 2016; Adams *et al.*, 2017; Ghisellini *et al.,* 2018; EC, 2020; Ferdous *et al.,* 2021). Furthermore, case studies appearing within the extant literature provide data on the practical application of the CE within the sector thus, increasing confidence in the application of the concept (Adams *et al.,* 2017; Ghisellini *et al.,* 2018; Ferdous *et al.,* 2021). However, within the construction sector, there is still limited knowledge amongst practitioners and academics to incentivise the adoption of CE practices. The value of the CE within construction and therefore requires elucidating for the increased acceptance and adoption of the strategy. Table 1 consists of a summary of the types of value of implementing the CE strategy within the construction industry and some driving factors of said value. Overall, the CE's reduction of consumption and waste has numerous effects on the problem domain which provides value in different forms driving the transition to a CE structure.

Table 1 Value driving the CE within the construction industry

VALUE	DESCRIPTION	REFERENCE
Reduced environmental implications	The environmental damage highlighted by the IPCC has provoked change within governments, organisations and consumers towards a less wasteful and damaging system.	(Ghisellini *et al.*, 2018; Hart *et al.*, 2019; Tazi *et al.*, 2021; Giorgi *et al.*, 2022)
Meeting government and consumer demand	The social opinion on industrial activities is changing toward green, sustainable and circular systems that cause fewer implications on the environment, economy, and society.	(Angrisano *et al.*, 2016; Adams *et al.*, 2017; Ghisellini *et al.*, 2018; Hart *et al.*, 2019; Çetin *et al.*, 2021; Giorgi *et al.*, 2022)
Considerate design and increased consumer value	Considering the CE at the design stage entails a large amount of consumer consideration - ultimately improving the value and quality for the consumer.	(Ghisellini *et al.*, 2018; Hart *et al.*, 2019; Charef *et al.*, 2022; Giorgi *et al.*, 2022)
Reduced risk from supply shortages and price fluctuations	Finite resource supplies cause fluctuations within the market resulting in volatile prices for materials.	(Adams *et al.*, 2017; Ghisellini *et al.*, 2018; Çetin *et al.*, 2021; Ferdous *et al.*, 2021; Tazi *et al.*, 2021; Charef *et al.*, 2022; Giorgi *et al.*, 2022)
Reduction of system waste	The reduction of waste in a system has numerous benefits for a business' production efficiency and financially.	(Adams *et al.*, 2017; Ghisellini *et al.*, 2018; Hart *et al.*, 2019; Benachio *et al.*, 2021; Çetin *et al.*, 2021; Ferdous *et al.*, 2021; Charef *et al.*, 2022)
Economic growth and new material markets	The CE provides new opportunities and markets for industries and organisations that are favourable for economic growth making the system favourable for governments.	(Adams *et al.*, 2017; Ghisellini *et al.*, 2018; Hart *et al.*, 2019; Çetin *et al.*, 2021; Ferdous *et al.*, 2021; Tazi *et al.*, 2021; Charef *et al.*, 2022; Giorgi *et al.*, 2022)
DRIVER OF VALUE	**DESCRIPTION**	**REFERENCE**
Laws, legislation, and development schemes	Top-down innovations from governments in the form of laws and legislation drive the CE.	(Angrisano *et al.*, 2016; Adams *et al.*, 2017; Ghisellini *et al.*, 2018; Hart *et al.*, 2019; Çetin *et al.*, 2021; Giorgi *et al.*, 2022)
Technological advances	Advancements in industry 4.0 have enabled more complex analysis required for understanding and application within the CE.	(Adams *et al.*, 2017; Hart *et al.*, 2019; Çetin *et al.*, 2021; Ferdous *et al.*, 2021; Giorgi *et al.*, 2022)
Case studies	Case studies and pilot projects provide an example of the CE concept in its application.	(Adams *et al.*, 2017; Ghisellini *et al.*, 2018; Hart *et al.*, 2019; Çetin *et al.*, 2021; Ferdous *et al.*, 2021)
Frameworks/business models	Frameworks and business models map and educate on the CE concept in its application within a system.	(Adams *et al.*, 2017; Ghisellini *et al.*, 2018; Hart *et al.*, 2019; Çetin *et al.*, 2021)

3.1 Economic value

The CE concept is based on economic performance and maximising value from resources inputted within a system (Leontief, 1991; MacArthur, 2013). Closed-loop supply chains reduce waste within a system, provide new resources, create new material markets which, consequently, creates jobs within an economy (Ferdous *et al.*, 2021; Tazi *et al.*, 2021; Charef *et al.*, 2022; Giorgi *et al.*, 2022). The European Commission (EC) 2020 and the United States Environmental Protection Agency (USEPA) 2021 have stated in their development plans the ability of the CE to improve the financial output of the economy while reducing the negative environmental impacts of industrial and municipal waste. Similarly, the Chinese National Development and Reform Commission (NDRC) 2021 has stated that the CE is key for the security of national resources. Governing policymakers are forming new laws and legislation to manage and mitigate the impacts on the natural environment (i.e., waste management and recycling) (EC, 2020; USEPA, 2021). Due to the increased level of environmental protection in new laws and legislation (in reaction to the increasing problem domain), supply chains are at risk from policy changes and supply fluctuations that may cause unforeseen costs and delays as a consequence of the environmental problem (i.e., material prices or system changes) (Ghisellini *et al.,* 2018; Tazi *et al.,* 2021; Giorgi *et al.,* 2022). The application of the CE, which requires long-term innovation, provides security from unforeseen expenditure by securing new sources of materials and developing in tandem with laws and legislation. Overall, in terms of value for the economy, the CE provides new sources of materials, resource security, new secondary markets, increased employment, and reduced risk from changes in government policy, as well as reduced expenditure for the government. These however are not inclusive of all economic development plans and select aspects have been prioritised (e.g., China and resource security).

Within the construction industry, the economic value of the CE in terms of economics is similar. Construction materials used can be utilised within the same system (i.e., a new project) or within other industrial systems (i.e., sold as a secondary resource for remanufacture) (Ghaffar *et al.,* 2020; Ferdous *et al.,* 2021; Tazi *et al.,* 2021). In comparison to other industries, the size and complexity of the construction supply chain provides a variety of integrated industrial resources for closed-loop development (Ghisellini *et al.,* 2018; Benachio *et al.,* 2020; Munaro *et al.,* 2020). The materials used within construction components are less complex than other industries and within their end-of-life stage are still valuable as secondary resources (Ferdous *et al.,* 2021; Tazi *et al.,* 2021). Similarly, the construction industry can reuse industrial wastes from other systems as secondary materials within new products, for example, plastic as concrete aggregates (Ghaffar *et al.,* 2020; Ferdous *et al.,* 2021). Thus, creating a new closed-loop market from secondary resources that add value from the sale of waste into new economic flows or retain value by being recycled within the same system. This engenders a more diverse and robust supply chain that reduces exposure to material price fluctuations, which is also deemed valuable within the economy for governments, organisations and consumers who gain variety from a diverse market (Charef *et al.,* 2022; Giorgi *et al.,* 2022). Overall, the CE within the construction industry provides economic resource value through smarter management of resources and industrial symbiosis.

3.2 Environmental value

The prominent factor of the CE is the environmental value gained from a reduced exchange between industrial and environmental systems (MacArthur, 2013). Over the lifecycle of a product waste is produced and indiscriminately exchanged with the environment disrupting the natural equilibrium. Increased environmental volatility is now more frequent due to this exchange, causing disruption and damage to biological and anthropogenic systems (Working Group II, 2022). The exchange of anthropogenic matter with the natural environment is driving the instability within the biosphere causing pollution (e.g., plastic waste and micro plastics). The damage from volatile environmental conditions (e.g., extreme weather), damages assets (e.g., infrastructure and stock) and further exchanges this damaging matter (e.g., plastic) with nature, causing a snowball effect that exchanges matter and requires further damaging resource extraction to replenish stock (Hsiang *et al.,* 2017). However, the application of the CE within the supply chain can reduce the levels of material extraction and supply, and consequently the impact it has on the natural environment. The application of the CE eases the economy's strain on the environment by reducing the resources required for products and creating new sources of resources by recycling waste with the 3Rs (Webster, 2017). Furthermore, by designing products and materials to be recovered and ensuring that they are symbiotic with natural processes of waste (e.g., compostable) (MacArthur, 2013). Ultimately, providing value through a symbiotic relationship between industry and the natural environment as opposed to the wasteful consumption and pollution of nature that brings forth repercussions for the environment, society, and economic activities.

The construction industry contributes to 20-35% of the waste produced annually (MacArthur, 2013). Thus, small CE innovations can produce larger results than within smaller industrial sectors and supply chains (Ghisellini *et al.,* 2020; Ferdous *et al.,* 2021). Furthermore, the lifecycle of construction projects span decades more than products in manufacturing and consumes resources throughout in the form of utilities, maintenance, municipal waste (Munaro *et al.*, 2021). Additionally, the materials used within the construction industry are sourced from damaging industrial activities such as mining, logging, and dredging (Ghaffar *et al.,* 2020; Ferdous *et al.*, 2021). All the above have made the built environment and construction industry a target for CE innovation to achieve the targets set within governmental policies and scientific reports (EC, 2020; NDRC, 2021; USEPA, 2021). Closed-loop recycling of materials within the sector can have tremendous value in reducing resource extraction and its impact on the environment (Geissdoerfer *et al.,* 2017; Charef *et al.,* 2022). Thus, making CE innovation within the construction industry paramount due to its connection to extractive industries - furthermore, adding tremendous value to the application of the CE strategy within the sector for reducing its large environmental impact. Within construction, the CE's application provides locally sourced materials as opposed to imports, reducing the impact on the environment caused by transportation (Ghisellini *et al.,* 2018). Additionally, downcycled secondary resources like glass, rubble, and plastics can be widely used within cement, tiling, and as aggregates allowing closed-loop recycling within the sector (Ghaffar *et al.,* 2020; Ferdous *et al.,* 2021). Overall, the environmental value provided by the application of the CE strategy is a more hospitable and stable environment for biodiversity and the health and well-being of consumers.

3.3 Social value

The value of the CE to society initially comes from a symbiotic relationship between industry and the environment (MacArthur, 2013; Tazi *et al.*, 2021; Giorgi *et al.*, 2022). In a construction context, this symbiosis is even more essential due to its convoluted (and inextricably linked) relationship with the environment, economy and society creating the anthropogenic world in which humanity exists. By reducing the impacts of economic consumption and waste on the environment through better design and consideration for the product's lifecycle, the implications on the health and wellbeing of society are also alleviated from indirect considerations for the lifecycle's implications (MacArthur, 2013; Tazi *et al.,* 2021; Giorgi *et al.,* 2022). Design considerations for the CE, also produce better quality products for the consumer as the designer must investigate and consider the products' lifecycle implications (Charef *et al.*, 2022; Giorgi *et al.*, 2022). Thus, improving the quality of the product and overall value to the consumer (Charef *et al.,* 2022; Giorgi *et al.,* 2022). CE strategies such as *product as a service* provides further value to society, increasing the lifespan of the product purchased (Adams *et al.,* 2017; Çetin *et al.*, 2021). Overall, society will largely gain value from a less damaging economy, producing higher quality products and services. Additionally, the economy will be more diverse with new opportunities, businesses, products, jobs, and a reduced risk within the economy to market fluctuations (EC, 2020; USEPA, 2021). Diversity within economic markets provides security for businesses, making them more stable and independent, providing valuable security from bankruptcy and securing jobs for society (Ferdous *et al.*, 2021; Tazi *et al.,* 2021; Charef *et al.,* 2022; Giorgi *et al.*, 2022). In totality, improved economic performance within the construction industry in terms of environmental symbiosis and overall product quality provides significant value for society by creating a more prosperous environment for humanity to exist. In summary, the CE provides value across multiple domains (i.e., economy, society, and the environment) as a solution for many individual and shared implications caused by linear consumption and waste.

3.4 The barriers to value from the circular economy in construction

Barriers to achieving value from the application of the CE within the construction industry have been split into two thematic categories which are: 1) barriers to the concept and its development; and 2) barriers to the application of the CE strategy within the supply chain. Barriers to the development of the CE largely surround the level at which the academic literature and industrial guidelines have progressed knowledge – at present, the subject resides within its infancy (Ghisellini *et al.,* 2018; Bilal *et al.*, 2020; Kanters, 2020). The lack of data surrounding the practical application of the CE has limited the data available within the sector (Adams *et al.*, 2017; Ghisellini *et al.*, 2018; Hart *et al.*, 2019; Çetin *et al.*, 2021; Giorgi *et al.*, 2022). In turn, the lack of data and evidence has limited the level of guidance and knowledge within academia and governing policymakers for industry practitioners (Bilal *et al.,* 2020). These barriers to the development of the CE could, however, be attributed to the standard process of concept development between academia, governing policymaking, and industry practice. As theory develops into practical testing, evaluation is then required to further refine the theory and so on until best practice is identified (Adams *et al.*, 2017). Suggesting that this barrier is temporary to achieving value from the application of the CE strategy. This theory is further reinforced by the appearance of case studies and pilot projects in recent literature which has increased confidence in the CE concept (Ghisellini *et al.*, 2018; Ferdous *et al.*, 2021). Barriers to achieving value from CE practices within the construction industry initially begin with the long-term nature of the strategy (Hart *et al.*, 2019; Bilal *et al.*, 2020;). Long-term strategies are not often considered, especially in short-term systems typically adopted by Small and Medium Enterprises (SMEs) (Hart *et al.*, 2019; Bilal *et al.*, 2020; Çetin *et al.*, 2021). Ultimately, this myopic stance deters SMEs from adopting CE strategies within the supply chain (Hart *et al.*, 2019; Bilal *et al.*, 2020), which by design requires lifecycle stakeholder participation for holistic application and value creation (Adams *et al.*, 2017; Hart *et al.*, 2019; Kanters, 2020). Furthermore, the sector's large lifecycle and high quantity of stakeholders increase the complexity in deciphering responsibility for the application and performance of CE strategies within the lifecycle (Hart *et al.*, 2019; Çetin *et al.*, 2021). Overall, the barriers mentioned suggest that collaboration and communication within the lifecycle are key to overcoming the long-term barriers between stakeholders to achieve value from CE practices.

Additionally, the lack of design for the CE strategy within the construction industry is also a barrier to achieving value from CE application (Giorgi *et al.*, 2022). Without designing for closed-loop resource recovery, the full value from the CE cannot be achieved (Hart *et al.*, 2019). The lack of CE design within the system can also pose a barrier due to the size and complexity of the sector's supply chain (Adams *et al.*, 2017; Kanters, 2020). A lack of education amongst designers and practitioners also further the barrier to achieving value from CE applications (Ghisellini *et al.*, 2018; Giorgi *et al.*, 2022). Incorrect application of CE practices does not achieve the same value as a uniform holistic application (Kanters, 2020), and can have a rebound effect that is more costly than linear methods to the environment or financially (Ottelin *et al.*, 2020). The rebound effect is a leading barrier as, within the correct infrastructure, the application and recovery of resources can have little value or negative implications (Giorgi *et al.*, 2022). Furthermore, due to the lack of infrastructure, the cost of privately innovating for recovery can incur high short-term costs mitigating long-term value, deterring innovators and trailblazers (Bilal *et al.*, 2020; Kanters, 2020). In all, the barriers to achieving value from the CE strategy within construction can be overcome via the education and design for closed-loop resource flows; the application and communication of the CE strategy throughout the stakeholders and processes of the lifecycle (Cradle-grave); and finally, the correct infrastructure to manage and retain value from waste resources in all the stages of the lifecycle (Cradle-grave).

Table 2 Barriers to achieving value through the implementation of the CE in the construction industry

CE BARRIERS	DESCRIPTION	REFERENCE
Low level of adoption in industry	Multiple barriers and a lack of incentives have reduced adoption within the construction industry preventing data collection and widescale innovation.	(Adams *et al.*, 2017; Ghisellini *et al.*, 2018; Hart *et al.*, 2019; Bilal *et al.*, 2020; Çetin *et al.*, 2021; Giorgi *et al.*, 2022)
Lack of research on the performance of the concept	Research within the construction industry on the CE is still in its early stages and requires more data collection on the practical application for the development of best practice.	(Adams *et al.*, 2017; Ghisellini *et al.*, 2018; Hart *et al.*, 2019; Bilal *et al.*, 2020; Kanters, 2020; Çetin *et al.*, 2021)
Lack of incentive to transition	More incentives are required to overcome this barrier and incentivise transition.	(Adams *et al.*, 2017; Ghisellini *et al.*, 2018; Hart *et al.*, 2019; Bilal *et al.*, 2020; Çetin *et al.*, 2021)
Lack of government support	Although support is increasing, a lack of laws, legislation, and supporting infrastructure is posing a barrier to the adoption of the CE.	(Hart *et al.*, 2019; Bilal *et al.*, 2020; Kanters, 2020; Çetin *et al.*, 2021; Giorgi *et al.*, 2022)
BARRIER TO VALUE	**DESCRIPTION**	**REFERENCE**
Long term strategy	The CE is a long-term strategy which poses a barrier for organisations that work within the short-term.	(Hart *et al.*, 2019; Bilal *et al.*, 2020; Çetin *et al.*, 2021)
Lack of end-of-life design	Failure to design for the CE reduces the amount of value that can be recovered through the lifecycle.	(Adams *et al.*, 2017; Ghisellini *et al.*, 2018; Hart *et al.*, 2019; Çetin *et al.*, 2021; Giorgi *et al.*, 2022)
Rebound effect of CE application	Some wastes are more costly or damaging to work within a closed-loop and therefore cause a rebound effect.	(Ottelin *et al.*, 2020; Giorgi *et al.*, 2022)
Size and complexity of construction	Construction is complex in comparison to other industries as it has an exacerbated supply chain structured around a project culture including multiple stakeholders.	(Adams *et al.*, 2017; Ghisellini *et al.*, 2018; Hart *et al.*, 2019; Bilal *et al.*, 2020; Kanters, 2020; Çetin *et al.*, 2021)
Lack of best practice	The construction industry works within 'best practices' making new innovations difficult to incorporate within the industry.	(Adams *et al.*, 2017; Ghisellini *et al.*, 2018; Hart *et al.*, 2019; Çetin *et al.*, 2021; Giorgi *et al.*, 2022)
Point of responsibility within lifecycle unknown	Due to the large number of stakeholders within the construction lifecycle, the point of responsibility for the implications and therefore application of the CE is debated.	(Adams *et al.*, 2017; Ghisellini *et al.*, 2018; Hart *et al.*, 2019; Çetin *et al.*, 2021)
Education within designers and practitioners	Without full development of theory, the education of CE practices is difficult within the construction industry.	(Ghisellini *et al.*, 2018; Hart *et al.*, 2019; Bilal *et al.*, 2020; Kanters, 2020; Çetin *et al.*, 2021; Giorgi *et al.*, 2022)
Lack of infrastructure for recovery	Infrastructure for closed-loop recovery and recycling are still in the early stages of application and development. Hindering trailblazers innovating for the CE.	(Adams *et al.*, 2017; Ghisellini *et al.*, 2018; Hart *et al.*, 2019; Bilal *et al.*, 2020; Kanters, 2020; Çetin *et al.*, 2021; Giorgi *et al.*, 2022)
Cost of innovation and products	The cost to innovate within the CE can be expensive and therefore increases the cost of the product making the strategy unfeasible.	(Adams *et al.*, 2017; Ghisellini *et al.*, 2018; Hart *et al.*, 2019; Bilal *et al.*, 2020; Kanters, 2020; Çetin *et al.*, 2021)

4 Findings and Discussion

The findings from the literature review identified that the CE within the construction industry is increasing in popularity as a solution to linear consumption and waste (Benachio *et al.,* 2020; Munaro *et al.,* 2020). However, it was identified that there is a limited level of CE adoption within the sector, posing a barrier to the development of the CE concept in construction. This lack of adoption within the sector suggests a rationale for the infancy of the practical data within the literature. Furthermore, within the literature a lack of education was identified as a key barrier to CE application within the construction industry (Hart *et al.,* 2019; Kanters, 2020). Another factor identified is the absence of incentives to transition to a CE strategy (Hart *et al.,* 2019; Bilal *et al.,* 2020) – overall, suggesting a dearth of knowledge amongst academics and practitioners on the practice and value of the CE concept. Furthermore, the literature review conducted found that the CE as a strategy for waste mitigation within the construction industry has numerous aspects which could be considered valuable. Specifically, the review focussed on the economic (Ferdous *et al.,* 2021; Charef *et al.,* 2022), environmental (Ghisellini *et al.,* 2018), and social value (Hart *et al.,* 2019; Giorgi *et al.,* 2022). The analysis of government goals for the CE, identified that aspects of the value gained from the CE can by prioritised by the organisation, such as the western use of the CE for environmental impact reduction or China's economic resource-focused use of the strategy. This suggests that the value of the CE can be used to incentives a variety of companies that could be seeking economic, environmental, or social value and the focus should be considered when incentivising organisations. Analysis of the values of the CE within construction found that there are multiple aspects that are valuable; to the economy through the retention of resource in the system, with valuable environmental impact reduction for the industry, and industrial symbiosis for invaluable health and well-being in society; all of which are inextricably linked to one another.

In the review of literature, the barrier between theory and practice was highlighted as the first barrier to overcome in the transition to a CE by Bilal *et al.* (2020). Therefore, it can be assumed the industry's development of the CE is still overcoming the initial barriers to gaining practical data from the application of the concept. Hence, the limited number of case studies identified within the literature (Adams *et al.,* 2017; Ghisellini *et al.,* 2018; Hart *et al.,* 2019; Çetin *et al.,* 2021; Giorgi *et al.,* 2022). Furthermore, this highlights the requirement of CE professionals to promote the value and incentives of the CE within the sector to increase industry adoption and data collection of the performance of the strategy. Other barriers stem from this unavailability of data viz; the notable absence of best practice, which is desired for long life products such as those within construction (Hart *et al.,* 2019; Giorgi *et al.,* 2022), the symbiosis of closed-loop circular supply chains (Ghisellini *et al.,* 2018; Kanters, 2020), and cost of innovation (Bilal *et al.,* 2020; Çetin *et al.,* 2021). Thus, the initial and overall barrier of the CE identified within the review of the literature is the infancy of the theory and the lack of data on the practical application and management of the CE strategy for informing education and practice within the sector. Overall, this suggests that the demand for an alternate path by governments and the IPCC is driven without informing or educating the industrial sector, or that the research on the best practice for the CE is unknown and therefore cannot be used to inform the industry. On the assumption that both are true to some degree it highlights the lack of knowledge on the CE in practice and comments on the stage at which the literature has developed. And finally, in the face of a planetary sustainability crisis, the requirement to change to a less impactful system has never been higher or as urgent, while the knowledge and application of the mitigation strategies are still wildly underdeveloped for the widescale implementation needed for industrial symbiosis in the Anthropocene.

5 Conclusion and Future Research

The research findings identified a notable dearth of knowledge within the construction industry surrounding the value of the CE strategy dissuading innovation. A lack of innovation is posing a further barrier to the development of the CE and requires addressing to advance CE research within the sector. The value gained from the CE strategy is widespread across the economy, environment, and society and thus, the incentive should be appropriated based on the desired output of the system. Furthermore, the research findings suggest that value from the CE should be purposefully selected to incentivise the strategy on a case-by-case basis to increase the adoption of the strategy. Thus, proposing a possible solution to the lack of adoption and incentive within the construction industry that hinders data collection required for the development of the concept. The novelty of this research is the contribution to knowledge on understanding the rationale of the novice practitioner and researcher in terms of understanding value in the CE. The study’s limitations are largely related to access to data on the evaluation of the practical application of the CE strategy within the sector. Furthermore, the level of explanation required to fully contextualise the value and barriers to value of the CE strategy to the sector cannot be comprehensively summarised within a concise and lucid overview of the literature. Future research could follow several paths, including a more detailed investigation into the value of the CE within the construction industry; determination of primary barriers to developing the CE within the sector and how to overcome these; and the practical application of the CE strategy to analyse the quantitative value to develop best practice and incentivise innovation with case study data.

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Opportunities for Energy Efficiency Using Biomimicry Strategies in the Construction Industry

Nicholas Donohoe[1] Alan Todhunter[1] and Laura Almeida[1*]

[1]School of Engineering Design & Built Environment, Western Sydney University,
Locked Bag 1797 Penrith NSW 2751, AUSTRALIA

19339030@student.westernsydney.edu.au; a.todhunter@westernsydney.edu.au; l.almeida@westernsydney.edu.au
* Corresponding author

Abstract:
Biomimicry studies the mimicked solutions of natural structures, processes, or systems that have evolved over time. It is seen as an alternative solution to sustainability issues concerning the built environment. This paper summarises a study performed, by analysing the opportunities for implementing biomimicry, also known as biomimetics, in the construction sector as a reliable solution to promote energy efficiency in buildings. The methodology adopted was a narrative literature review performed in a structured manner. Prior to the methodology a general literature review was completed to identify and describe key components of the research which developed a structure for the paper to adhere to. Following the methodology, a qualitative analysis of existing examples of the implementation of biomimicry in the built environment was argued against the increased energy efficiency. Results have shown that biomimicry is a reliable alternative to reducing energy usage in buildings. Additionally, the combination of biomimetic principles within multiple elements of the building increases the effectiveness of the overall strategy. Most of the studies examples show that the standard implementation of biomimetic solutions is within the façade, structure, or HVAC system. Results also show that significant energy savings resulted from a behavioural or eco-system level of biomimicry, where the building mimics the process or function of a natural structure, system, or process. Due to its recent recognition as a science and alternative architectural solution, biomimicry is yet to be seen as an emerging sustainable strategy.

Keywords:
Biomimetics, biomimicry, construction, energy efficiency, sustainability

1 Introduction

Biomimetics is the study of mimicking a natural process, system or structure, and using its evolved solutions within the built environment. The construction industry is regarded as unsustainable, and detrimental to the environment, due to its high energy use among many other factors such as water usage, use of raw resources, impact to natural land and excessive waste (Ding 2008). To solve these issues presented to the industry, conventional and alternate solutions are needed. Biomimicry is seen as an alternative solution, with the potential to solve all problems within the built environment (Harman 2013).

Due to the construction industry's impact on environmental, economic, and social impacts, it is critisised as being unsustainable (Pero et al. 2017). Once a building is constructed, it is extremely beneficial for them to be sustainable and maintain an extended, clean, life cycle. This is a desirability as it is estimated that the construction industry is responsible for using 50% of raw materials, globally (Sev 2009). This abundance of material mining, transportation and usage accounts to significant carbon emissions, as well as energy expended during the actual construction of the building is not where energy usage ceases. Buildings and the construction sector are directly responsible for the usage of over one third of the global energy usage, as well as over 40% of the global carbon emissions (International Energy Agency 2020).

Research into the alternate solution of biomimicry is required as it is a new type of science proposed in the industry. To further analyse the existing examples of biomimicry as a solution to energy usage, a narrative literature review was employed to draw conclusions on the effectiveness of these buildings. Existing biomimetic structures were found through inputting keywords into search engines such as Google Scholar and Scopus, whilst also researching within the WSU Library database. Each example was then reviewed in a narrative literaure review and collating like for like information in each paper in order to compare each building accurately. After analysing the research, discussions and a conclusion can made on the potential future trends surrounding greater implementation of biomimetic principles within the built environment.

Biomimetics and Sustainability: Biomimicry has a deep history that can be traced back to 1482, where Leonardo da Vinci developed detailed sketches of a flying machine after being inspired by the flight of birds and bats. Later, in the early 18th century, during the construction of the first underwater tunnel, Marc Brunel was influenced by a naval shipworm, a saltwater clam that he had observed boring into wood without being crushed, by gradually bracing the walls with a thin layer of limestone (Kennedy 2017). This method of tunnelling is still employed today, whether it be using dynamite or a boring machine. In 1941, George de Mestral became intrigued by a plant's ability to stick on his clothing. After analysing these burs under a microscope, de Mestral identified that these burs had tiny hooks that could attach themselves to any fabric, and thus the idea for Velcro was invented (Swearingen 2016).

The levels of biomimicry can be divided into three main categories being form, process and eco-system (Benyus 1997). Zari (2007) further explains these levels and explains the terms organism (form), behavioural (process), and eco-system. Each level refers to a different method of biomimetic implementation and can be applied to applications within the built environment. The organism level of biomimicry refers to a plant or animal that has been mimicked in part or whole and how a building can implement their principles. The behavioural level refers to how an organism behaves or interacts within its environment. The eco-system level refers to how a building can mimic the multiple functions of an organism which allow them to successfully operate. Zari (2007) further breaks down these levels of biomimicry to create five dimensions in which each biomimetic application exists. These are form (how it appears), material (what it is made of), construction (how it is built), process (how it operates), and function (what it can accomplish).

Innovative and creative advancements in architecture and building are constantly being researched and developed, and often the designer is inspired by a range of different sources. One of these methods is to observe nature and analyse ways in which it has evolved to overcome certain environmental challenges (Yurtkuran, Kırlı & Taneli 2013). Nature is often regarded as optimising its environment by adapting and evolving, to live whilst using the least amount of energy required and making the most of the available resources (Amer 2019). Amer (2019) also clarifies that biomimetics in the construction industry directly refers to the understanding of natural principles and procedures to directly relate this knowledge to technological applications.

Although the origins of biomimetics stem from multiple industries and sectors, the importance, and benefits of biomimicry in the built environment are becoming more apparent because of recent applications. Biomimicry has the potential to create more sustainable buildings using regenerative architecture and innovation (Helmy & Aboulnaga 2020).

The sustainability of the built environment is often criticised due to its lack of forward thinking in terms of reducing the environmental impact of the construction industry. The definition of sustainability has been amended over time, with ambiguity surrounding the current meaning of the term (Moore et al. 2017). Although the definitive meaning regarding sustainability has been debated over time, there are three clear parameters of sustainability, being social, economic, and environmental. UCLA Sustainability Charter (2016) define sustainability as the ability to create a healthy, thriving, and diverse community for current and future generations, through the unification of a healthy environment, social fairness, and economic exuberance. For the construction industry to achieve these goals, buildings need to be designed and constructed in a sustainable manner.

Energy efficiency in the construction industry: Buildings and the construction sector are directly responsible for the usage of over one third of the global energy usage, as well as over 40% of the global carbon emissions (International Energy Agency 2020). It is often misunderstood that energy is a resource that is abundantly available, with simple everyday items such as household lights and heating and cooling obscuring the reality of this perception. For example, Sagan (2000) estimated that the human population currently uses 70% of the available energy on Earth; however, this percentage is likely to have increased to 75% in 2020 (Kurzgesagt 2020). Therefore, as the population begins to use most of the energy available, it is critical that renewable processes and energy efficiency are employed within the construction industry. Moreover, most of the energy produced in Australia is from non-renewable resources such as coal and natural gas, which correspond to 79% of Australia’s energy resources (Department of Industry, Science, Energy and Resources 2021).

Embodied energy refers to the energy expended to construct and demolish a building, inclusive of material production, transportation, construction, renovation and finally, demolition (Dixit et al. 2012). According to Green & Taggart (2020), 25% of the total energy used in buildings is related to embodied energy. The other 75% corresponds to the operational energy, which is generally much higher than the embodied energy and corresponds to the energy used in the operation of the building for heating and cooling, lighting, operation of building appliances, and other similar events (Dixit, Culp & Fernandez-Solis 2013). The embodied energy combined with the operational energy is referred to as the buildings’ total life cycle energy. Comparatively, with the recent increase in buildings with reduced operational energy, the embodied component has seen an increase (Green & Taggart 2020).

2 Research Methodology

This research used secondary data that was qualitatively summarised after being collected by informal or subjective methods. To ensure the reliability of this research, a narrative review was adopted as methodology. Data on existing examples of biomimetic developments in the built environment and the sustainability impact of these developments in direct relation to energy efficiency have been searched. This research method has been chosen to provide a broad perspective on the possibilities of biomimicry in the construction industry. The narrative review allows flexibility in the research problem to be amended as the review is completed (Kysh 2013). The collected data combines scholarly articles from databases such as the WSU Library eResources and the search engine Google Scholar, and the following combinations of keywords were used during the data search:

("biomimicry" OR "biomimetics" OR “nature”) and ("Construction" OR "built environment" OR "building") and ("energy efficiency" OR "operational energy" OR "operational carbon" OR "sustainability") and ("case study" OR "case studies")

2.1 Method

The aim of this research was to collect data on existing examples of biomimetic developments in the built environment and the sustainability impact of these developments in direct relation to energy efficiency. From the scholarly articles collected from the above-mentioned databases, the data was initially analysed to determine the quality of the publication, ensuring that the information presented was true and reputable. This determination was made by developing a summarising matrix of the information sources and ideas. An example of this matrix is in Table 1.

Table 1. Example of the proposed resource summarisation matrix

Year	Country	Type of Publication	Type of Biomimicry (Behavioural, Physical, or System)	Impact on Energy Efficiency	Reference	Summary

Reviewing the papers led to further expansion of the summarisation matrix to include Year, Location, Type of Paper, Title, Citation Summary, Biomimetic Approach and Relation to Part of Building, Type of Biomimicry, Type of Development, Impact on Energy Efficiency and Other Information.

2.2 Choice of narrative literature review

A systematic review was initially proposed for this research. However, the main feature of systematic reviews was the requirement of more than one author and having an average duration of 18 months (Kysh 2013). The systematic review also requires a clearly defined clinical question to be proposed at the commencement of the review. In contrast, due to the novelty of the topic, a narrative literature review only requires a general topic or question to be proposed, with the goal of the review to provide a summary of the chosen topic or question (Kysh 2013). The flexibility of this method and the short time available in line with an Honours degree with a duration of 2 semesters were detrimental to the selection of the proposed method.

The narrative analysis allowed determining whether implementing biomimetic principles in the built environment would positively impact the sustainability of the construction industry in terms of energy efficiency. It has been identified that mid-rise commercial-style buildings benefit the most from sustainable, biomimetic implementations, whilst there is a lack of information regarding small and large developments. From the information collected and analysed, a discussion will be made on the predicted future trends of biomimetic implementation in the built environment.

3 Findings and Discussion

The levels of biomimicry were divided into three main categories: form, process and eco-system (Benyus 1997). The results of the literature review identified 28 papers from the keyword search.

3.1 Levels of Biomimicry

From Figure 1, the results produced determine a range of statistics, being that from the 28 examples analysed, 14 mimic the organism, 15 mimic the behaviour, and 10 mimic the eco-system. The total amount of 39 is higher than 28 due to some developments implementing a range of biomimetic applications. The greatest spread across each level of biomimicry is found within the organism category, whilst the behaviour and eco-system categories are mostly grouped into the process and function level. This highlights that it is either difficult to mimic the form, material and construction of the behaviour or eco-system category, or this is an area that is lacking research and practical applications. The most common levels of biomimicry implemented within the researched examples are organism (form), behaviour (process), and eco-system (process). It can be determined that organism (form) is the easiest method of biomimetic adaptation, as a structure only needs to mimic the appearance of a natural organism, however, the behaviour and eco-system (process and function) are the most in-depth applications with the best results in terms of energy efficiency. It can also be considered that the most difficult level of biomimicry to imitate is material, with only 1 example across the 39 studied.

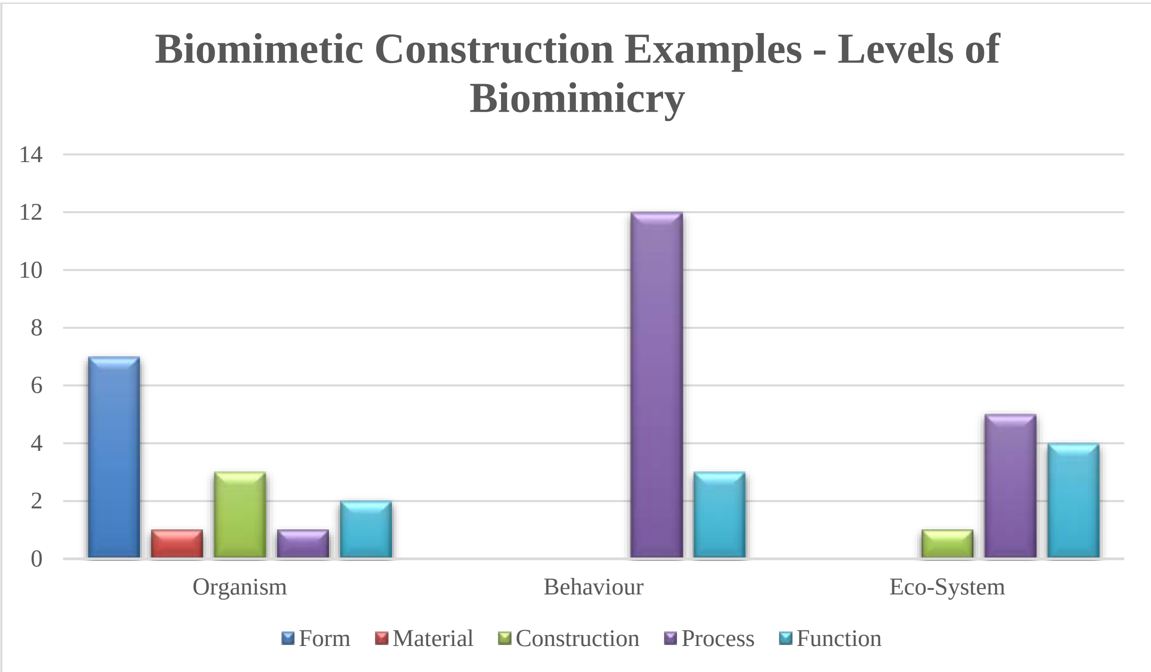

Figure 1. Levels of biomimicry within researched examples

3.2 Project Element

As identified in the literature review, the building skin or façade is often the project element that implements the biomimetic approach. This is likely because this is where the built environment interacts with and borders the natural world. Using the extracted data, the following chart was produced to allow a comparison of the 28 examples studied.

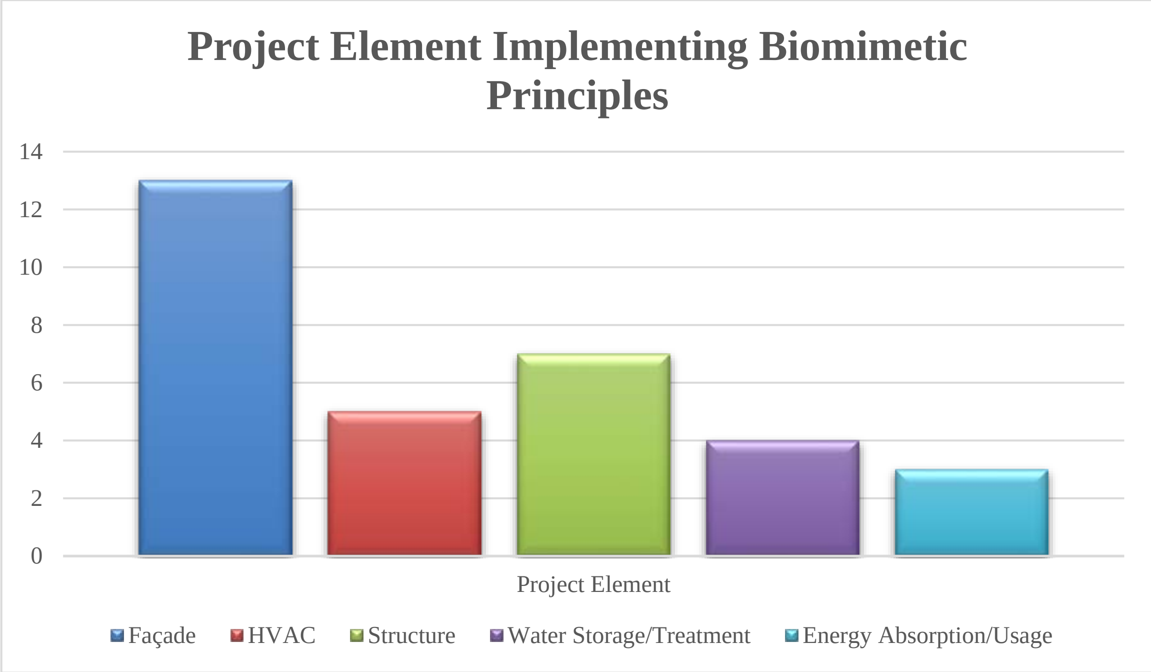

Figure 2. Biomimetic project element within researched examples

The idea that the building façade is the most common method of biomimetic implementation is proven in Figure 2 above, where 13 out of the total 28 examples feature biomimicry in the façade. Although only 28 buildings, developments or products were studied, 4 examples employ a combination of biomimetic principles within the project, hence the total value of 32 within Figure 2. When comparing these results, it can be determined that the entire city developments are most likely to utilise water storage/treatment and/or energy absorption/usage. The structural examples are the second most common and range from a small sculpture in the form of the Tree Pods in Boston to a high-rise building, being the Gherkin Tower in London. This shows that structural inspiration can be drawn from small organisms within the natural world, which is then transformed into large, energy efficient developments. Where biomimetic strategies are employed within the HVAC system of a development, significant energy efficiency can be seen. This is because HVAC systems within traditional developments use an abundance of operational energy, and reducing this requirement has a positive impact on the environment and sustainability of the construction industry. Although the façade is the most common project element, developments that employ a combination of systems produce the best results. This is proven within Melbourne CH2, where the façade mimics the properties and functions of a tree, whilst the HVAC system is inspired by the natural cooling mechanisms of a termite nest. This combination of biomimetic applications resulted in an 82% reduction in energy usage and 87% reduction in GHG emissions when compared to a traditional, midrise office building. It can be determined that each project element assists in the development of producing energy efficient properties, whether it be a direct reduction in operational due to passive heating and cooling or reducing embodied energy by efficiently using renewable construction materials within the structure.

3.3 Country of Building

Biomimetic developments have been constructed in many countries around the world, with 28 of the researched examples spread across 12 separate countries. The results of the research matrix have been tabled in the chart below.

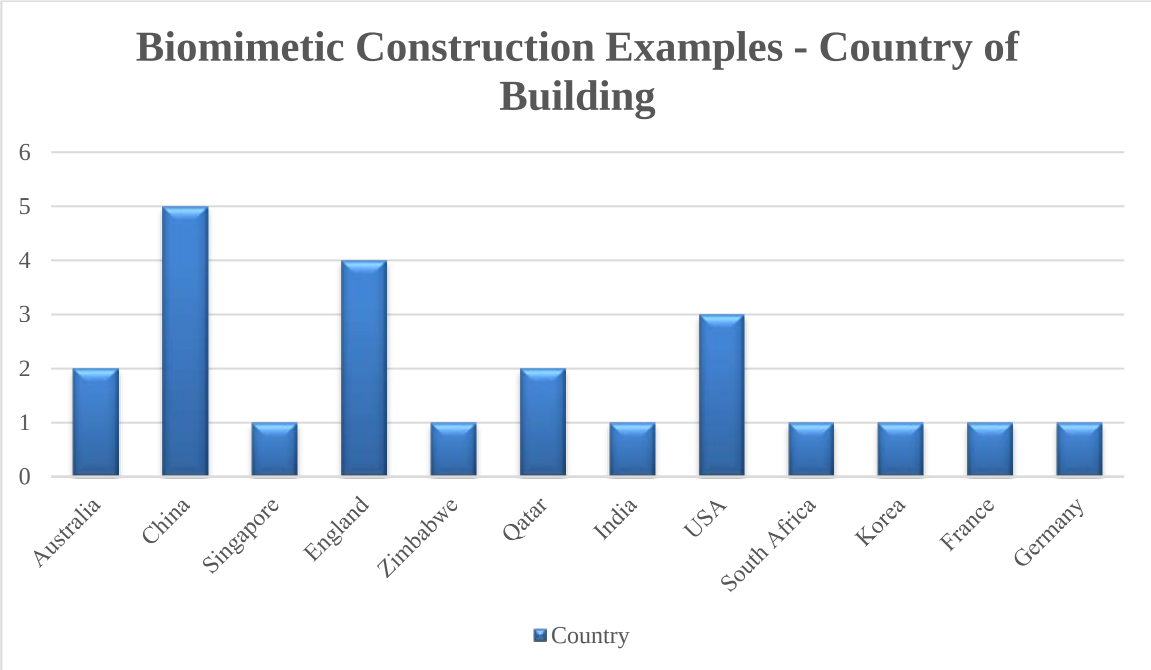

Figure 3. Country of biomimetic building/development within researched examples\

Figure 3 conveys the quantity of biomimetic examples within separate countries. It shows that the countries with the most developments are China, England, USA, Australia, and Qatar, with the remaining countries having one example in each. This raises the question that there may be a direct link between the developments and the challenging climates of the respective countries. Each country contains vastly different climates, for example, the cool, oceanic climate of England and Melbourne, Australia, compared to the arid, desert climate of Qatar (Köppen climate classification n.d.). Although these climates are significantly different, they pose climate conditions that can benefit by drawing inspiration from organisms and species that have survived and adapted to the harsh environment. This idea that harsher climates more commonly implement biomimetic approaches is an opportunity for further research. However, it can also be theorised that richer, more developed countries are able to invest in innovative design and construction methods. Although, as proven by Melbourne CH2, the initial larger investments when compared to traditional buildings can be paid back due to reductions in operational energy and GHG emissions.

3.4 Year of Paper Publication

Benyus (1997) introduced the term biomimicry to the built environment in the late 1990s, and although it was not an entirely new concept, it allowed the term to gain greater exposure which led to practical applications within the industry. The published date of the 14 papers researched and analysed into a graph which is shown in Figure 4 below.

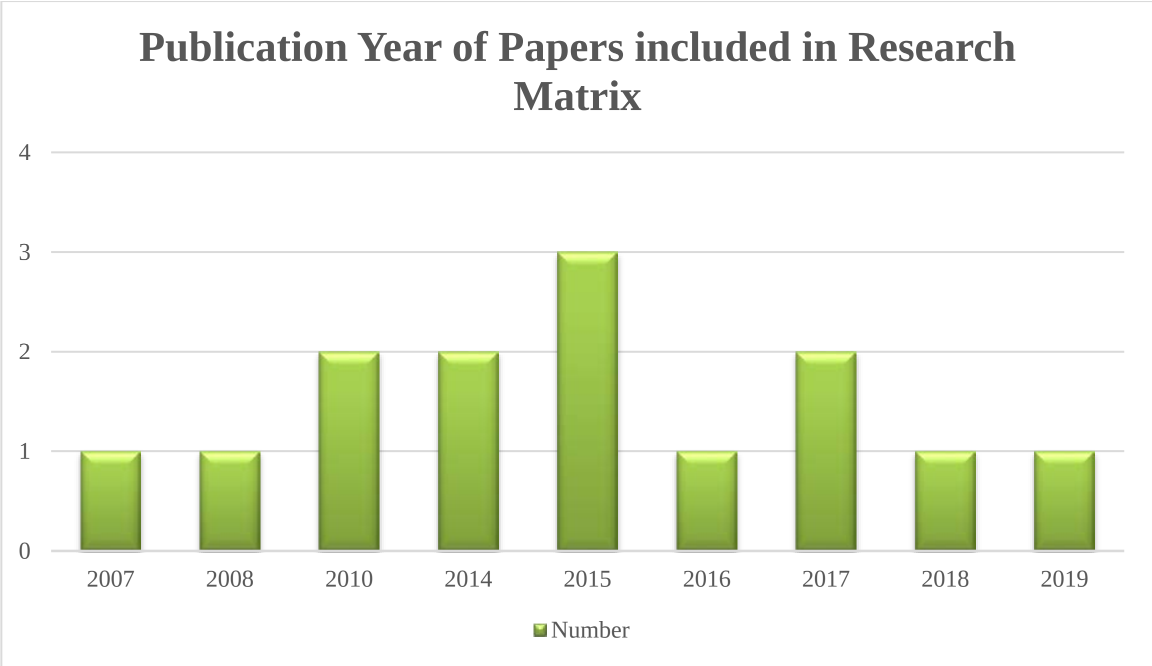

Figure 4. Year of published papers within researched examples

The concept of biomimicry is a new field within the built environment; however, it is gaining popularity as a real solution to issues in the construction industry. The popularity of research and practical applications in biomimicry has increased in recent years since the term was introduced in the late 1990s. This is evident in Figure 4 above, as of the 14 papers researched, 10 are within the last decade, and only 4 in the decade prior. This chart also highlights the lack of existing examples within the built environment. Although biomimetic implementation within the built environment is a new form of architecture, it is expected that examples in the construction industry will increase in the future. This can be assumed because of further exposure to the term, as well as studies of the current developments, and their positive impacts on energy efficiency and sustainability.

3.5 Type of Development

The types of development column within the research matrix have been grouped into similar styles of developments. For example, the Beijing National Stadium and the Beijing Aquatic Centre were grouped into the category of Sports Centre. This lets the data to be collated into related building categories, which allows the scope of biomimicry to be analysed whilst identifying trends. From the 28 developments included within the research matrix, Figure 5 below has been developed.

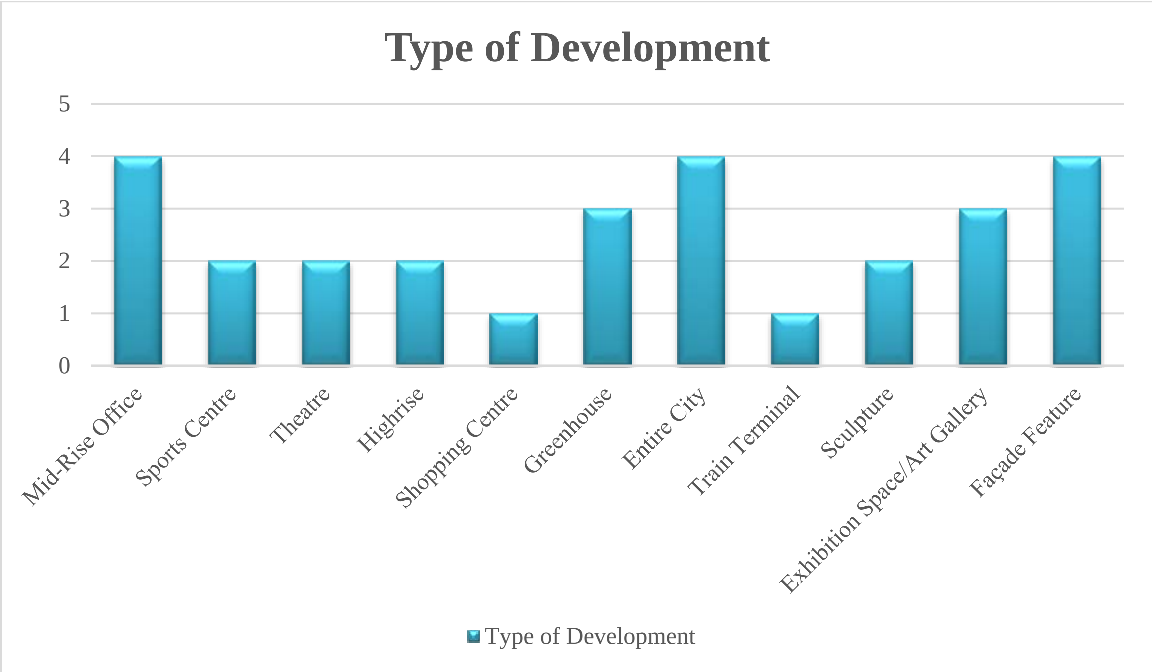

Figure 5. Type of development within researched examples

Figure 5 shows the significantly wide range of biomimetic implementation within the built environment, ranging from the entire city of HOK Lavasa in India, to the small, artificial tree sculpture of the Boston Tree Pods. This highlights those biomimetic applications can be included in most developments. The most common developments which are inspired by biomimicry are mid-rise offices, entire cities, and features of a façade. The high amount of façade feature examples further reinforces that the building skin is the most common building aspect which mimics nature.

Although most types of developments are covered in the research matrix, there are no existing examples of implementation within the housing residential industry. This is an opportunity for further research into how affordable biomimetic applications can be included in the construction of houses which would ultimately result in beneficial energy efficiency. The introduction of biomimicry within the residential industry may cause resistance from developers and builders due to this cost premium.

4 Conclusion and Further Research

According to this research organism (form), behaviour (process), and eco-system (process) were the most common levels identified in projects where the biomimicry concept was implemented. There was a lack of existing examples in relation to behaviour and eco-system (form, organism, and construction). The element of the project that most commonly emulates nature in buildings from an energy point of view was the façade, followed by structure and HVAC where significant energy savings in the operational stage of buildings can be achieved. Entire city developments are most likely to utilise water storage/treatment and/or energy absorption/usage. Structural inspiration can be drawn from small organisms within the natural world, which is then transformed into large, energy-efficient developments. When several levels of biomimetic applications are combined, significant energy and GHG emissions reductions are expected by more than 80%. China, England, USA, Australia & Qatar were the countries where the concepts of biomimicry are more frequently adapted to buildings. There may be a direct link between the existing examples of biomimicry being located within countries or cities with harsher climates. Therefore, this result raised an opportunity for further research into whether countries with harsher climates are more likely to draw inspiration from the surrounding natural organisms, structures, or systems. Or the relationship between climate and a biomimetic building by posing the question: if a biomimetic development that draws inspiration from the surrounding nature and climate could be constructed in another part of the world with the same climate? Biomimetic studies have been increasing over the past decade when compared to the amount in the decade prior, with significantly wide range of biomimetic applications especially on mid-rise offices, façade features and at city level. Additionally, as no existing examples of biomimetic houses were found during the narrative literature review, this led to the potential question for further research on how biomimicry can be introduced to the residential construction sector. There is a potential improvement for passive systems within houses, which can reduce operational energy usage and assist in achieving BASIX certification and higher NABERS ratings, in Australia. Finally, future research is required to determine the economic benefits of constructing biomimetic developments. This poses another avenue for future research into determining the potential economic benefits of constructing a biomimetic, sustainable development.

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Estimation of Construction and Demolition Waste using Meta-Analysis

Ali Alashwal[1*] and Awornit Shrestha[1]

[1]School of Engineering Design & Built Environment, Western Sydney University, Locked Bag 1797 Penrith NSW 2751, AUSTRALIA

a.al-ashwal@westernsydney.edu.au

* Corresponding author

Abstract:

Construction and demolition waste estimation help to make important decisions during project planning and execution. For instance, contractors need to estimate the cost of the waste levy, determine waste material types and methods of hauling waste off-site, and other logistics. Waste estimation provides a benchmark to compare the actual waste generated during construction. This topic has attracted many researchers who have provided estimates of construction and demolition waste using various estimation methods. However, there is still no unified value of the waste amount to generate new estimates. The purpose of this paper is to benefit from the many studies available in the literature and use meta-analysis to synthesise and analyse previous estimates and develop a new estimate for construction building projects. Based on the analysis of 26 papers, the results of the analysis revealed a mean value of 41.31 kg per square meter of gross floor area for residential and non-residential projects (standard deviation = 21.89 kg per square meter). This result is useful to aid contractors and project managers to predict construction and demolition waste amounts and develop waste management plans.

Keywords:

Construction Waste Management, Meta-analysis, Waste Estimation, Waste Prediction

1 Introduction

The construction industry around the world generates a considerable amount of waste. For instance, during the 2018-2019 period, the total amount of construction and demolition waste was estimated to be about 27 million tonnes representing 44% of all generated waste in Australia (Pickin et al., 2020). The National Waste Report noted that construction waste has increased by 32% as compared to the last 15 years due to unprecedented development, especially in major cities (Pickin et al., 2020). Construction and demolition waste consist of three main types, which are inert materials, non-inert materials, and hazardous waste (Bakshan et al., 2015; Shang et al., 2013). The inert type includes materials such as soil, rocks, sand, and masonry. The second type includes other materials such as gypsum, metal, wood, paper, and plastic. The last category includes hazardous waste such as asbestos, paint, acids, bases, and other chemicals. Most of the generated waste is masonry materials, which consist of rubble, concrete, bricks, and others. Different types of construction waste are generated during the different phases of the project. For example, at the early stage of construction, most waste is in a form of inert materials such as soil and organic materials. Metal, glass, and masonry waste are often generated during the construction stage. Drywall/gypsum and asbestos may be generated during the renovation and demolition stages. Waste management strategies and processes aim to prevent, reduce, reuse, and recycle waste during the different stages of the project.

Waste estimation is an integral process of waste prevention. The purpose of waste estimation is to provide information regarding the predicted amount and type of construction waste at the early stage of the project to make decisions and conduct informed planning. With an accurate outcome, waste estimation can be a proactive and cost-effective process to manage waste. In addition, waste estimation provides quantitative and qualitative information to aid future forecasts. Waste estimation is beneficial to contractors, property developers, consultants, and local authorities to facilitate future planning of waste management (Mahayuddin & Zaharuddin, 2013). Therefore, waste estimation is important to develop waste management plans to manage and control waste effectively during the construction and demolition stages. Contractors need to use reliable information to plan waste logistics on site such as waste levy charges, number of bins on site, methods to handle waste on site, and haulage waste off-site. Besides, waste estimation and the development of the Waste Management Plan provide a method to benchmark and control waste during project execution (Lu et al., 2016). For effective waste management, it is important to know what is being generated, how much is being generated, and what is the fate of what is being generated (Paz & Lafayette, 2016).

The previous discussion indicates that accurate waste estimation is important for effective waste management, but it is difficult to attain in practice. This is because projects differ based on size, location, construction methods used, technology, and the variety of construction materials used in construction. On the other hand, there are different methods and approaches that can be used to estimate and predict construction waste. Several studies produced different estimates of the amount of waste based on the constructed area or volume. In New Zealand, for instance, Domingo and Batty (2021) provide an estimation of the amount of waste as 63.74 kg per square metre of the built-up area of residential building projects. Many studies in the literature provide similar or different estimates based on project type, the construction method used, and location. Therefore, the purpose of this paper is to develop an estimation of construction waste by taking advantage of the many estimates provided in previous research. The next section provides an overview of waste estimation methods from the literature followed by difficulties of waste estimation in construction.

2 Waste Estimation Methods

Construction waste estimation methods can be categorised into two main approaches: actual quantification and forecast quantification. The actual quantification includes direct measurement of waste amount on-site using different methods such as waste sorting, weighing, and observation (Bakshan et al., 2015; Mah et al., 2016). Other actual quantification methods include material flow analysis. On the other hand, the forecast quantification approach is the approximation or prediction of waste amount and type generated using historical data. In the forecast quantification approach, several mathematical modelling can be used to facilitate the estimation based on the availability and accuracy of data. Examples of models used in waste forecasting are simple linear and mathematical equation models (Bakshan et al., 2015; Bossink & Brouwers, 1996; Solís-Guzmán et al., 2009), linear regression models (Paz & Lafayette, 2016; Sáez et al., 2018), S-curve and Artificial Neural Network model (Lu et al., 2016), Building Information Modelling (BIM) (Akinade et al., 2018; Lu et al., 2017), and Big Data (Bilal et al., 2016). Due to issues in the availability and accuracy of data, other predictions models can be used to estimate waste such as Grey Model (1,1) (Shang et al., 2013), Gray Model – Support Vector Regression (GM-SVR) (Song et al., 2017), ARIMA (Song et al., 2015), Gray Verhulst prediction model (Wang et al., 2016), Exponential Smoothing Method (Qiao et al., 2020), and Gene Expression Programming (GEP) (Wu et al., 2015).

The actual quantification approach is more accurate compared with the forecast quantification approach, but the latter is less costly and may take less time to produce the prediction. However, forecast quantification requires a high level of data reliability and accuracy. The actual quantification approach is often used at the construction project level while the forecast approach is usually used to predict waste at the regional level (Villoria Sáez et al., 2018). Table 1 provides a summary of the differences between the two main methods.

Table 1. Actual vs. forecast quantification approaches of construction waste

	Actual Quantification	**Forecast Quantification**
Purpose	Managing waste after it is generated on-site mainly for waste handling	Forecasting waste before or after it is generated mainly for waste management planning and handling
Level	Project	Regional (i.e., city or country)
Accuracy	High	Depends on the data input
Time and Resource Consumption	High	Low
Quantification Methods	• On-site weighing • On-site sorting • Visual observation • Material flow analysis • Building component index	• Total constructed area • Construction database • Physical layout estimation (stockpiled, gathered, scattered, and stacked waste – e.g., equation of the pyramid volume to estimate stockpiled waste)
Measurement Methods / Models	• Waste weight or volume • Waste materials • Waste categories	• Simple mathematical quantification models and probability • Regression models • BIM • Artificial Neural Network and S-curve • Big Data • Grey Prediction Models • Gene Expression Programming • ARIMA

3 Difficulties in Construction Waste Estimation

Due to the dynamic nature of construction activities (Mahayuddin & Zaharuddin, 2013), waste estimation can be a difficult task. Waste estimation depends very much on the availability and accuracy of data (Song et al., 2015). There is a lack of comprehensive records of construction waste or the fate of waste while per capita estimation is often inaccurate (Yost & Halstead, 1996). Onsite evaluation of waste can be difficult due to difficulty to access waste information or simply due to the lack of waste sorting and quantification practice. Actual estimation requires additional resources and can be time-consuming and costly. Workers are usually busy completing the project and waste management may be regarded as a secondary activity.

Similar to the quantification of construction materials, waste can be estimated using different measurement units. Weight per square metres of built-up area (e.g., kg/m^2) (Bakshan et al., 2015) or volume (e.g. m^3/m^2) (Parisi Kern et al., 2015; Solís-Guzmán et al., 2009) are the most common measurement units of waste amount. Other quantification methods of waste include the waste percentage of building materials, waste amount per building component, material flow analysis, and forms of physical layout (e.g., stockpiled, gathered, scattered, and stacked) (Bakshan et al., 2015). Different quantification units mean difficulty in conducting the estimation process. Construction materials quantities can be measured using different units such as square metres, cubic metres, items, and so on. The various units to quantify the different building materials can result in a less accurate estimation of waste especially if the waste amount is aggregated using more than one unit.

Many factors are affecting the output of waste estimation including internal and external factors (Alashwal, 2019). Characteristics of construction projects such as type, location, construction method or system, construction technology, and construction materials are factors that influence the amount of waste produced in construction. For example, steel structures produce different amounts of waste materials compared with concrete structures. Pre-cast construction usually produces less waste compared with the conventional or in-situ construction method. Other factors that influence the amount of waste, as well as the estimation, are legislations and regulations of waste management and recycling, waste management maturity level of the performing organisation, levy charges on the landfill, and availability of technology and resources to manage and handle the waste. The different internal and external factors affecting the amount of waste make producing accurate waste estimation a complex task.

4 Research Methodology

4.1 Meta-analysis

Research on construction waste management, particularly waste estimation, is vast but can be beneficial to make sense of the findings of the literature. Meta-analysis involves statistical analysis of previous studies' results to integrate and synthesise findings (Glass, 1976). The statistical analysis uses summary findings or statistics from previous studies as data points in the new study. In construction, meta-analysis was used to discern trends, find the relationship between variables, and determine the average effect sizes of the level of wasted time (Horman & Kenley, 2005). However, meta-analysis has four main practical issues (Glass, 1976):

1. Different measuring techniques of previous studies make aggregating and analysing data a bit difficult.

2. Combining different results from previous studies may make results uninterpretable.

3. Bias in using significant results in the analysis as nonsignificant results are rarely published.

4. Reliability of data used in the analysis.

These issues can be addressed through proper design and conduct of the analysis and by acknowledging any variances between studies (Horman & Kenley, 2005).

4.2 Collection of Previous Studies

To identify the relevant studies from the literature, the following keywords were used during the search in Scopus and Web of Science databases: construction project, demolition, waste, forecast, estimation, prediction, and waste quantification. As shown in Figure 1, the main criterion used to select the papers for meta-analysis is that the studies should predict or produce a certain amount of waste regardless of the method of estimation or project type or location. This study was restricted to identifying studies that used kilogram per square metres in the estimation, which is the most common measurement unit. Other papers show estimation based on cubic metres of waste per square metres of constructed area (called also Waste Index) but those were not considered in this study to ensure a unified unit to aggregate data easily. The filtration processes resulted in 26 papers to be considered for the meta-analysis as shown in Table 2. All studies used gross floor area (GFA) as a basis for the estimation.

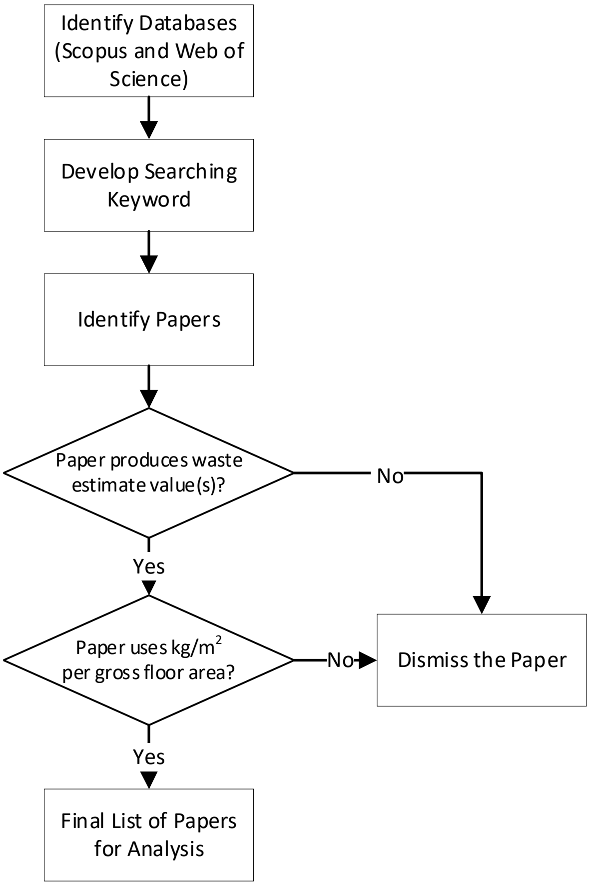

Figure 1. Method of journal papers selection for analysis

Table 2. Identified papers for meta-analysis

Reference	Project type	Waste quantification	Measurement method/model	Waste Generation Rate
1. (Bakshan et al., 2015)	Different types	Actual	Simple linear equations	38 - 43 kg/m^2
2. (Bergsdal et al., 2007)	Different types	Forecast	Simple linear equations and Monte Carlo simulation	45 kg/m^2
3. (Cochran et al., 2007)	Residential and nonpresidential	Forecast	Based on previous studies	12 - 82 kg/m^2 (construction and renovation) 195 - 910 kg/m^2 (demolition)
4. (Domingo & Batty, 2021)	Residential	Actual	Simple mathematical quantification and regression	32.2 kg/m^2
5. (Hu et al., 2021)	Commercial	Actual	Support vector machine (SVM) prediction model	13 kg/m^2 (average of one waste material)
6. (Islam et al., 2019)	Different types	Forecast	Regression analysis	63.74 kg/m^2
7. (Jafari, 2014)	Residential	Actual	Simple quantification model	43.87 kg/m^2
8. (Kartam et al., 2004)	Different types	Forecast	Statistical analysis of existing C&D landfill sites	45 kg/m^2
9. (Kofoworola & Gheewala, 2009)	Residential and non-residential	Forecast	Simple quantification method	21.38 - 18.99 kg/m^2

Reference	Project type	Waste quantification	Measurement method/model	Waste Generation Rate
10. (Lage et al., 2010)	Different types	Forecast	Simple quantification	80 - 90 kg/m^2 (construction and renovation) 1350 kg/m^2 (demolition)
11. (Lau et al., 2008)	Residential	Actual	On-site weighing and sorting	14.095, 8.634, and 22.97 kg/m^2 (based on different sites)
12. (Li et al., 2013)	Residential	Actual	Simple quantification model	40.7 kg/m^2
13. (Liu et al., 2018)	Residential	Actual	BP Neural Network Model based on PSO	55.4 kg/m^2 (average)
14. (Mália et al. 2011 cited Teixeira et al., 2020)	Residential	_	_	44 - 115 kg/m^2
15. (Mercader-Moyano & Ramírez-de-Arellano-Agudo, 2013)	Residential	Forecast	Simple quantification model	79.79kg/m^2
16. (Ram & Kalidindi, 2017)	Different types	Actual and Forecast	Simple mathematical quantification	60 kg/m^2
17. (Seo & Hwang, 1999)	Different types	Forecast	Simple quantification model	38.37, 47.83, and 54.74 kg/m^2 (total based on building type)
18. (Shang et al., 2013)	Residential	Forecast	Grey prediction model	44.3 kg/m^2 (average)
19. (Song et al., 2017)	Residential	Forecast	Gray model (GM (1, 1)) and support vector regression (SVR) method	37.5 kg/m^2 (average)
20. (Teixeira et al., 2020)	Residential and nonpresidential	_	_	50 - 150 kg/m^2 (cited different studies)
21. (Thongkamsuk et al., 2017)	High-rise residential and non-residential	Forecast	Simple quantification model	56.23 - 30. 47 kg/m^2
22. (Villoria Sáez et al., 2014)	Residential	Actual	Simple quantification model	123.29 kg/m^2
23. (Villoria Sáez et al., 2018)	Residential	Actual	Theoretical method	65.24 kg/m^2
24. (Vilventhan et al., 2019)	High-rise	Actual	On-site volumetric estimation and Value Stream Mapping	66.26 kg/m^2
25. (Yost & Halstead, 1996)	Residential and commercial	Actual	Simple quantification method and regression analysis	4.83, 2.15, 2.44, and 1.07 kg/m-^{2} (for different types of projects)
26. (Yu et al., 2019)	Different types	Forecast	Hybrid trilogy	1246 kg/m^2

5 Findings and Discussion

Before conducting the analysis, outliers observed using the box plot were eliminated first for better distribution of data and accurate findings. Subsequently, descriptive data analysis was conducted using central tendency and dispersion of data such as mean and standard deviation analysis. The result of the descriptive data analysis is shown in Table 3. Figure 2 shows the distribution of waste estimates based on the final dataset. The data seems to be slightly skewed towards the left side as shown in the histogram. This is caused by the fact that some studies provided estimates for certain types of materials, not the total amount of waste. The relatively small sample size of data may also cause this slight skewness. More input data can result in a normally distributed curve.

Table 3. Descriptive analysis results of waste estimates

Test	Result (kg/m²)	Test	Result (kg/m²)
Mean	41.31	Max. – Mini.	90 - 6.8
Mode	12.00	Range	83.20
Median	43.35	Standard Error (SE)	3.46
Variance	467.19	Skewness	0.30
Standard Deviation (SD)	21.89	Kurtosis	-0.52

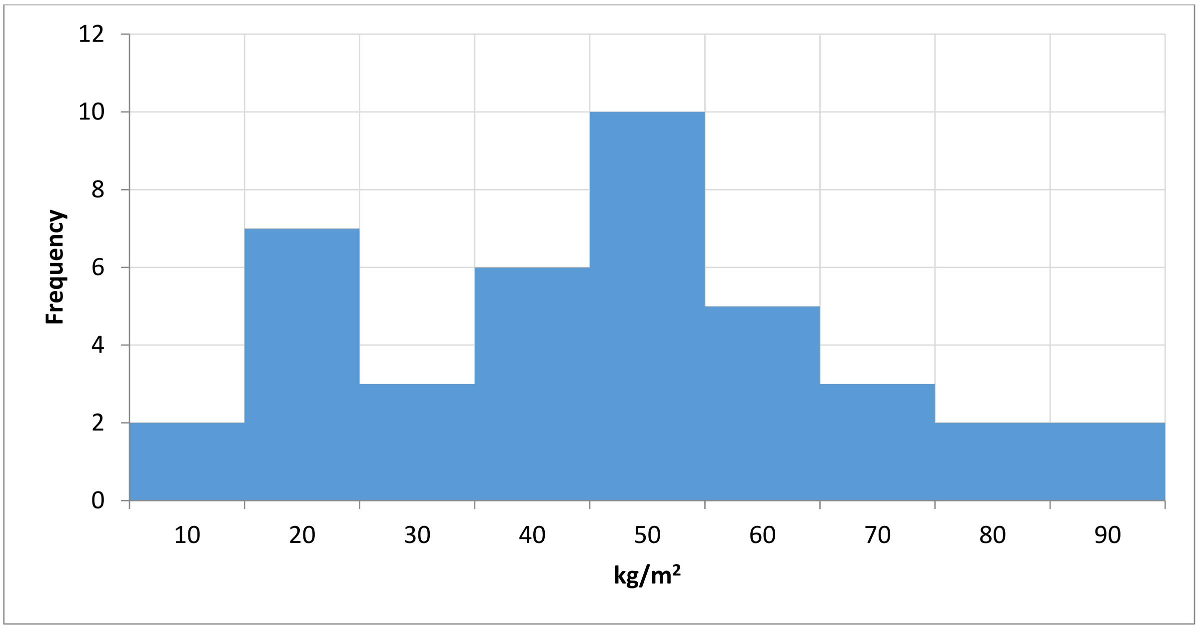

Figure 2. Frequency distribution (histogram) of waste estimates

The result shows that the average amount of waste based on the analysis is 41.31 kg/m^2 with a standard deviation of 21.89 kg/m^2. The average waste amount is estimated based on the total GFA of the construction project.

The estimated amount applies to any type of project regardless of size or type. The result of mean value and standard deviation are particularly useful to conduct a quick estimation of construction and demolition waste of building projects. In addition, this result is useful to estimate waste amount based on the total gross area of the building. For example, a building project with 500 square metres of GFA will result in about 20.7 tonnes of waste (minus or plus the value of the standard deviation of 10.9 tonnes). The estimated amount of waste in this project will range between 9.8 and 31.6 tonnes depending on the construction method, materials used, and other factors.

6 Conclusion and Further Research

This study is the first attempt to quantify construction waste based on previous studies. The result of this study indicated about 41 kilograms per square meter of waste based on the GFA of residential and nonpresidential building projects. This result is useful for contractors and project managers to conduct a quick estimation of the waste amount to be generated during the construction stage. Practitioners can use the estimated average waste to develop a waste management plan and determine the logistics to handle waste during construction.

This research was conducted with some limitations. First, the selected papers were limited to studies that used weight in kilogram per square metre as a waste measurement unit. Second, no in-depth analysis was conducted to determine if waste estimation can be affected by project type, location, estimation method and waste material type due to the small data size.

Therefore, future research can be conducted using meta-analysis by undertaking a detailed analysis of waste based on building materials or categories of waste such as inert and non-inert materials. Besides, estimates based on construction, renovation, and demolition work should be analysed separately as demolition waste usually results in a higher amount compared with construction and renovation waste. Studies that used the waste volume unit (i.e. cubic metre) can be converted into kilograms using the bulk density of 830.6 kg/m3 as suggested by (Mália et al., 2013). However, the accuracy of this conversion factor should be verified first before it can be used to identify more relevant studies and produce a more accurate estimation.

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Developing an Assessment System on Green Construction Sites in Australia

Xiancun Hu[1*], Sarah Elattar[1], Aifang Wei[1] and Charles Lemckert[2]

[1]School of Design and the Built Environment, University of Canberra, 11 Kirinari St Bruce ACT 2601, AUSTRALIA
[2]Faculty of Science and Engineering, Sothern Cross University, Military Road, East Lismore NSW 2480, AUSTRALIA

larry.hu@canberra.edu.au; sarah.elattar@canberra.edu.au; amy.wei@canberra.edu.au; charles.lemckert@scu.edu.au

* Corresponding author

Abstract:
Around the world, there are many assessment systems for green building, such as the LEED system in America and the BREEAM system in the U.K. In Australia, the Green Star rating system is widely considered the standard for assessing healthy, resilient, positive buildings and places. However, these assessment systems are generally limited to new buildings from life-cycle viewpoints, and are less focused on environmental sustainability assessment at construction sites. Moreover, few countries have published green assessment systems for construction projects. How to assess and improve the environmental sustainability of projects during the on-site construction stage plays an important role in enhancing the sustainable performance of construction companies and products. This study will develop an assessment framework for rating green construction projects during the on-site stage. An extensive literature review was first conducted to develop the framework based on identifying the relevant system and indicators of green construction practices. The developed framework will be further tested and improved through the Expert Evaluation method. Therefore, the framework could be used to assess green construction practices and provide education resources for construction managers, engineers, academics, students and workers to improve their awareness and abilities in promoting green construction in Australia.

Keywords:
Assessment, Australia, Construction Site, Environmental Performance, Green Construction.

1 Introduction

Environmental problems have become a serious global issue, particularly in the building and construction industry. The building and construction sector in the world contributes 36% and 37% to global final energy consumption and energy-related CO_2 emissions, separately (United Nations Environment Programme (UNEP), 2021). More importantly, construction activities have negative impacts on natural habitats and the natural behaviour of wildlife. For example, construction activities have serious effects on terrestrial and aquatic flora and fauna, such as 'clearing of native vegetation (including habitat); works around and within watercourses; noise, vibration and light impacts; disturbance of soils, consequential erosion and the mobilisation of sediment; use of chemicals/fuels (potential for spills)' (NSW Government Transport Roads & Maritime Services, 2017). According to the fact sheet from World Wildlife Fund in 2017, the problem of impacting habitats and wildlife from human activities in Australia is exceptionally severe, such that more mammal species have been lost more than in all other continents combined in the past two centuries. More importantly, human error activities can also impact the environment negatively during construction. Due to the complexity of building and the long-term process of building construction, human errors are not uncommon in different building components and construction stages due to a wide range of reasons, which can contribute to more energy and material consumption, but also cause more greenhouse gas (GHG) emissions and waste. Therefore, the negative effects need to be controlled to achieve environmental sustainability in the construction industry.

In order to solve the environmental problems in the building and construction industry, the concept of green buildings (sometimes called sustainable buildings) has been developed in theoretical and practical research. Green buildings are designed to meet the needs of residents with very low or even zero GHG emissions. Furthermore, in order to promote the implementation of green buildings, various stakeholders have been always searching for certification systems that prove the ecological approach used in new buildings (Freitas and Zhang, 2018). For example, one of the world's leading certification systems for rating Green Building is BREEAM (standing for stands for Building Research Establishment Environmental Assessment Method) which is the first to be established in the UK. The rating systems as assessment tools were also established depending on each country's needs such as the LEED (standing for Leadership in Energy and Environmental Design) system in the U.S., the Assessment Standard for Green Building in China, and the Comprehensive Assessment System for Built Environment Efficiency in Japan. However, green buildings have not been widely and properly explored by the building and construction industry, government, and civil society researchers (Melchert, 2007). Particularly, these certification systems are generally focusing on rating the green performance of buildings in the design and usage stages and obscuring their green performance during the construction stage on construction sites. For example, Khanna et al. (2014) have indicated that China's rating system is mainly concerned with energy efficiency integrations such as HVAC design, heat pump systems, using solar energy and natural lighting. Accordingly, this study aims to develop an evaluation framework for green construction sites by employing a series of research methods and expert verification.

2 Literature Review

2.1 The Conception of Green Construction

The Green Construction Guideline issued by MOC defined 'On the premise of ensuring quality, safety and other basic requirements, scientific management and technological progress should be used in engineering construction, to maximise the conservation of resources and reduce the construction activities which will bring negative impacts on the environmental, and to achieve the goal of four savings (energy, land, water and materials) and environmental protection' (Shi, et al., 2013). Green construction can benefit to find solutions to diminish the consumption of energy resources, materials, and land during the construction phase of projects. Cole (2000) pointed out that good green construction practices can improve construction cost efficiency and productivity and benefit environmental, social, and economic performance. The significance of implementing green construction embodies reducing energy and water consumption; decreasing emissions and pollution; improving waste recycling; using low-carbon, recyclable and renewable materials; and minimising construction activity impacts on ecosystems and wildlife. For example, green construction practices in Australia require waste disposal actions such as avoiding, reducing, reusing, and recycling (Park and Tucker 2017). Therefore, promoting green construction practices can support environment recovery, improve material usage efficiency, and benefit climate change mitigation objectives.

It is noted that the concept of green construction is different from green building, which is generally evaluated from an environmental perspective during a building life cycle, whereas green construction is evaluated for buildings during a construction stage. More importantly, the concept of green construction can be used for other kinds of construction projects, such as industrial and infrastructure projects. Besides, there are structural differences between the concepts of sustainable construction and green construction, although sometimes they can be interchangeably used in practice (Owusu-Manu et al., 2022). Green construction is evaluated from environmental and social perspectives but mainly on environmental aspects, however, sustainable construction shall be assessed through all the three pillars of sustainable development — environmental, social, and economic sustainability (Susanti et al., 2019).

2.2 Green Construction Assessment

As more and more countries, entities, and persons are aware of the importance and requirements of sustainable development, environmental management is widely implemented and studied by practices and researchers, such as the United Nations Environment Programme. Environmental assessment is a tool to evaluate environmental performance for different business sectors, which can provide reliable, objective and verifiable results to manage organisations' environmental objectives and achievements, check the satisfaction and compliance relating to environmental protection regulations, and forecast the future trend of environmental development and then formulate suitable environmental strategies (Tam et al., 2004). In the global building and construction sector, there are approximately 40 systems to assess and/or rate the environmental performance of buildings and construction projects (Thaickavil and Thomas, 2019). However, these assessment and rating systems are generally to evaluate the environmental performance of buildings through a life-cycle viewpoint. For instance, according to the Green Building Council of Australia, the assessment categories of Green Star consist of management, indoor environmental quality, energy use, transport, water, materials, land use and ecology, emissions, and innovation. Besides, there are very few rating systems focusing on green construction sites.

Previous studies have tried to develop a framework to assess green construction performance from different perspectives. Cole (2000) investigated building environmental assessment methods to assess construction environmental performance from resource use, ecological loading, and health impacts associated with building production and operation. Tam et al., (2004) proposed a system called 'green construction assessment' to assess green construction consisting of six environmental management indicators of management involvement, training, investment, environmental management programme, research and development and environmental planning; and seven operational performance indicators of maintenance of equipment, air pollution control, noise pollution control, water pollution control, waste pollution control, ecological impact, and energy consumption. Li and Luo (2011) established a framework for rating green construction through three themes including energy and resource conservation, reduction of environmental impact, and on-site construction supervision. Moreover, Zhou et al. (2013) developed a sustainability assessment framework encompassing environmental, economic, social, and technical aspects through the life cycle of the procurement process. In order to enhance a green construction operation, Zou and Moon (2014) evaluated the environmental performance of on-site construction through the categories of the ecosystem, natural resources, and human health. To quantitatively assess the sustainable green performance of ongoing construction projects, Firmawan et al. (2016) introduced the green construction site index by measuring an efficiency index, productivity index and awareness index. Furthermore, in order to identify the gaps between the awareness and activities on green construction in China, Zhou et al. (2018) evaluated green construction from an on-site personnel viewpoint including the categories of environmental protection, material saving, water saving, energy saving, and sustainable land use. Recently, to assess and link green construction and environmental performance, the level of significance of environmental performance is assessed using the indicators of air quality, water, and sanitation (Owusu-Manu et al., 2022). In summary, different studies generally develop different evaluation and rate systems including various categories and indicators based on their specific requirements and objectives. Therefore, it is necessary to further investigate an evaluation framework for green construction sites, particularly in the Australian construction domain.

2.3 The Requirements of Green Construction in Australia

Australia is considered one of the highest GHG emitters in the world, as Australia's per capita GHG emissions are very high. Furthermore, Australia, as a signatory to the Paris Climate Agreement, has committed to reducing GHG emissions to under 43 per cent of 2005 levels by 2030 and to achieve net-zero emissions by 2050 (Climate Action Tracker, 2022). In Australia, one of the key emitters is the construction industry, as approximately 25% of the nation's annual GHG emissions were consumed in building construction, operation, and maintenance (Martek and Hosseini, 2019). For example, according to the calculated results from the data of the Australian Government Department of Industry, Science, Energy and Resources, GHG emissions in the NSW construction industry have increased by 2.8% annually from 2004 to 2018. Accordingly, it is very necessary to study the GHG reduction pathways in the Australian construction industry to contribute to the Australian commitment to GHG reduction targets.

Australia is also recognised as a leader in developing and applying green construction schemes to reduce the environmental impact of construction activities. For example, Australia has effective waste management codes, regulations, and waste reduction projects in different regions, e.g., ACT promotion of on-site waste re-use and the Waste Authority in Western Australia (Li and Du 2015). There are two programmes related to green construction in the Australian construction area, including the Green Star rating system and the Infrastructure Sustainable rating system. The Green Star rating system was published by the Green Building Council of Australia in 2003 and has been internationally acknowledged as a sustainability rating and certification system. The system consists of four rating tools for certificating building design and construction, operation, fitouts and communities, named Communities, Design and As-Built, Interiors and Performance. Moreover, the Infrastructure Sustainability system was established by the Infrastructure Sustainability Council of Australia (ISCA) in 2007, which is a voluntary rating system to promote resource efficiency, waste reduction, and cost savings in infrastructure projects. However, policies and regulations in Australia mainly focus on the immediate GHG emissions released from operating the building and paid no attention to the gases released from the construction process (Yu et al., 2017). For example, the *Green Star* rating system is mainly a tool for performance prediction during building planning and design (Martek and Hosseini 2018), focuses on energy use (building operations after construction) and indoor environmental quality (Doan et al. 2016), and mostly assesses building performance after the building is built (Tuohy and Murphy 2012). There has been little research to examine the extent to which the adoption of green construction programs in achieving the advantages outlined under the main Australian Green Construction schemes (Shooshtarian et al., 2019). Therefore, it is necessary to develop a rating system to systematically focus on evaluating the environmental performance of Australia's construction sites while a project is being built.

3 Research Methodology

The research method of this study includes four steps which are presented in Figure 1. The first step is to develop a rough framework for assessing green construction sites by using brainstorming methods among all authors through several meeting discussions and improvements. The developed rough framework could provide directions, instructions, and structure classifications for the following steps. Secondly, the scientometric literature review and content analysis are used to review the literature on green construction. The database is based on Scopus as the citation database due to its more comprehensive coverage compared to the other databases. The literature search strategy is (TITLE-ABS-KEY ("green construction”) OR TITLE-ABS-KEY ("sustainable construction”) AND TITLE-ABS-KEY (rating) OR TITLE-ABS-KEY (assessment) OR TITLE-ABS-KEY (evaluation) OR TITLE-ABS-KEY (framework)) AND (LIMIT-TO (SRCTYPE, "j")) AND (LIMIT-TO (DOCTYPE, “ar”)) AND (LIMIT-TO (LANGUAGE, "English")).

The initial search identified 890 publications. Subsequently, the title and abstract of articles were manually analysed to look for publications related to evaluating green construction on the project site level, where 112 articles were initially selected. As this study focuses on establishing a framework/system to systemically assess green project sites during the construction stage, most publications that partly assess green construction are neglected. Finally, only 26 journal papers are selected to be emphatically analysed. Due to the length limitation of the paper, Table 1 only shows the key journal papers which have developed a framework to assess green performance for construction sites. Consequently, the indicators which have been used to assess green construction sites are identified by summarising these identified papers. Thirdly, the research will critically compare and analyse these indicators and then improve the rough framework into a formal draft. Finally, the developed framework will be further verified and improved by using an expert evaluation method mainly through email commutation. 6 professionals in the construction management areas were emailed, and 3 of them presented their viewpoints on the evaluation framework and indicators.

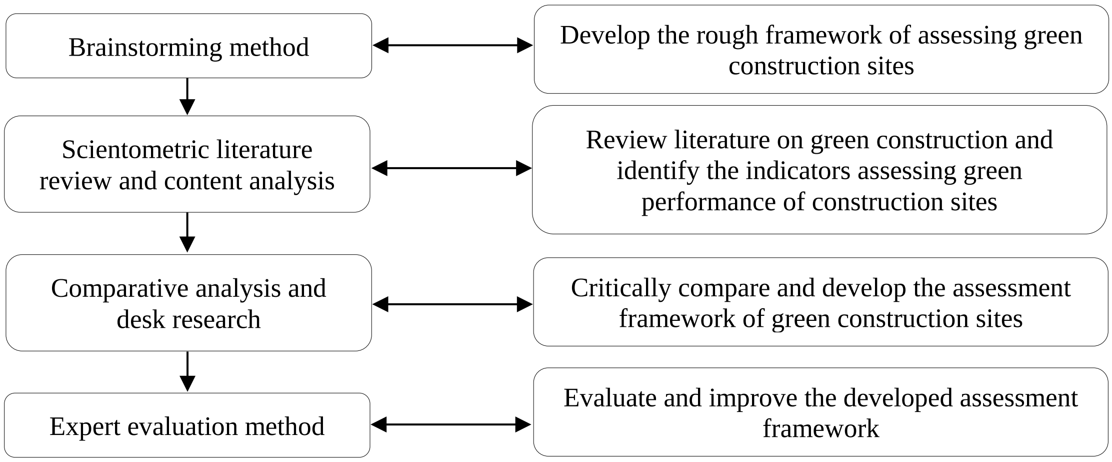

Figure 1. Research methodology

4 Findings and Discussion

4.1 Key Indicators of Assessing Green Construction

By implementing the first two steps of the research method, previous key studies which had attempted to develop rating systems for evaluating green construction are identified in Table 1. It can be concluded that the rating indicators which are widely employed to assess the performance of green construction consist of construction materials, site waste, site protection and energy consumption. Although the BREEAM, LEED, and Green Star rating systems include all environmental factors to assess green building performance, they pay more attention to evaluating building performance during the operation and maintenance stage, instead of during the construction stage. For example, in the LEED rating system, the energy consumption and GHG emissions of kitchen equipment are measured, not of excavation equipment. Besides, it is understandable that these rating systems do not consider social factors as credit points, as they only assess building environmental performance.

Table 1 shows the assessment indicators used in these academic studies. First, construction materials, site waste, site protection, and energy consumption are the common indicators, although different studies have different measurement scopes. Material and energy resources are consumed on construction sites due to various construction activities such as site preparation, demolition, assembling, altering, installing, and clearing, which could directly affect the environment. Demolition and construction waste is another crucial matter to affect the environmental performance of construction sites. For example, according to the Australian Bureau of Statistics in 2018, 33% of construction waste ends up in landfill which could reduce air quality, destruct soil structures, and risk fire and water pollution. Construction sites have a negative impact on natural habitats and the natural behaviour of wildlife. For instance, construction noise can cause alteration in feeding and breeding patterns, which is detrimental to the surrounding flora and fauna. Second, the indicator of missions is another direct important factor affecting green construction. It is not only related to energy consumption, but embodied carbon emissions of buildings are a negative and significant effect on improving construction environmental performance due to huge consumptions of building materials. For example, Huang et al. (2018) pointed out that 94% of the total emissions of the construction sector are indirect emissions by measuring GHG emissions related to energy-use in the whole world. Third, site management in the environment shall be considered in evaluating the green performance of construction sites, as it will indirectly affect the environment by controlling the construction activities of workers. Their awareness and ability in protecting the environment during construction will affect green construction practices. Fourth, introducing green construction innovation as an evaluation indicator is an efficient pathway to promote green construction practices. Finally, the social factors shall be considered to assess green construction sites, as construction activities can affect the surroundings such as producing lots of noise, dust, and traffic jams. Therefore, these indicators shall be included in the evaluation framework as they affect the environmental performance of construction on sites.

Table 1. Key indicators of assessing green construction used in previous studies

	BREEAM	LEED	Green star	(Cole 2000)	(Tam et al., 2004)	(Li and Luo, 2011)	(Zhou et al., 2013)	(Zou and Moon, 2014)	(Firmawan et al., 2016)	(Zhou et al., 2018)	(Owusu-Manu et al., 2022)
Construction materials	√	√	√	√	√	√	√	√	√	√	√
Site protection	√	√	√	√	√	√	√	√	√	√	√
Site waste	√	√	√	√	√	√	√	√	√	√	√
Energy consumption	√	√	√	√	√	√	√	√	-	√	√
Emissions	√	√	√	√	-	-	-	√	-	√	√
Site management	√	√	√	√	√	√	-	-	-		-
Green construction innovation	√	√	√	-	-	-	√	-	-	-	-
Social responsibility	-	-	-	√	-	√	√	√	-	-	-

4.2 Framework for Assessing Green Construction on Sites

By implementing the last two steps of the research method, the final framework for assessing green construction on sites was developed in Table 2. After the verification of expert evaluation, the concept of emissions will not be considered as a theme, as it is mainly related to energy consumption and the air quality indicator is located in the theme of Site Protection. The framework consists of seven themes: construction materials with five indicators, site protection with seven indicators, waste management with five indicators, energy consumption with four indicators, site management with three indicators, green construction innovation with three indicators, and social responsibility with four indicators. Accordingly, the total 31 indicators are identified and developed on the basis of literature review and expert verification.

During the evaluation of green construction, the theme of construction materials needs to consider green procurement where the procurement process and products are green. For instance, material procurement gives high priority to the local product market, and optimises the procurement plan aiming for zero inventory, which could reduce GHG emissions. Moreover, green construction materials are encouraged to be utilised, for example, which are made from renewable sources, easy to recycle, and have a long-life span that can lower the chances of multiple maintenance procedures. Controlling material and water usage in construction is also crucial to improve usage efficiency, decrease waste and cost, and reduce GHG emissions, such as adopting water-saving and water recycling devices. Particularly, toxic materials shall be voided, e.g., Asbestos, Chemicals, Batteries, Solvents, Pesticides, and Oils.

Table 2. Framework for assessing green construction on sites

Theme	Indicator
Construction materials	Green procurement
	Green materials used
	Control material usage
	Control water consumption
	Control toxic materials
Site protection	Demolition management/site preparation
	Landscape protection
	Pollution control
	Level of vibration&noise&light control
	Level of air quality/temperature/dust/humidity control
	Level of groundwater protection
	Eco-efficiency level of construction site layout
Waste management	Construction waste generation ratio
	Waste reuse&recycle ratio
	Waste disposal (landfill) ratio
	Wastewater treatment/reuse rate
	Control hazardous waste
Energy consumption	Total energy consumption ratio
	Renewable energy consumption ratio
	Fossil fuel consumption ratio
	Clean-energy and energy-efficient equipment used
Site management	Green construction objectives, planning, and management implementation
	Green construction management organisation and accountability
	Green construction training and awareness
Green construction innovation	Clean construction technologies/methods applied
	Level of off-site manufacture
	Level of promoting green construction innovation
Social responsibility	Local community contributions
	Neighbourhood disturbance
	Public traffic disruptions
	Worker's health and safety

Site protection in green construction is to preserve the land of construction sites and surroundings by protecting the natural original landscape, for instance, to keep soil, trees vegetation, and biodiversity during demolition and site preparation; to diminish the degree of landscape damage, stormwater damage and topsoil erosion during construction; to improve eco-efficiency of the construction site layout by arranging the site layout compactly and making site loading reasonably; to control pollutions spreading to the land, water and air; to reduce the linkage of vibration, noise and light; and to ensure air quality by controlling air dust, temperature, and humidity; to protect groundwater by avoiding dumping and contamination. Besides, building construction education programs can impact this significantly through enhancing education resources. Indeed, this is the easiest one for them to address.

Waste management is the management of construction waste produced from, for instance, assembling and disassembling of building materials on site, disposal of waste and transportation to landfill, and demolition and renovation work. The efficiency and effectiveness of waste management activities can be measured through these indicators of the construction waste generation ratio, waste disposal ratio, waste reuse and recycle ratio, and wastewater treatment and reuse rate. The measurement results can provide efficient useful information and compare these waste management activities, benchmark the best waste management sites, and then identify the aspects and pathways to improve waste management performance. Particularly, hazardous construction waste must be managed completely.

Energy consumption during construction is crucial as it can directly affect the environmental performance of construction sites. Energy consumed during construction is mostly about the transportation and operation of construction equipment such as backhoe loaders, dampers, cranes, and hydraulic excavators. Besides, the energy consumed to generate electricity and to use facilities for natural light and ventilation shall also be considered in evaluating green construction. Accordingly, the total energy consumption ratio, renewable energy consumption ratio, and fossil fuel consumption ratio are separately measured to investigate and compare the different performances in energy consumption. Clean-energy and energy-efficient equipment are encouraged to be used on sites.

Site management is an indicator to evaluate whether there are management planning, organisation and persons, accountability, measures, and objectives for green construction on sites. It is mainly to evaluate whether this management has been documented and implemented efficiently and effectively. The management process focuses on the whole construction processes on sites, from setting out and preparing the site, procurement, transporting building materials to the site, construction, and post-construction. Besides, it is recommended to offer green construction knowledge training for all stakeholders who are involved on construction sites (e.g., engineers, builders, contractors, subcontractors, and construction workers). The awareness and abilities of the stakeholders on green construction could be checked and improved by a series of testing and questionnaire.

Green construction innovation and application can significantly enhance the environmental performance of construction sites. Green construction innovation is to use and apply clean construction technologies and methods with less energy and material consumption, such as technologies to manage wastewater, solar energy for lighting and electricity on site, and smart construction machines and equipment. For example, off-site manufacture (e.g., modular structures) and prefabricated construction are encouraged, so that construction sites are without heavy construction activities. Lean construction is also an innovative construction method to reduce the cost, energy, material, and time consumption of construction processes.

Social responsibility in green construction is to take measures and activities that obligate social responsibilities during construction such as avoiding neighbourhood disturbances and public traffic disruptions, and caring about workers' health and safety. It is widely noted that construction activities may produce inconveniences for the surroundings, such as power outages, waste, noise, vibration, parking, and traffic restrictions. Moreover, the health of the workers, staff and the public influenced by construction shall be considered as an indicator to evaluate green construction, due to its significance for sustainability. Contributions to the local community could add credit points to rate the green construction performance, such as doing some volunteer work for the local community.

5 Conclusion and Further Research

The current green building rating system generally and mainly evaluate building performance from a building life cycle. It is necessary to investigate and assess green construction performance for buildings during the construction stage. This study employed a systematic literature review and an expert verification method to develop a framework to evaluate green construction on sites. Previous studies had explored various evaluation systems and indicators. These indicators are normally related to construction materials, site protection, site waste, energy consumption, emissions, site management, green construction innovation, and social responsibility. Accordingly, the evaluation systems were developed, including the seven themes of construction materials, site protection, site waste, energy consumption, site management, green construction innovation, and social responsibility, and 31 evaluation indicators.

This study systematically developed the framework to evaluate green construction sites while projects are being constructed. The framework indicators are critically identified and verified, which can benefit contractors and builders to assess and benchmark their performance in construction activities and project management. The developed evaluation indicators and framework are not only for rating the green performance of construction projects, but also provide pathways, technologies, and techniques to improve their green construction performance. More importantly, the results contribute to the theoretical research and practical application of green construction. The outcomes from this work can and should be applied to the education of our student cohorts to ensure an enhancement of their sustainability knowledge.

Although the developed framework could be used for all kinds of construction sites in the world, the building construction sites in Australia are focused, as the verification experts are all from the building construction industry in Australia. However, although this framework had been verified by expert evaluation, it has not been tested on construction sites. Further studies could further evaluate and test the evaluation systems on construction sites. It is a long-term study process to improve the performance of green construction in Australia. Therefore, how to promote and apply the framework to assess construction projects in the Australian construction sector shall be further studied, with an emphasis on the education system.

6 Acknowledgement

The research is assisted by the NSW Government through its Environmental Trust and the ECARD grant of the University of Canberra.

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Theme:

Resilience in Built Environment

The Adaptation of the Facility Condition Index (FCI) in the Australian Tertiary Education Sectors Management of a Building Portfolio

Jye West[1*], Milind Siddhpura[1], Ana Evangelista[1] and Assed Haddad[2]

[1]Engineering Institute of Technology,
1031 Wellington St, West Perth, WA 6005, AUSTRALIA
[2]Programa de Engenharia Ambiental,
Universidade Federal do Rio de Janeiro, Rio de Janeiro 21941-901, BRAZIL

1064170@student.eit.edu.au; Milind.siddhpura@eit.edu.au; ana.evangelista@eit.edu.au; assed@poli.ufrj.br
* Corresponding author

Abstract:
The asset value of a typical university portfolio is in the billions of dollars as specialised facilities, laboratories, and architecturally designed structures dominate the portfolio landscape. The annual expenditure to service and maintain these assets continue to be scrutinised as the cost to service and maintain these structures are constantly being reviewed and assessed against rising inflation, and the ever-increasing costs of utilities and the associated infrastructure. Over the years, different methodologies to determine an accurate Facility Condition Index (FCI) were and continue to be adopted as estate management strives to be nimble, agile, and flexible as their portfolios increase in size, reduce in allocated funding, and continue to age and approach the end of their economic lifecycles. Utilising frequently used information from the Asset Replacement Valuations (ARV), combined with asset field data from the Facility Condition Assessments (FCA) different calculation methodologies are discussed to evaluate their level of reporting accuracy. Furthermore, this paper discusses the comparative results of architecturally upgrading a building asset, yet the investment appears to have limited impact on reducing backlog, statutory and non-statutory maintenance requirements. Similar to other industries, a cost effective, transparent and reliable evaluation methodology of determining a buildings Facility Condition Index (FCI) is becoming increasingly important to determine the level of risk and liabilities (some hidden) when valuing a multi-million dollar building asset during an acquisition, equity or insurance evaluation process.

Keywords:
Facility Condition Index, Governance, Stakeholder Management, Strategic Asset Management

1 Introduction

As the Australian-built environment evolves and matures, economic and financial pressures continue to influence and challenge the status quo. Property professionals and managers seek a definitive solution to assigning property capital funding for asset renewal, upgrade, and replacement activities. Furthermore, the global impact of late 2021 and early 2022 CPI (Consumer Price Index) on the Australian inflation and labour rates directly impacts the costs and overhead expenses associated with performing condition assessments, field data acquisitions and maintaining accurate data in computer-based analytical systems.

Similarly, the Australian Tertiary Education Sector is guided by TEFMA (Tertiary Education Facility Management Association). They provide national governance and operating frameworks for member universities and institutes to follow and be guided by. The information provided in this report represents consolidated data from a nonspecific selection of contributing member university's data up to April 2021, including Facility Condition Index (FCI), Facility Functionality Index (FFI), Backlog Maintenance, Refurbishment and Replacement Costs. The TEFMA Benchmark Reporting Portal (TEFMA, n.d.) offers additional information regarding property operations, expenditure, utility cost and space utilisation; however, this report will focus on the principal aspect of FCI as TEFMA amalgamates these elements under their Strategic Asset Management Plans and Frameworks.

2 Literature Review

Regardless of the building form, construction methodology and materials used, all building assets are susceptible to progressive deterioration and damage due to construction quality, weather/ environment, geographic location, operating demands, and the general use of the asset. (Nguyen, et al., 2018) However, inconsistencies and variations exist in the definitions and techniques associated with performing a Facility Condition Assessment (FCA), the analysis process, and reporting the results related to the Building Condition Index (BCI). The BCI methodology is an engineering-oriented approach to evaluating the deterioration of the building asset. An asset inspector must assess and rate multiple elements such as architectural, structural, civil, mechanical, electrical etc. (Anuar, et al., 2018). When performing a FCA audit, the principal objective is to identify and rate the extent of deterioration of the different building's element's identified in the field survey (Uzarski & Grussing, 2013). According to (Uzarski & Grussing, 2013), the structured inspection method requires the specific observation, identification and recording of the defects that have occurred at a particular point in time. However, as (Pitt, 1997) explains, no matter what condition categories are scheduled to be inspected and evaluated, the asset inspector must be suitably experienced and qualified across multiple engineering disciplines to ensure the data is accurate and reliable.

One of the most significant variables that directly impact logical and robust data acquisition during the FCA is the element of subjectivity and the auditor's technical knowledge, expertise, and thorough appreciation of the extent of damage or deterioration of the building element's condition. Traditionally, a condition assessment for a building is performed through visual inspection resulting in qualitative and subjective outcomes such as "poor", "average", "good" (Besiktepe, et al., 2021), however, TEFMA has established a numerical methodology of "5 = Near New", "4 = Very Good", "3 = Good/ Average", "2 = Below Average", and "1 = Very Poor or End of Life".

Once the FCA survey is completed, the accumulated data is analysed against each building element's deterioration lifecycles and assessed against industry rates for repair to develop the Backlog Maintenance (BM) figure. The objective of the BM report is to provide sufficient engineering assessment information, combined with market rate budgetary information, to address the deficiencies and repairs to enable asset management to prioritise and decide the best approach or options when maintaining the building asset. (Anuar, et al., 2020)

Expanding and advancing on the BM matrix calculation is the addition of the Asset Replacement Value (ARV). This figure can fluctuate depending on market conditions, availability of building materials, geographic location, and the availability of resources or even changes in surrounding districts/ neighbourhoods (ie re-zoning). Australian universities regularly undertake an ARV assessment by an external third-party professional for asset depreciation and standard accounting requirements as a part of asset replacement valuations (Twin, 2021).

When you take both figures and divide the current physical state of a building repair/disrepair (BM) against the cost of replacement of the same building asset as new construction (Parson, 2018) you arrive at the Facility Condition Index (FCI) number. The FCI has the capability of reporting at a component level of an asset, the whole building or the entire property portfolio (Maltese, et al., 2017) as the basic equation [1] is used for the calculation of the metric:

$$FCI = \frac{BM}{ARV} \quad [1]$$

Where:

FCI = Facility Condition Index references as a number between 0.00 – 1.00

BM = is the cost of the deferred maintenance that was identified in the FCA

ARV = is the current replacement value of the component, building or portfolio

The Facility Condition Index (FCI) allows asset management professionals to quantify the condition of the assets on a scale of 0 to 100 (or, for TEFMA, 0.00 to 1.00). Therefore, as a simplified reference, TEFMA considers the same FCI calculation by dividing the cost of correcting deficiencies (or identified maintenance value BM from the FCA audit) against the facilities' asset replacement value (ARV). (Cecconi, et al., 2019)

The TEFMA Benchmark Reporting Portal (TEFMA, n.d.) offers multiple charts and reference data statistics as the below graph represents the cost of BM as a percentage of the ARV with an average figure of 4.52% p/a BM liabilities across the selected university group.

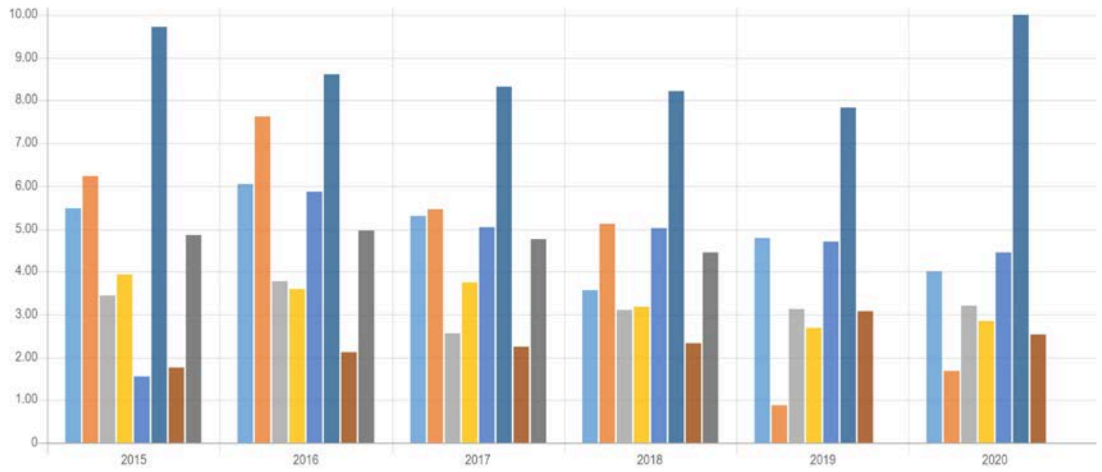

Figure 1. Graph - Backlog liability as % of ARV (buildings & infrastructure)
(Selected AUD Universities) 2015 – 2020. Source – TEFMA Benchmark Reporting Portal

Institute	2015	2016	2017	2018	2019	2020	AVG
University #01	5.490	6.050	5.300	3.570	4.770	4.000	4.863
University #02	6.240	7.630	5.440	5.110	0.880	1.680	4.497
University #03	3.440	3.760	2.550	3.100	3.130	3.210	3.198
University #04	3.920	3.590	3.740	3.190	2.680	2.830	3.325
University #05	1.560	5.870	5.040	5.020	4.700	4.440	4.438
University #06	9.720	8.610	8.310	8.220	7.830	10.000	8.782
University #07	1.760	2.130	2.250	2.330	3.080	2.540	2.348
University #08	4.850	4.950	4.750	4.440			4.748
					Group Average		4.525

Figure 1. Supporting Data - Backlog liability as % of ARV (buildings & infrastructure)
(Selected AUD Universities) 2015 – 2020. Source – TEFMA Benchmark Reporting Portal

Conversely, discussions regarding the accuracy or reflection of this standard matrix are frequently undertaken by global asset management practitioners, as an updated equation variant is emerging based on this original formula (Moretti & Cecconi, 2019). When you combine the above original formula (adopted by TEFMA) with other typical building maintenance activities, we have the potential to gain greater and more accurate insights into an accurate FCI indicator.

For example

a) Some versions of the FCI calculation consider the effect of obsolescence due to a lack of compliance with current building or safety codes (IFMA, 2008). TEFMA addresses this variant as a (Functional Facility Index) FFI.

b) Another consideration is that the BM index also considers the costs associated with renewals, upgrades, and improvements (Maltese, et al., 2017).

c) And there are other methodologies associated with determining the BM index value for unique or heritage (US Department of Interior, 2008)

Suppose we consider the above variations and include the additional expenditure associated with major rehabilitation, obsolescence and backlog maintenance identified during the FCA. In that case, these other elements may be used to determine a more accurate FCI index.

$$FCI = \frac{(BM + EOL)}{(ARV - MR)} \qquad [2]$$

Where:

FCI = Facility Condition Index references as a number between 0.00 – 1.00

BM = is the cost of the deferred maintenance that was identified in the FCA

MR = is the costs associated with cosmetic or architectural refurbishments

EOL = assets that are functional, but are obsolete or not fit for purpose

ARV = is the current replacement value of the component, building or portfolio

Further fuelling the debate regarding the complexities associated with the calculations of an accurate FCI reporting index, is the consideration of sustainability, energy efficiencies and the global desire for many corporations and institutions to reduce emissions by 45% by 2030 and reach net zero by 2050 (Unitied Nations, 2022). With a lot of the central plant equipment (HVAC, Main Switchboards, Power Factor Correction Equipment etc.) having long lifecycles and subjected to moderate to reasonable maintenance regimes, these assets face the possibility of being upgraded and replaced well before their end of useful economic life – or in an accounting term “accelerated depreciation” (Koowattanatianchai, et al., 2019).

In the TEFMA Benchmark Reporting Portal (TEFMA, n.d.) the selected universities represent the costs associated with MR (Major Refurbishment) expenditure as a percentage of the ARV as the average of the selected group of universities was calculated to be 1.86% p/a.

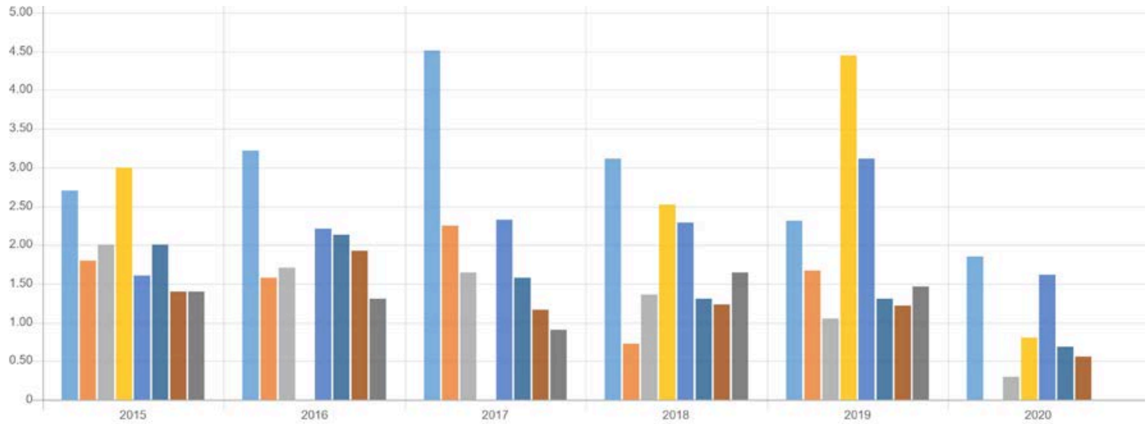

Figure 2. Graph - Refurbishment Expenditure as a Percentage of ARV
(Selected AUD Universities) 2015 – 2020 Source – TEFMA Benchmark Reporting Portal

Institute	2015	2016	2017	2018	2019	2020	AVG
University #01	2.700	3.220	4.510	3.110	2.310	1.850	2.950
University #02	1.800	1.580	2.250	0.720	1.670		1.604
University #03	2.000	1.710	1.640	1.360	1.050	0.300	1.343
University #04	3.000			2.520	4.440	0.800	2.690
University #05	1.600	2.210	2.330	2.290	3.120	1.620	2.195
University #06	2.000	2.130	1.580	1.310	1.300	0.680	1.500
University #07	1.400	1.920	1.160	1.230	1.210	0.560	1.247
University #08	1.400	1.300	0.910	1.640	1.460		1.342
					Group Average		1.859

Figure 2. Supporting Data - Refurbishment Expenditure as a Percentage of ARV
(Selected AUD Universities) 2015 – 2020 Source – TEFMA Benchmark Reporting Portal

3 Research Methodology

This research paper has considered a hybrid of quantitative and qualitative data presented from scholar articles and was able to utilise factual financial and conditioned based data submitted by contributing university members in the TEFMA Benchmark Portal (TEFMA, n.d.). An initial review of approximately 138 academic articles regarding FCI, BCI, FCA and ARV was performed. This evaluation was concentrated to 86 articles when we increased the filters to recent publications. While further filtration was performed to focus on specific international best practices, the methodologies and theories discussed in this paper remain relevant and applicable across almost any government, or private commercial, educational, healthcare, or similar portfolio.

There remains an extensive amount of property operating data, combined with the analytical tools within the TEFMA Benchmark Portal, to undertake and perform further analysis and investigations into a more detailed assessment of FCI within the Australian tertiary education sector.

Figure 3. Research Methodology Diagram

The existence of the FCI index in the broader property industry (for example - government, commercial, healthcare, education, and superannuation funds) offers asset management practitioners the foundations for further development through the utilisation of standard accounting, finance, and engineering practices to form a quick reference index of the building assets value, risk and liabilities. The adaptation of the same, similar, or modified formula based on further research offers additional insights into potential over-capitalisation (through cosmetic refurbishment programs) or under capitalisation (through excessively high BM).

While in Australia, at the time of publication, federal government funding is not linked to annual asset reporting requirements, through industry recognition and standardisation, these practices and protocols have the potential to be adopted, as is the current practice in New Zealand (NZ Tertiary Education Commission, 2022) and an active initiative throughout multiple European countries (Pruvot, et al., 2015).

4 Findings and Discussion

Many Australian universities continue to reinvest approximately 1.86% p/a of their ARV into asset refurbishment and upgrades that offer attractive, modern, and ascetically pleasing facilities for the students and faculties. In (Figure 4), the Facility Function Index (FFI) has been considered for the selected group of universities and is calculated by using equation [3]

$$FFI = \frac{SBM + NSBM + ABM + BM}{ARV} \qquad [3]$$

Where:

FFI = is the facility function index

SBM = is the statutory backlog liabilities (life safety systems etc.)

NSBM = is the non-statutory backlog liabilities

ABM = is the access related deferred liabilities

BM = is the cost of the deferred maintenance that was identified in the FCA

ARV = is the current replacement value of the component, building or portfolio

Figure 4 indicates that despite the reinvestment expenditure noted in Figure 2, approximately 96.9% of the ARV remains outstanding as backlog maintenance or pending statutory liabilities within the same asset or portfolio.

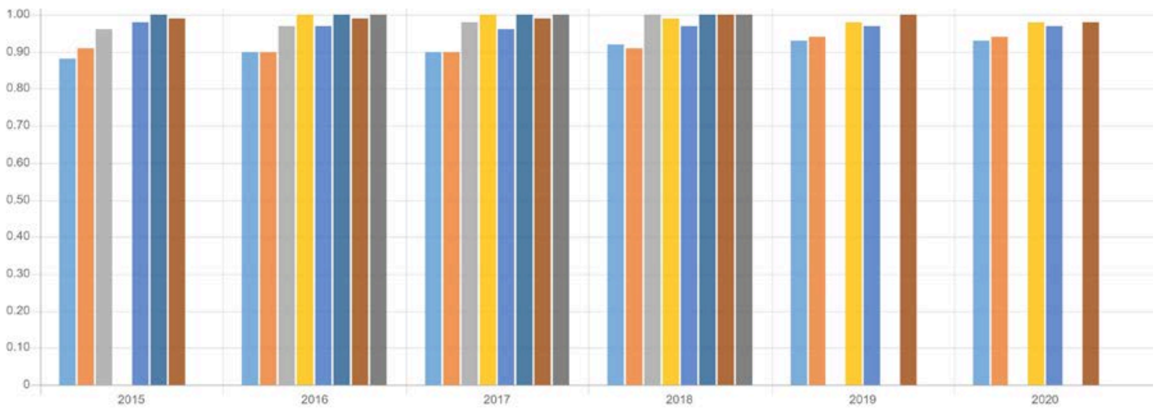

Figure 4. Graph - Facility Function Index
(Selected AUD Universities) 2015 – 2020 Source – TEFMA Benchmark Reporting Portal

	Institute	2015	2016	2017	2018	2019	2020	AVG
	University #01	0.880	0.900	0.900	0.920	0.930	0.930	0.910
	University #02	0.910	0.900	0.900	0.910	0.940	0.940	0.917
	University #03	0.960	0.970	0.980	1.000			0.978
	University #04		1.000	1.000	0.990	0.980	0.980	0.990
	University #05	0.980	0.970	0.960	0.970	0.970	0.970	0.970
	University #06	1.000	1.000	1.000	1.000			1.000
	University #07	0.990	0.990	0.990	1.000	1.000	0.980	0.992
	University #08		1.000	1.000	1.000			1.000
						Group Average		0.969

Figure 4. Supporting Data - Facility Function Index
(Selected AUD Universities) 2015 – 2020 Source – TEFMA Benchmark Reporting Portal

As an alternative method of determining the building asset's risk, liability, or value, by utilising the same data and considering the more straightforward calculation of FCI in equation [1], the below demonstrates that an average of 93.5% of the building assets value remains outstanding as BM liabilities and that there is little to no change over the five-year sample period.

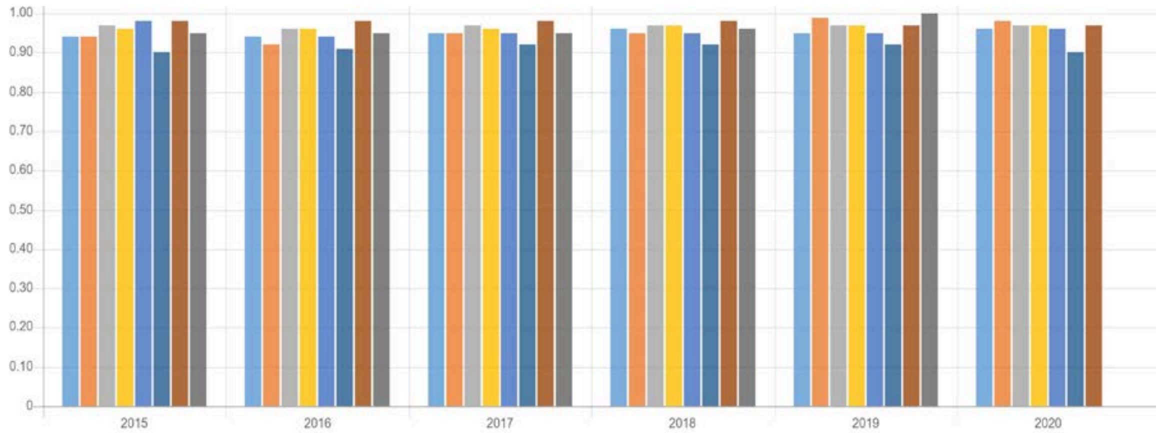

Figure 5. Graph - Facility Condition Index
(Selected AUD Universities) 2015 – 2020 Source – TEFMA Benchmark Reporting Portal

	Institute	2015	2016	2017	2018	2019	2020	AVG
	University #01	0.940	0.940	0.950	0.960	0.950	0.960	0.950
	University #02	0.940	0.920	0.950	0.950	0.990	0.980	0.955
	University #03	0.970	0.960	0.970	0.970	0.970	0.970	0.968
	University #04	0.960	0.960	0.960	0.970	0.970	0.970	0.965
	University #05	0.980	0.940	0.950	0.950	0.950	0.960	0.955
	University #06	0.900	0.910	0.920	0.920	0.920	0.900	0.912
	University #07	0.980	0.980	0.980	0.980	0.970	0.970	0.977
	University #08	0.950	0.950	0.950	0.960	1.000	0.000	0.802
						Group Average		0.935

Figure 5. Supporting Data - Facility Condition Index
(Selected AUD Universities) 2015 – 2020 Source – TEFMA Benchmark Reporting Portal

The existence of the Facility Condition Index (FCI) is a widely accepted and recognised index in the Australian tertiary education sector and one that is supported by a majority of Australian universities. While reinvestment continues to be performed on upgrading and refurbishing the building assets, the impact on backlog maintenance and statutory liabilities does not appear to be impacted, reduced, or improved by the refurbishment expenditure works across the selected universities over the five years between 2015 and 2020.

5 Conclusion and Further Research

The process of evaluating the building assets owned by an organisation to determine the best maintenance needed was defined by (Rugless, 1993) as "*a process of systematically evaluating an organisation's capital assets to determine the extent of repair, renewal, or replacement needs*", that will preserve the assets condition as they were initially assigned to serve.

Regardless of the industry or sector, utilising the FCI remains an essential tool in determining a building's value or liability and provides asset management practitioners with valuable insights into the level of property risk. But while debate continues to encircle the methodology of determining a mutually agreeable FCI, the proposed equation [2] potentially offers another level of scrutiny and insight.

$$FCI = \frac{(BM + EOL)}{(ARV - MR)} \qquad [4]$$

Where:

FCI = Facility Condition Index references as a number between 0.00 – 1.00

BM = is the cost of the deferred maintenance that was identified in the FCA

MR = is the costs associated with cosmetic or architectural refurbishments

EOL = assets are functional, but are obsolete, require upgrade or are not fit for purpose

ARV = is the current replacement value of the component, building or portfolio

If the above equation was considered, could it be determined in a majority of the cases that if

a) <u>the FCI was > 1.00</u>

   over capitalisation could have occurred with an elevated level of hidden or building infrastructure assets still requiring upgrades, while if

b) <u>the FCI was < 1.00</u>

   that under capitalisation (or reinvestment) has occurred with a high degree of backlog maintenance liabilities and infrastructure approaching or exceeding End of Life or not Fit for Purpose.

c) the FCI was close to 1.00

   that a reasonable balance of capital upgrades has been performed that addresses both architectural and building infrastructure risks.

d) Could the FCI index be improved by including the asset lifecycle depreciated % value to the calculation (i.e. 40 year life cycle or 2.5% per year).

The TEFMA has taken steps to identify specific backlog maintenance infrastructure categories (some of which are hidden or undisclosed to a buildings occupant) yet remain critical and essential in the correct functionality of the building and require upgrading and replacement due to economic life expiry. The identification of these asset components have a direct impact on the FCI and FFI of the building asset enabling asset management practitioners better and invaluable insights into the risks and liabilities associated with operating, acquiring or assessing the value of a building asset.

6 Acknowledgement

We want to acknowledge the Tertiary Education Facility Management Association (TEFMA), each member university and the technical officers of those universities who, each year, process and analyse the data gathered to advance the industry and sector further.

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Climate Change Impact on Cooling and Heating Demand of Buildings in Penrith

Mohammadreza Khanarmuei[1], Keivan Bamdad[1*], Srinath Perera[1]

[1]School of Engineering, Design and Built Environment, Western Sydney University, AUSTRALIA

r.khanarmuei@westernsydney.edu.au; k.bamdad@westernsydney.edu.au; srinath.perera@westernsydney.edu.au
* Corresponding author

Abstract

On January 4, 2020, Penrith was the hottest place on Earth. According to the Intergovernmental Panel on Climate Change (IPCC), extreme weather conditions will become more severe in the future, which not only increases cooling energy demands but also poses threats to the health of occupants in buildings. Therefore, improving the thermal performance of buildings is critical to enhancing occupants' thermal comfort and mitigating climate change. Accordingly, this research aims to quantify the climate change impacts on the cooling and heating demands of buildings in Penrith, Australia. Heating and Cooling Degree days (HDDs and CDDs) methods are used to predict the cooling and heating demands under present and future climate conditions. It is predicted that Penrith would experience up to a 5.1°C temperature increase by 2100 under the high emission scenario. It is estimated that CDDs would increase approximately from 900 to 1400 by 2100 under the SSP2-4.5 emission scenario. This increase could roughly reach up to 2500 under the SSP5-8.5 emission scenario. In contrast, HDDs are expected to decline approximately from 630 to below 100 under the high (SSP5-8.5) emission scenario by the end of this century. It is expected that the findings of this research can be used as a guideline for architects and building designers to improve the energy performance of buildings in one of the fastest growing cities in Australia.

Keywords:
Building energy demand, Climate change, Cooling degree days, Heating degree days, Shared Socioeconomic Pathways

1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) predicts that the magnitude of the global mean surface temperature will rise in the range of 0.3 °C – 4.8 °C by the end of the 21st century relative to the 1986–2005 period . This temperature rise can lead to serious consequences, such as extreme weather events, heat waves, and an increase in the number of heat-related deaths. Of all the energy-intensive sectors, the building sector has substantially contributed to global warming and is responsible for nearly one-third of global greenhouse gas (GHG) emissions . It is noteworthy that in developed societies, people spend roughly 90% of their time indoors (Klepeis et al., 2001), and therefore it is vital to improve buildings' design so as mitigate the risks of climate change on human health. To this end, the first step is to predict the impact of climate change on buildings.

To evaluate the impact of global warming on the heating and cooling requirements in buildings, either building simulation tools or degree-day methods can be used. Building simulation tools such as EnergyPlus use hourly weather data and a simulated building model to predict the energy requirements for space heating and cooling energy demand (Bamdad Masouleh et al., 2017). The heating and cooling degree-days (HDDs and CDDs) are based on summations of temperature differences between the outdoor temperature and a base temperature over time, and can be seen as indicators for predicting energy requirements for space heating and cooling in buildings. HDDs and CDDs have been widely used by researchers due to their simplicity, and generalizability. Different methods to calculate CDDs and HDDs were studied in (De Rosa et al., 2015, Hitchin, 1983, Schoenau and Kehrig, 1990, Bonhomme, 2000). Spinoni et al. (Spinoni et al., 2018) studied trends in HDDs and CDDs from 1981 to 2100 in Europe. It was predicted that the increase in CDDs would peak in the Mediterranean region and the Balkans. Petri and Caldeira (Petri and Caldeira, 2015) analysed the impact of climate change on residential buildings in the United States, and the trend of combined HDDs + CDDs was investigated in different cities under both the present and business as usual climate change scenario. In another study (Ramon et al., 2020), future heating and cooling degree days for Belgium under a high-end climate change scenario were investigated. It was found that HDDs will experience a decrease of 27% in the future, however, the CDDs were found to be increased by a factor of 2.4. A research study (Ukey and Rai, 2021) investigated the impact of climate change on cooling and heating degree days in major Indian cities. It was found that CDDs may increase by 83.0% in the 2080s, while heating degree days can drop up to 97.1%. Other studies were also carried out to analyse CDDs and HDDs in Australia (Ahmed et al., 2018), North-East India (Borah et al., 2015), Chile (Carpio et al., 2022), Switzerland (Christenson et al., 2006), Greece (Papakostas and Kyriakis, 2005), Saudi Arabia (Şen and Kadioglȋu, 1998), Turkey (Sarak and Satman, 2003), UK (McGilligan et al., 2011), Italy (D'Amico et al., 2019, Fantini and Schenone, 2001), Ethiopia (Abebe and Assefa, 2022) and around the globe (Isaac and van Vuuren, 2009).

Prior studies have demonstrated that HDDs have decreased while CDDs have increased over the last decades as a result of global warming. The magnitude of these increases and decreases, however, is not the same in different regions. Importantly, the magnitude of these changes may vary in the future under different climate change scenarios. Thus, this research aims to evaluate the climate change impacts on cooling and heating demands in buildings using CDDs, and HDDs methods in Penrith, Australia.

The reminder of this paper is structured as follows. Section 2 is the methodology section, detailing the historical and future weather datasets, and heating and cooling degree days methods. Section 3 discusses the results and compares different future climate scenarios, and Section 4 presents the conclusions and future work of the research.

2 Methodology

2.1 Datasets

To investigate the impact of climate change on the heating and cooling energy requirements for residential buildings in Penrith, we used historical and future temperature data.

Historical temperature data: Data were obtained from the Australian Bureau of Meteorology (BoM). This dataset contains the maximum and minimum daily temperatures that are freely available at http://www.bom.gov.au/climate/data/. The BoM dataset for Penrith (i.e., station 067113 at Penrith Lake, NSW) covers from January 1995, however, there are many missing data from the period of 1995-1997. Therefore, we used temperature data from 1998-2021. For this period, there are 1.4% missing values. To fill the missing data, we used a secondary source of historical data that was obtained from Solcast (https://solcast.com), a global solar forecasting and historical solar irradiance data company. Solcast provides historical weather data including more than 20 parameters (e.g., air temperature, wind, pressure, precipitation and dewpoint temperature) from 2007 until now with temporal resolutions of 5, 10, 15, 30 and 60 minutes and spatial resolution of $0.025^{\circ} \times 0.025^{\circ}$ by using two sources of the reanalysis datasets: (i) the European Centre for Medium-Range Weather Forecasts (ECMWF) interim *reanalysis* and (ii) analysis from the Global Forecast System (GFS) numerical weather prediction model from the National Oceanic and Atmospheric Administration (NOAA). Solcast historical weather data is freely available for researchers. Detailed information about the historical datasets can be found at https://solcast.com, and (Bright, 2019) discussed the *validation* of the Solcast satellite-derived *solar irradiance* dataset. After using the Solcast historical data to fill in the missing data, there were still 0.6% missing values, and we used a linear interpolation to fill in the remaining data.

Future data: Future temperature data from 2022 to 2100 is obtained from the National Aeronautics and Space Administration (NASA) Earth Exchange (NEX)-Global Daily Downscaled Projections (GDDP)-Coupled Model Intercomparison Projects 6th (CMIP6) dataset (or in short form, NEX-GDDP-CMIP6). This dataset is made up of the global downscaled climate scenarios derived from the General Circulation Model (GCM) runs conducted under CMIP6 for the sixth assessment report by the IPCC report. The NEX-GDDP-CMIP6 dataset presents the projected weather data from 2015 to 2100 for the group of four Tier 1 Shared Socio-economic Pathway (SSP) scenarios. These scenarios are: (i) SSP1-2.6 with a nominal 2.6 W m^{-2} radiation forcing level by 2100, (ii) SSP2-4.5 with a nominal 4.5 W m^{-2} radiation forcing level by 2100, (iii) SSP3-7.0, which is a medium-high reference scenario, and SSP4-8.5, which is a very high greenhouse gas emission scenario (Meinshausen et al., 2020). The NEX-GDDP-CMIP6 dataset is in a grided format with a 24-hour temporal resolution and spatial resolution of , and it is freely available (https://www.nasa.gov/nex/gddp) for researchers. This high-resolution dataset has been widely used by researchers to study the impact of global climate change on various regional weather parameters (Ukey and Rai, 2021, Ghalami et al., 2021, Wu et al., 2020). Using this dataset, in this study we retrieved the daily maximum and minimum air temperatures from the Australian Community Climate and Earth System Simulator Coupled Model 2, ACCESS-CM2, which is Australia's contribution to the CMIP6. To estimate the representative temperatures of Penrith city, the temperature data was retrieved for the closest four grid points to Penrith, and then we used a bilinear interpolation approach for Penrith's temperatures.

2.2 Cooling and Heating degree-days

To investigate the impact of climate change on the heating and cooling energy requirements of the residential buildings in Penrith, we calculated the annual CDDs and HDDs by using the following equations suggested by the American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE 2009):

$$CDD = \sum_{i=1}^{N} (T_i - T_b)^+ \tag{1}$$

$$HDD = \sum_{i=1}^{N} (T_b - T_i)^+ \tag{2}$$

where T_b is the balanced point temperature, T_i is the daily average air temperature, and N is the number of days in the year. In equations 1 and 2, only positive values contribute to the CDDs and HDDs annual values. The balance point temperature is a threshold level; for a building, cooling is required if the air temperature is higher than this threshold and heating is required when the air temperature is lower than this threshold (Ahmed et al., 2012). Howden and Crimp suggested that 17.5°C can be used as the balance temperature point for Sydney, and in this study, we also use the same value for Penrith. The daily mean temperature is calculated as the mean of the daily minimum and maximum temperatures.

3 Results

In this work, we studied the impact of climate change on the heating and cooling energy requirements of the residential buildings in Penrith by investigating the historical and future air temperature, HDDs and CDDs. This section first discusses our analysis of the historical and future temperature data in Penrith, and then discussions of CDDs and HDDs are presented.

3.1 Historical and Future Air Temperature

To study the impact of climate change on the air temperature in Penrith, we analysed the historical temperature data from 1998 to the end of 2021 and future data from 2022 to 2100. Figure 1 shows the annual mean temperature anomalies for Penrith over 1998–2100. The mean annual temperature anomaly is the difference between the annual mean temperature and the average temperature (i.e., 18.53°C) over 1998–2021. As this figure shows, the historical annual mean temperature had a sinusoidal fluctuation around the base temperature (mean temperature), and having a historical dataset covering a longer period might be useful to better extract the historical trend of change in annual mean temperature. On the other hand, both SSP scenarios show a significant increase in annual mean temperature almost throughout the 21st century. As it can be seen, in the first years of the forecast, both scenarios showed some level of decrease in the annual mean temperature; however, after 2035, there is a significant increase with a growing rate until the end of the century, when the temperature anomalies reach 2 °C and 5.1 °C under the SSP2-4.5 and SSP5-8.5 scenarios, respectively.

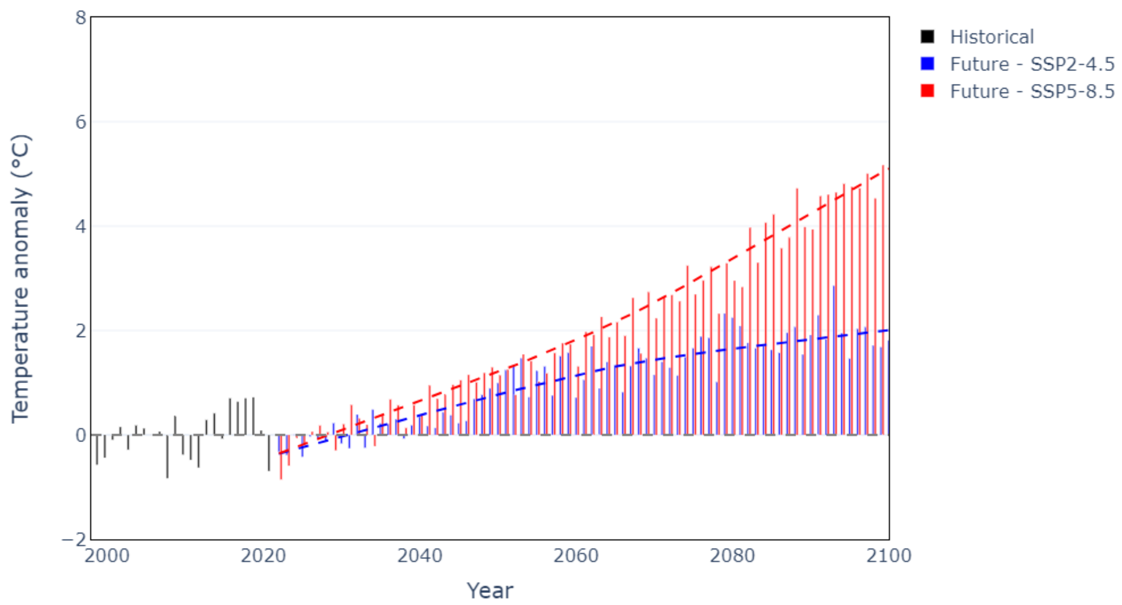

Figure 1. Historical and future annual mean air temperature anomalies in Penrith (SSP2 and SSP5 scenarios known as middle of the road and fossil-fuel development, respectively)

To better compare these two scenarios, we divided the period of 2021-2100 into four 20-year intervals and presented the mean temperature anomalies for these intervals in Figure 2. Results show that for the first period (2021–2040), there is a marginal increase (0.07 °C) in annual mean temperature using the SSP5-8.5 scenario, whereas the SSP2-4.5 showed almost no change. However, both scenarios estimated a significant increase in the mean annual temperature in Penrith for all the next intervals. Using SSP2-4.5 and SSP5-8.5 scenarios, predictions for the increase in annual mean temperature are 0.84 and 1.19°C in 2041–2060, 1.45 and 2.49°C in 2061–2080, and 1.88 and 4.3°C in 2081-2100 (larger values are obtained from SSP5-8.5). This level of increase in the air temperature in the Penrith area is consistent with the findings of a recent study where Chen et al (2021) estimated greater than 2.5°C and 4.0°C projected temperature increases under representative concentration pathways (RCPs) 4.5 and 8.5 scenarios, respectively, in the 2090s (2080–2099) in Sydney city [30].

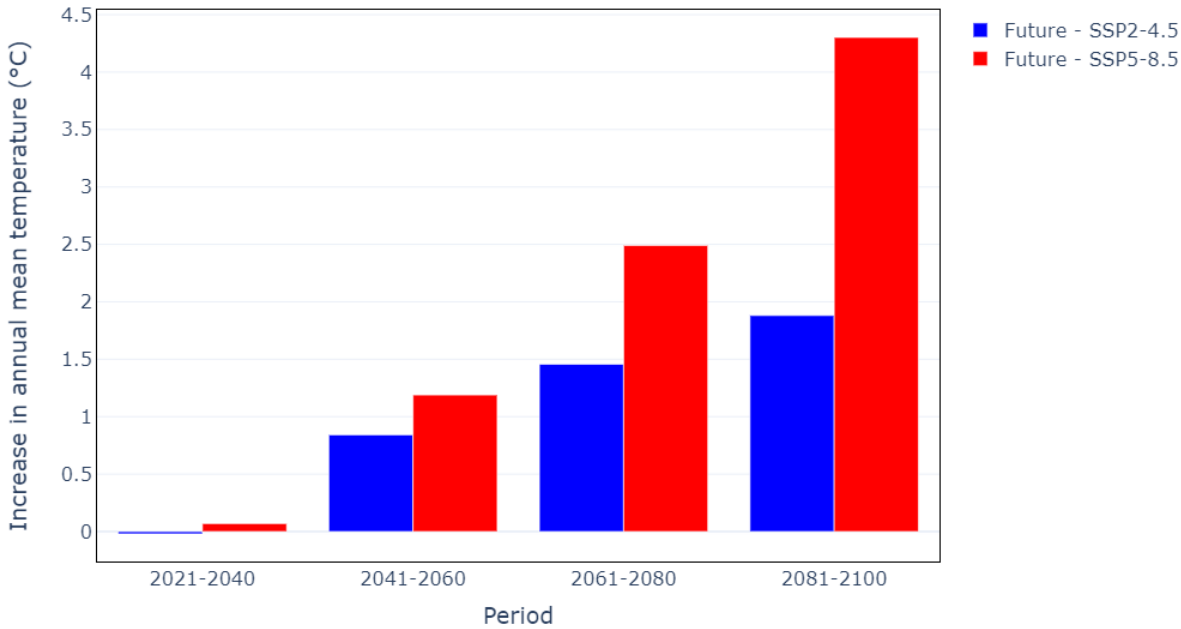

Figure 2. Increase in the mean annual air temperature in Penrith using SSP scenarios

3.2 Historical and Future Cooling degree-days

Fig. 3 indicates the historical and future projections of CDDs in Penrith from 1998 to 2100 under the SSP2-4.5 and SSP5-8.5 scenarios. In this figure, the base CDDs as the mean CDDs over the historical period is also displayed, which can help to better discuss the level of change in CDDs in the future estimations compared to the historical data. As it can be seen, the CDDs will not go beyond the base CDDs value under both the emission scenarios by 2040. However, from 2040 onwards, the CDDs start to rise by a large magnitude under the SSP5-8.5 scenario, while estimates under SSP2-4.5 show that CDDs noticeably go beyond the baseline after 2050. CDDs are expected to increase approximately from 1000 to 1400 by 2100 under SSP2-4.5, compared to the baseline. As shown, a significant increase in CDDs is predicted under SSP5-8.5 (high emission scenario), so that CDDs would be more than double by the end of the century. Similar to the temperature discussion, we divided the period of 2020–2100 into four 20-year intervals and presented the increase in CDDs in Penrith for these intervals in Figure 4. Consistent with what has been discussed for Fig3, Fig 4 shows that for 2020–2040 we expect a mean CDDs smaller than the baseline under both scenarios, while the mean CDDs for the rest periods is significantly larger than the baseline, especially under the SSP5-8.5 scenario.

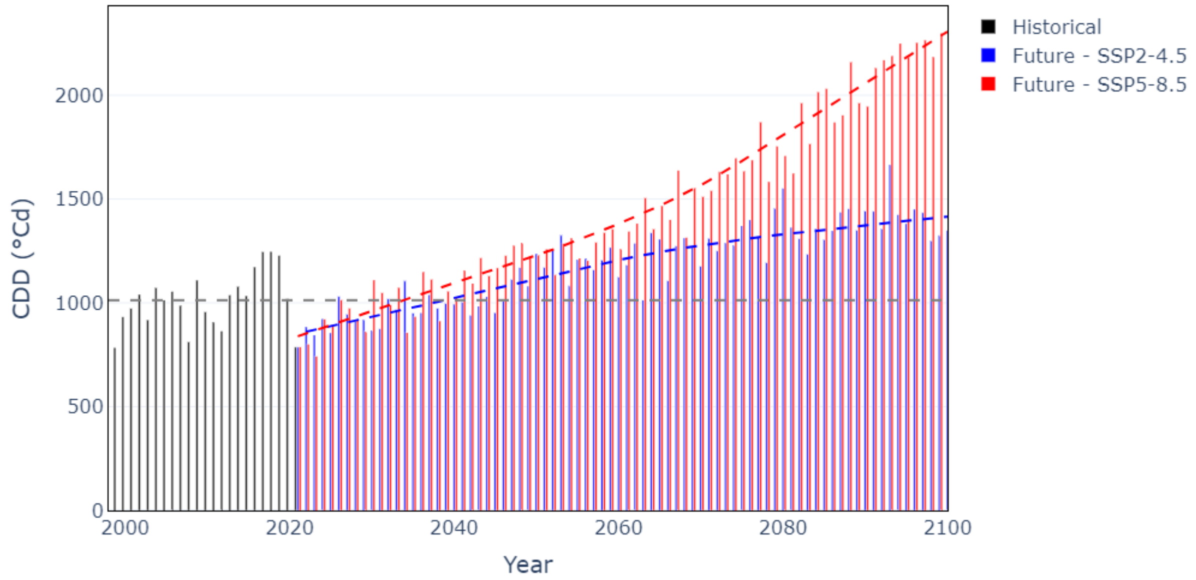

Figure 3. Historical and future CDD in Penrith

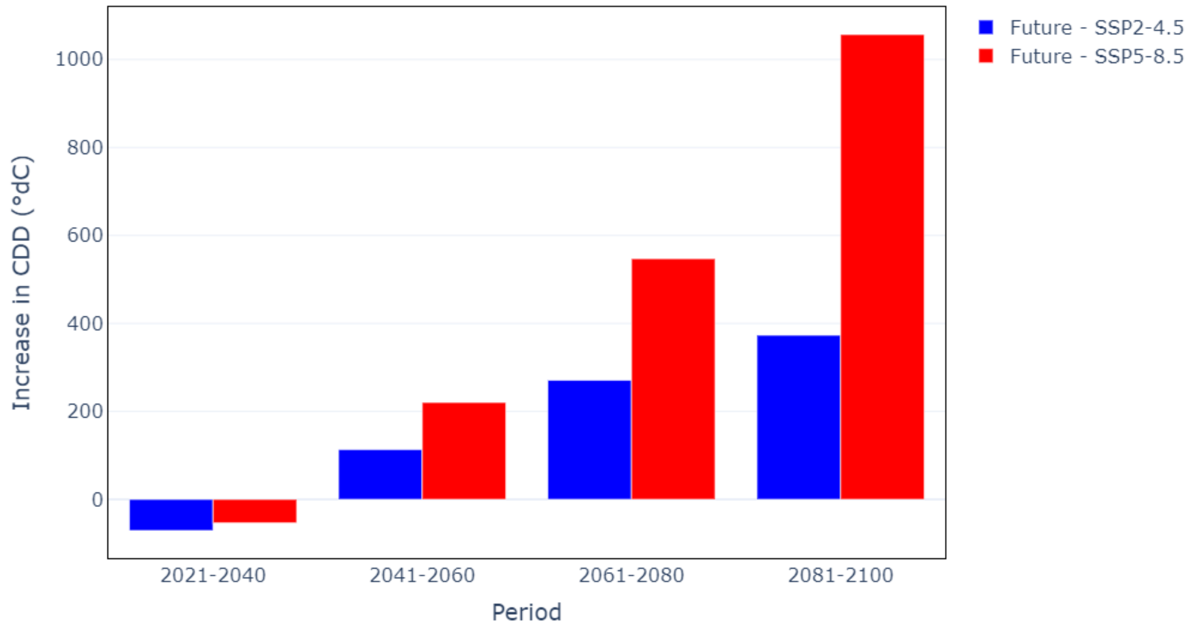

Figure 4. Increase in CDDs in Penrith using air temperature estimates under SSP scenarios

3.3 Historical and Future Heating degree-days

Fig. 5 indicates the historical and future projections of HDDs in Penrith from 1988 to 2100 under the SSP2-4.5 and SSP5-8.5 scenarios. In this figure, the baseline HDDs (mean HDDs over the historical period, 1988–2022) is also displayed. As it can be seen, there is a significant decrease in HDDs compared to the baseline using projected temperature under both scenarios. HDDs are expected to decline approximately from 630 to 300 under SSP2-4.5 by 2100. This drop would be noticeably higher under SSP5-8.5 scenarios. It is predicted that HDDs will be reduced to below 100 under the high (SSP5-8.5) scenario by the end of this century. By dividing the future period into four 20-year intervals, we can better discuss the level of decrease in HDDs for the rest of this century. Fig. 6 displays the difference between mean HDDs under SSP scenarios and the baseline HDDs for four intervals. These results show a significant decrease in HDDs even in the first future interval (2020–2040), and the level of decrease constantly grows over the next intervals. The mean decreases in HDDs for the 2080–2100 interval are greater than 300 and 500 under the SSP2-4.5 and SSP5-8.5 scenarios, respectively.

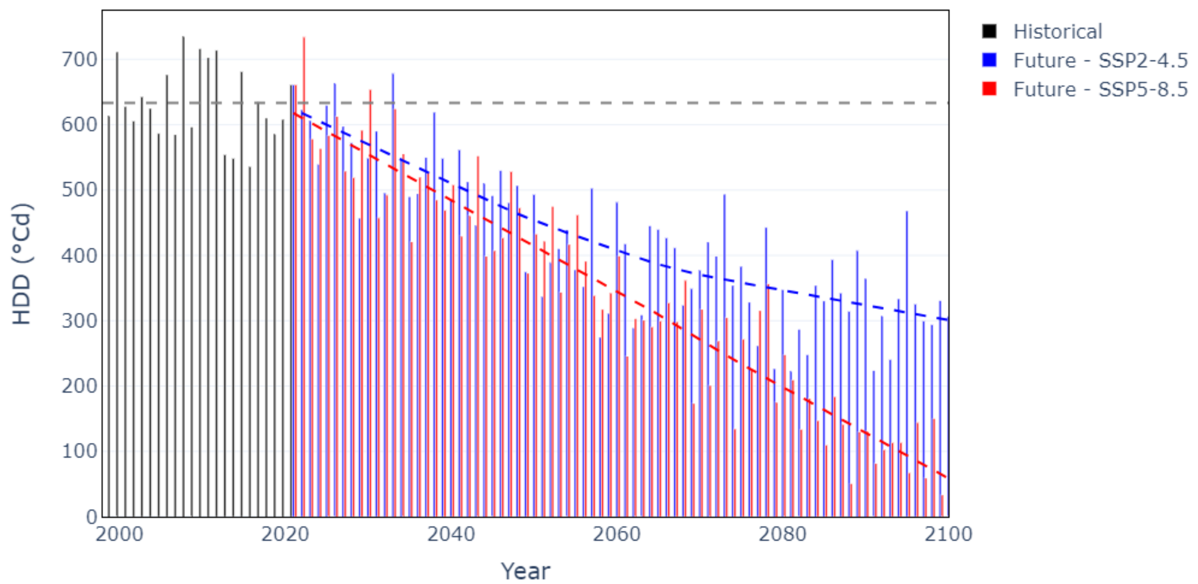

Figure 5. Historical and future HDDs in Penrith

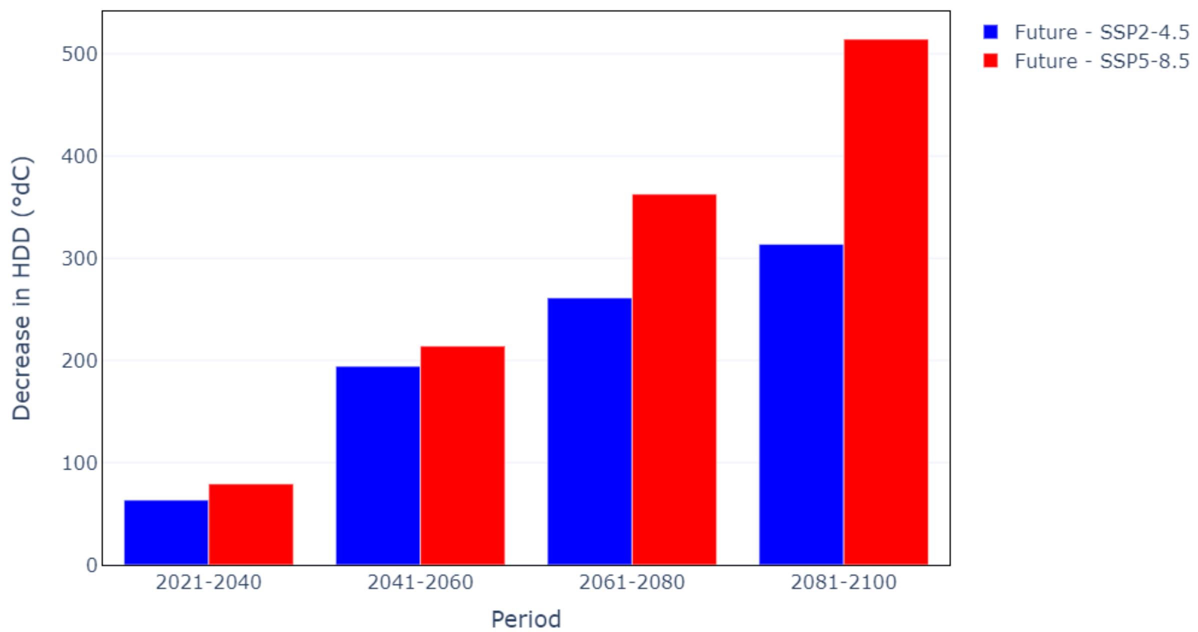

Figure 6. Decrease in HDDs in Penrith using air temperature estimates under the SSP scenarios

4 Conclusion

This research quantified the climate change impacts on the cooling and heating demand of buildings in Penrith, Australia. The Heating and Cooling Degree days (HDDs and CDDs) methods were used to predict building cooling and heating demands under present and future climate conditions. Data from the National Aeronautics and Space Administration (NASA) based on future climate change scenarios called "Shared Socioeconomic Pathways (SSPs)" introduced in the IPCC Sixth Assessment Report was used to analyse future climate conditions in Penrith. It is predicted that Penrith will experience a temperature rise of 2°C and 5.1°C by 2100 under the SSP2-4.5 and SSP5-8.5 scenarios, respectively. With regards to building cooling and heating demands, it is estimated that CDDs would increase approximately from 900 to 1400 by 2100 under the SSP2-4.5 emission scenario. This increase could roughly reach up to 2500 under the SSP5-8.5 emission scenario. In contrast, HDDs are expected to decline approximately from 630 to below 100 under the high (SSP5-8.5) emission scenario by the end of this century. HDDs and CCDs are well-established methods that are commonly used by researchers to predict energy requirements for space heating and cooling in buildings. It is expected that the findings of this research can be used as a guideline for architects and building designers to improve the energy performance of buildings in one of the fastest growing cities in Australia.

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An A-Priori Framework for Community Transformation through Inclusive Risk-Sensitive Urban Development

Devindi Geekiyanage[1*], Terrence Fernando[1] and Kaushal Keraminiyage[1]

[1]THINKlab, School of Science, Engineering and Environment, The University of Salford, Maxwell Building, 43 Crescent, M5 4WT, UNITED KINGDOM

m.d.hembageekiyanage@edu.salford.ac.uk; t.fernando@salford.ac.uk; k.p.keraminiyage@salford.ac.uk
* Corresponding author

Abstract:
Community-inclusive decision-making in developing equitable and risk-sensitive developments, particularly in urban settings, is becoming trending for achieving sustainable development goals (particularly SDG 10 and 11) set by the United Nations in 2015. A long-standing challenge in community-inclusive, equitable and risk-sensitive urban development has been to anchor practice and continuous evaluation in a relevant and comprehensive theoretical framework of community change. This study describes the development of a multidimensional theoretical framework that builds on the prevailing community/social change models and theories to identify key components of community transformation processes through civic engagement 3.0. An 'A-Priori framework' was developed adopting the "Best-fit" framework synthesis approach following a slightly adapted version of the BeHEMoTh search strategy for literature selection. The systematic review resulted in 46 publications where only 12 publications containing 09 models that provide theoretical underpinnings for community change were included in the study. The study identified 12 key constructs to be integrated into a community transformation model for participatory development. They are; the context, phases of transformation, change triggers, lead agency and institutional collaboration, change process, implementation, resources, cognitive factor, behaviour factors, environmental factors, change, and assessment and evaluation towards inclusive cities. The theoretical framework presented will be of use for industry practitioners, voluntary organisations and academicians in developing a conceptual framework by referring to empirical literature and data, and thereby establishing relationships among constructs to generate a meaningful model for mobilising communities through community engagement.

Keywords:
Civic engagement 3.0, Community transformation, Framework synthesis, Risk-sensitive urban development, SDG 11

1 Introduction

Community inclusive decision-making in building equitable and risk-sensitive developments, particularly in urban settings, have been recognised as a key enabler in achieving Sustainable Development Goals, particularly, SDG 11 aimed at "making cities and human settlements inclusive, safe, resilient and sustainable" and SDG 10 that is focusing on "reducing inequality within and among countries", as set by the United Nations in 2015 (United Nations Office for Disaster Risk Reduction [UNDRR], 2015). The 'Civic Engagement 3.0', which seeks to redefine the roles of citizens in city-making, is a recent revolution in community engagement. It focuses on empowering people and groups in society to facilitate effective, short-term community transformation leading to a complete social transformation in the long run (Mäenpää *et al*., 2017; Taylor *et al*., 2018). The version 3.0 of the Civic Engagement movement aims to build communities by integrating physical and social development, placing people above the market, and infusing non-market elements (e.g., community organisations and media) into market dynamics to moderate and reduce its undesirable effect on neighbourhood development

(Emerson & Smiley, 2019). The literature asserts that civic participation in urban planning and development aims to transform communities' knowledge and attitudes (i.e., beliefs and values) and consequently pave the way for behavioural changes in individuals, neighbourhoods, and the population at large (Calder & Beckie, 2013).

Within this context, researchers argue that centralised power needs to be decentralised and fairly distributed among project stakeholders, including communities, to achieve an effective community transformation in public projects such as urban planning and development (Morchain & Kelsey, 2016). A key challenge in establishing an effective community transformation is the lack of a comprehensive theoretical framework that can offer a coherent explanation on how community transformation can be fostered to create systemic changes in the context of risk-sensitive urban development (RSUD). Existing models, such as the Modernisation model (Janos, 1986) and Marxian revolutionary model (Holton, 1981), are based on social theories such as Social Cognitive Theory (SCT) (Luszczynska & Schwarzer, 2020), Theory of Planned Behaviour (ToPB) (Pavlova & Silbereisen, 2015; Taylor *et al*., 2006), and Theory of Change (ToC) (Cuéllar-Gálvez *et al*., 2018; Reid *et al*., 2019), and are more geared towards modelling transformation of societies as opposed to communities. To elaborate on the basic difference between societies and communities, a society is a group of people with a common territory and culture interacting with one another, while a community is a group of people living in the same place or having a particular characteristic in common (Tönnies., 2012). Furthermore, current models have focused on resolving conflicts between social classes or describing social dynamics that can lead to successful collaborations (Moczek *et al*., 2021; Schulz *et al*., 2003). Therefore, these models generally lack a comprehensive theoretical explanation of the dynamic processes that can lead to community transformation in the context of inclusive developments. Fawcett *et al*. (2011) suggest that the vital concepts used in the aforementioned social theories and models can be used to develop a road map for community transformation.

This study, therefore, draws on a 'best-fit' framework synthesis (Carroll *et al*., 2011; Carroll *et al*., 2013; Dixon-Woods, 2011) of crucial community/social transformation theories, frameworks and models to identify the fundamental constructs of community transformation. Thereby the study proposes a theoretical framework for community transformation through inclusive developments.

2 Background of Transforming Communities through Inclusive Developments

2.1 Inclusive Risk-Sensitive Urban Developments

During the last decade, many initiatives (e.g., preparation of disaster relief plans, public awareness, early warning system, evacuation services etc.) have been undertaken to make progress in disaster risk reduction (DRR) and response in cities (UNDRR, 2015). However, it is argued that while focusing on implementing strategies to respond to and recover from disaster events, practitioners have overlooked mitigating anticipated disaster risks (Fraser *et al*., 2017; Leck *et al*., 2018). Disaster risk mitigation in urban development requires acknowledging and addressing the development processes as the root causes of disasters and properly assessing anticipated development and climate-induced disaster risks. In the context of the disaster-development nexus, an integrated approach to DRR and development interventions from the national to local level had been lacking (Leck *et al*., 2018). Due to the above gaps in the current development processes, there is an urgent need to promote collaborative RSUD approaches to make cities and human settlements inclusive, safe, resilient, and sustainable (Thomalla *et al*., 2018). RSUD is an innovative planning approach that can transform the way cities are built in order to face the uncertainties that arise from climate-induced disaster risks (Roslan *et al*., 2021). Leck *et al*. (2018) suggest that the transition towards RSUD requires inclusive approaches. Inclusive development is a recent dimension of development which puts a strong emphasis on the poorest and most marginalised by taking into account economic, social and environmental dimensions and structural factors that hinder the poorest from participating in the development process (Shand, 2018; Ziervogel *et al*., 2016). Such inclusive approaches demand community actions in all development programs at all stages (planning, design, implementation /construction, and monitoring and evaluation) (Geekiyanage *et al*., 2021). This process is often described as 'mainstreaming', which evolves from individual to community transformation (Shand, 2018).

2.2 Transforming Communities through Participation in Risk-Sensitive Urban Planning and Development

The concept of community transformation, also known as community change and mobilisation, intends to bring a significant change in a distressed community that would not be promptly measurable (Hille, 2008). It is a longitudinal process requiring a wide range of concentrated efforts in a given community over a long period. The state-of-the-art literature on community transformation is deeply entrenched in understanding the required structural changes and the importance of broader social transformation (Pelling *et al*., 2015; Ziervogel *et al*., 2016). It is argued that this broader social transformation is often stimulated through a decentralised approach, where civic engagement plays a major role (Ziervogel *et al*., 2016). Community transformation through civic engagement requires three catalysts of change: (1) relationships: how people relate to themselves, each other, and those affected by inequity; (2) improvement: how the community approaches the change process; and (3) equity: how the community creates abundance through leadership, adaptability, empowerment, and connection (Domlyn *et al*., 2021). One of the best examples that illustrates a decentralised social transformation through engagement is the worldwide '#MeToo movement' which has brought renewed attention to the issue of sexual harassment in the workplace. The #MeToo movement inspired the public to consider sexual harassment as a social issue and empowered them to raise their voices to receive protection (O'Neil *et al*., 2018). As a result, system changes were implemented within institutions, regulations, policies, and practices.

The transformation of communities through inclusive development approaches is indeed a complex task as it is highly constrained by communities' lack of knowledge (i.e., of government-led development practices and the benefits of engagement) and silos conducted by different agencies, institutions and other actors with differing priorities, perspectives and time horizons (Geekiyanage *et al*., 2020). In order to promote community transformation through inclusive RSUD, a number of studies have been conducted from various perspectives, including (1) investigating the opportunities for inclusive developments (Emerson & Smiley, 2019; Shand, 2018); (2) examining the barriers and enablers to inclusive developments (Geekiyanage *et al*., 2020); (3) best-practices to inclusive developments (Mäenpää et al., 2017; Moczek et al., 2021); (4) participatory methods (Geekiyanage *et al*., 2021). While providing valuable insights for promoting inclusive developments to mainstream DRM into urban development, these studies have failed to elaborate on a methodology for transforming communities through inclusive urban development.

Therefore, drawing from the community transformation theories and models triggered by community engagement in other contexts, which has relation to development, this study attempted to develop a theoretical framework to promote community transformation, particularly in the scope of inclusive RSUDs. The synthesis thereby attempts to lay the basis for filling a noteworthy gap in the knowledge base of fundamental concepts related to transforming communities through engagement.

3 Research Methodology

The technique of Best Fit Framework Synthesis (BFFS), an advanced account of Framework Synthesis (FS), offers a means to test, reinforce and build on published models that are conceived for potentially different but relevant contexts (Carroll *et al.*, 2013; Dixon-Woods, 2011). The authors chose the BFFS approach since there are a few published theories, models and frameworks that are conceptualised for community transformation in different but related domains. These seminal works were reviewed to identify their key concepts and variables, which form themes for the 'A-Priori Framework'. Thematic analysis was chosen for creating the A-Priori Framework as it is a widely-used form of inductive coding and is consistent with the final synthesis process for the 'Best Fit' method (Fereday & Muir-Cochrane, 2006).

Booth and Carroll (2015) published a reliable strategy called 'BeHEMoTh' for establishing the A-Priori framework ensuring reproducibility. This BeHEMoTh strategy (named as a mnemonic from the component elements Behaviour of Interest, Health context, Exclusions, and Models/Theories) initially developed and used within medical research, provides a multi-stage, systematic approach to identifying relevant models and theories specifically for behavioural change. In this study, it is necessary to combine free text and database thesaurus terms for the behaviour of interest (civic engagement) and health context (where in our research, we used RSUD as the context) with terms for models and theories (see Table 1).

Table 1. Application of BeHEMoTh search strategy for establishing the A-Priori framework

Strategy	**Terms**
Be - Behaviour of Interest	(community OR social) AND (transformation OR change OR mobilisation OR transition)
H – Health (in this study, this is replaced to represent the subject area)	disaster risk-sensitive urban development
E - Exclusions	The articles related to individual, interpersonal, or organisational transformation
MoTh – Models and Theories	theory OR framework OR model

The search for models to inform the exemplar review included terms for community transformation and social transformation to be as sensitive as possible and identify related theories, frameworks and models. This broad approach was adapted to anticipate a circumstance where no model specifically relating to community transformation can be identified from the literature. In accordance with the emerging practice in social science research, core databases judiciously selected for the topic and study types of interest are considered sufficient to retrieve a critical majority of the relevant literature (Ganann *et al.*, 2010). Additionally, Moher et al. (2009) commented that at least one database should be thoroughly searched and presented in a systematic review. In this study, three indexed bibliographic databases: Scopus, Web of Science Core Collection, and Science Direct, that are related to the study scope were considered (Papaioannou *et al.*, 2010). Several filters, such as publication year, subject/research area, document type and language, were applied during the database searches to fulfil basic study selection criteria (see Table 2).

Table 2. Study eligibility criteria

Criteria	Inclusion criteria	Rational
Publication year	From 2001 to May 2022	To exclude outdated content that may not be fitting to the transformation of current urban communities
Subject/ Research area	Social science, Arts and Humanities, Urban Studies, Development Studies, Decision-making	To exclude studies irreverent to the study focus on inclusive urban developments
Document type	Journal article	Academic journals are a favoured source of academic information and have credibility due to the process of peer review
Language	English	Most of the relevant works are published in English, and the authors are not fluent in other languages
Study content	Publications with a theory/framework /model related to community transformation	To comply with the requirements of adapting the best-fit framework synthesis approach (the paper should show some relation to inclusive or urban developments)
Study design	Publications exploring, testing or creating frameworks, models, and theories	To comply with the requirements of adapting the best-fit framework synthesis approach

4 Findings and Discussion

4.1 Systematic Search Results

The systematic search generated 249 records from across the three databases. Given the limitations of identifying social science literature through systematic searching of electronic databases alone (Papaioannou *et al*., 2010), a manual search (i.e., a generic Google search) was conducted to test various combinations of terms to add any missing seminal work; thereby found another three records. Subsequently, five records were removed following a search for duplicates. A total of 247 records were screened against titles, keywords, and abstracts, where 180 records were excluded either due to no model/framework presented or irrelevant field of study. 49 full-text retrieved were then reviewed against the eligibility criteria established in Table 2. Additionally, the reference lists of all included studies were checked for additional literature, and full papers of four potentially relevant citations were also retrieved and checked for relevance. Accordingly, 53 full-text articles were assessed subjected to the study eligibility criteria. From those, 12 publications were identified, including nine theories and models that seemed to represent a good 'fit' to the research focus.

4.2 Review of Theories, Frameworks and Models for Community Transformation

The systematic review resulted in nine seminal works: five theories and four models that provide different theoretical underpinnings for civic transformation in different contexts. These theories and models were then critically analysed to identify the key concepts of community transformation that could use to conceptualise a framework to transform communities through engagement in the context of RSUDs. The results are presented in Table 3. Even though none of the reviewed transformation models has fully captured a community transformation approach for urban development, all can make significant contributions towards modelling community transformation through civic engagement in urban development. Therefore, this study integrates the strengths of the presented social or community change conceptions with a normative direction for a community transformation influenced by civic engagement.

Table 3. An overview of the community/social transformation models included

Best-fit Theories* / Models†		Disciplinary origins	Focus / Strength	Concepts / Constructs
A	Community Coalition Action Theory (CCAT)* (Osmond, 2008)	Health + Social	Comprehensively addresses coalition building of a community to work together to achieve a common goal	• Stages of development • Community context • Lead agency or convening group • Coalition membership • Processes • Leadership and staffing • Structures • Pooled membership • External resources • Member engagement • Collaborative synergy • Assessment and planning • Implementation of strategies • Community change outcomes • Health/social outcomes • Community capacity
B	Transitions: A Middle-Range Theory* (Im, 2011)	Nursing science + Social	Describes and predicts human beings' experiences in various types of transitions: health/illness, situational, developmental, and organisational	• Change triggers • Types and patterns of transitions • Properties of transition experiences • Transition conditions • Patterns of response/process • Outcome indicators
C	Social Cognitive Theory* (SCT) (Luszczynska & Schwarzer, 2020)	Psychology	Explain how people regulate their behaviour through control and reinforcement to achieve goal-directed behaviour that can be maintained over time.	• Reciprocal Determinism • Behavioural Capability • Observational Learning • Reinforcements • Expectations • Self-efficacy
D	Theory of Planned Behaviour (ToPB)* (Pavlova & Silbereisen, 2015; Taylor *et al*., 2006)	Psychology	Explain all behaviours over which people have the ability to exert self-control.	• Attitudes • Behavioural intention • Subjective norms • Social norms • Perceived power • Perceived behavioural control
E	Theory of Change (ToC)* (Cuéllar-Gálvez *et al*., 2018; De Silva *et al*., 2014; Reid *et al*., 2019)	Program theory and program evaluation	A description of how and why a set of activities is expected to lead to early, intermediate, and long-term outcomes over a specified period	• Outcome (Impact) • Purpose • Indicator (validation measure) • Intervention • Preconditions • Assumptions

F	A conceptual framework for transformative adaptation† (Ajulo *et al.*, 2020)	Disaster induced resettlements	Illustrates how each of the aspects is transformed from a socially ascribed to a transformed status after administering the intervention	• Trigger • Exposure unit • Process • Change
G	The Social transformation model† (Esterhuizen, 2015)	Education	A framework for integrating technology-enhanced learning in open distance learning	• Resources (Preconditions to transformation) • Transformation process (transformation aspects, intervention, aspects to be transformed) • Transformation • Transformed status • Ascribed status
H	The Social transformation framework† (Bukari *et al.*, 2017)	Social	For an effective cultural change for women's political emancipation	• Event • Vulnerability context • Psycho-social domains (human capacity, cultural values, social ecology) • Transformational strategies and processes • Outcomes • Review
I	Community-Based Participatory Research (CBPR) mobilisation processes† (Tremblay *et al.*, 2017)	CBPR	A context-specific model to generate a new, innovative understanding of CBPR mobilisation processes	• Problem • Partnership • Cause • Collective action strategy • Framing processes • Opportunities • Resources • Community and system changes • Lifecycle of CBPR projects (Stages 1–4)

4.3 Development of the A-Priori Framework

There are a few options for developing the A-Priori framework: (1) to privilege one of the models (i.e., to choose one particular model and reject others arbitrarily or using post hoc criteria); (2) use two or more models in combination; or (3) to consider all identified models (Carroll *et al*., 2013). In this study, all nine models seem equally relevant with variants, and no justification can be provided for selecting one model over another. Thus, all nine models were considered for developing the A-Priori framework as it offers a more comprehensive foundation for the synthesis than possible with a single arbitrarily-chosen model. The inductive thematic analysis identified the commonalities and differences between the models and named them themes (Fereday & Muir-Cochrane, 2006). These themes form the A-Priori framework, as presented in Table 4. Therefore, each theme was supported with a definition based on the elements in the original papers, thus creating ‘concepts’.

Table 4. The A-Priori framework for enabling community transformation through community engagement in risk-sensitive urban developments: Themes extracted from previous models/theories

Theme	**Description**	**Models / theories contributed**
1. Context	A setting in which a group of people is operating under considerably common characteristics.	A, E, F, H
2. Phases of Transformation	Specific stages that transformation progresses through, though not necessarily linearly.	A, H

3. Change Triggers	Change should have been triggered by something; anything that positively influences or disrupts the proper functioning of a system for which the transformation is required.	B, F, G, H
4. Lead Agency	A conveying group that needs to work together with other stakeholders from initialisation to the evaluation of the intended community transformation.	A, I
5. Process	Formal and non-formal practices that govern community interactions, roles, activities, programs, policies, initiatives, and campaigns to be implemented to achieve a specific level of community transformation.	A, B, E, F, G, H, I
6. Implementation / Action	Executing the actions planned during the process of formation.	C, D
7. Resources	Tangible and intangible assets used by the movement to carry out its action, brought by organisations and individuals.	A, G, I
8. Cognitive Factors	Characteristics of a person that affect the way they learn and perform (sometimes called personal factors) (e.g., knowledge, attitudes, observational learning).	C, D,
9. Behaviour Factors	Factors that determine an individual's conduct (e.g., self-efficacy, skills, practice).	C, D
10. Environmental Factors	Any factor physically external to the individual that can impact one's behaviour (e.g., social factors such as family, friends, observational learning, and physical factors such as weather).	C, D, H
11. Change	Individual and community outcomes that the community engagement is working towards or intending to influence.	A, B, E, F, G, H, I
12. Assessment and Evaluation	An evaluation that focused on the outcomes or impacts of collaboration activities, such as health, education, environmental, economic and other impacts.	A, B, E, H

As observed in Table 4, the data extracted from included models resulted in 12 themes that underpin the key concepts of community or social transformation efforts. It is observed that, statistically, the original model that describes the CCAT is the most contributed model representing seven out of 12 themes of the A-Priori framework. Furthermore, the social transformation framework (Bukari *et al*., 2017) and the CBPR mobilisation processes model (Tremblay *et al*., 2017) have contributed to seven and five themes, respectively. In addition, four models, namely the Transitions Theory model, the ToC model, the conceptual framework for transformative adaptation, and the social transformation model, have each been the foundation for four themes, while the rest of the models have contributed only to three themes.

5 Conclusion and Further Research

BFFS has been recognised as a useful analytic strategy for conceiving and mapping community transformation processes in the context of inclusive and RSUD. The resulting framework that draws on existing theoretical foundations provides a holistic, evidence-based and generalisable framework to generate an innovative understanding of transforming communities through engagement. Unlike existing models, the proposed framework offers an extensive number of critical concepts for community transformation through inclusive development, with the added advantage of providing a temporal perspective on the development of these processes. These results provide valuable theoretical guidance to researchers, intervention developers, and community actors by clarifying and detailing how transformation processes and consequent community and system changes emerge and develop. Even though the search strategies adopted in the study are exhaustive, still some of the relevant works could have been potentially excluded given the limitations of systematic reviews. As this work has been conducted as part of an ongoing doctoral study, future research may include populating the identified key concept and building relationships among them to develop a community transformation model for promoting civic engagement for achieving RSUDs. Moreover, as the framework was generated by combining the evidence extracted from global research, the proposed framework may not be context-specific, thus requiring validations and refinements.

6 Acknowledgement

This work was supported by the Global Challenges Research Fund (GCRF) and the Economic and Social Research Council (ESRC) under the Grant ES/T003219/1 entitled ‘Technology Enhanced Stakeholder Collaboration for Supporting Risk-Sensitive Sustainable Urban Development’.

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Overview of New Zealand Legislation for Flood Resilience

Widi Auliagisni[1*], Suzanne Wilkinson[1] and Mohamed Elkharboutly[1]

[1]School of Built Environment, Massey University,
Massey University Private Bag 102904, North Shore Auckland 0745, NEW ZEALAND

w.auliagisni@massey.ac.nz; s.wilkinson@massey.ac.nz; m.elkharboutly@massey.ac.nz
* Corresponding author

Abstract:
Floods affect more people than any other hazard in the world and are also a hindrance to countries meeting their Sustainable Development Goals. A shift from traditional flood protection action to a more risk-aware and resilient approach is required especially in protecting communities at risk from the recurring flood. In New Zealand, the shift can be encouraged by the legal system, such as policy development for national flood management or local catchment management activities. The challenges of climate change, however, could exacerbate the existing flood risk, change flood management priorities, and create uncertainty. The New Zealand government prompted to consider whether flood protection in the country is sustainable for now and for the foreseeable future, especially at the local level. A literature analysis study is used, and the reviewed documents include media, government documents, non-governmental organisations' documents, academic journals, best practices, and local law. Drawing from the analysis of flood-related documents and legislation this research found that the existing legislative framework provides the policies and implementation tools for regional councils to better manage the flood risk. Additionally, through the best practices of local law implementation, this study provides some recommendations for an effective legal framework that will facilitate sustainable flood management and flood resilience.

Keywords:
Flood resilience, Literature analysis, Local law, Sustainable flood management

1 Introduction

Flood hazards are becoming more common in many parts of the world as land use changes and climate change's impacts rise (Rogger et al., 2017; Mehryar and Surminski, 2021). While climate change is caused by long-term shifts in temperatures and weather patterns, land-use changes are caused by the increasing number of people settling closer to waterbodies, establishing industrial areas near the shores, and building along rivers (Florina, 2007). Regardless any flood related regulation, many riverside developments frequently do not respect the provisions of laws or do not consider technical standards exposing people to hazard risk. For example, there are urban informal riverside settlements (Carrasco and Dangol, 2019), keeping the debris obstructing rivers which pass through some private land (Bodoque et al., 2016), and the building is not within the permitted area of the floodplain (Komac et al., 2008).

River management and the treatment and construction of buildings in risk-exposed areas should be strictly governed by law (Cirillo and Albrecht, 2015). To live and build property in an area prone to flood, people must apply different flood-related regulations such as building codes, flood insurance requirements, emergency strategies, risk communication, and riparian management, and other related regulations (Piyumi et al., 2021; Saifulsyahira et al., 2016; Benson et al., 2018; Ministry for the Environment, 2010). Riparian and upstream management are important to control the inundation caused by overflowing river and stopbanks' breach. The term riparian includes the land beside waterways (rivers, streams, creeks, drains, ponds, wetlands, springs, estuaries and the coast) that go through or border the private land (Northland Regional Council, 2018a). Moreover, researchers believe that balancing upstream and downstream management will reduce flooding (Sear, 2014; Wenger, 2015; Seher and Löschner, 2018).

Flood risk management (FRM) contributes to achieving Sustainable Development Goal 6 (water) through better water and river management schemes. The scheme includes the protection of water ecosystems, clean water sources, and water-related disasters (UNECE, 2019). However, based on the international trends, traditional flood management methods that emphasize activism after disasters are not enough to assist a nation in attaining sustainable development (Huck et al., 2020). A shift toward more forward-looking, risk-aware, and resilient approaches is necessary, and countries' legal systems play a vital role in fostering such a shift (Thaler and Hartmann, 2016). Through policy development, effective and low-cost flood control can be achieved.

In New Zealand, local authorities are the bodies primarily tasked with protecting communities against flooding through a range of measures including physical and non-physical works such as stopbanks, river cleaning, and flood resilience action plan. Generally, local government created local laws serve to protect assets and are designed to be complemented by central government law (Lawrence and Quade, 2011), where the regional authorities control the use of land and the territorial authorities control the actual or potential effects of the use, development or protection of land (NRC, 2018). For example, in the Northland, community in the highland started building the floodwalls and stopbanks in their private property as a protection action towards flood. However, this action creates a bigger problem for the community downhills as the river overflows with high velocity and breaking the stopbanks.

It is common for community protection actions to be based on the best practices gathered from experience and hereditary knowledge, but sometimes the application is perceived as not being right for the intended target. Some research stated that traditional knowledge are outdated, having a weak contribution for disaster management with current the change of geomorphology, climate, and natural environment and ecosystem (Shin, 2017; Gorjestani, 2001). On the other hands, many still believes that local and indigenous knowledge’s potential are overlooked as it could be the key for achieving disaster resilience and sustainable development if it is addressed correctly (Senanayake, 2006; Harmsworth, 2002; Auliagisni et al., 2022a). Therefore, the local authorities use the legislation measures to control people and organisation in responding to flood risk. Further, by combining local knowledge, science and technology, and national regulation, it can create an integrated and comprehensive local law.

However, within the natural hazard studies, the influence of laws on the nature of flood risk management, in particular, the ability to increase flood resilience in the context of climate change and the involvement of indigenous resilience concept, is still not widely explored. While more and more decision-makers recognise the importance of resilience as a concept, the management of flood risk remains a very reactive process (Blakeley, 2016). Specifically, the management in local level is still largely driven by response and recovery rather than readiness and reduction approach (Auliagisni et al., 2022b). This paper aims to provide insight into the role of local laws in regulating and encouraging current and future flood risk and resilience for communities. A framework and suggestions for Northland Region flood protection laws addressed using documents and a critical analysis approach to answer the research questions.

2 Literature Review

In traditional flood control, the effects of interventions on other areas of the river basin (upstream and downstream) or on other components of the water system (land use, drinking water, ecological services) have largely been overlooked. Public awareness of flood risks has also reduced by the construction of "visible" flood protection measures. Therefore, the law plays a fundamental role to identify protection structures and liabilities in river areas (Cirillo and Albrecht, 2015). This is to protect people considering the current and future risks and raise the overall public resilience level regardless individual awareness level (Mehryar and Surminski, 2020).

2.1 The background of flood management law

Internationally, a Water Convention (UNECE) enacted in 1992 is considered the starting law which has influenced the global vision to include flood management as a part of the more general water and river basin management (Cirillo and Albrecht, 2015). Further, in 2000 this convention then affirms the importance of cooperation at governmental levels and coordination of different policies to deal with flood which is natural event (UNECE, 2009; Nwokike, 2021). The development of a long-term management of the river basin, are considered to be the core model for flood risk management. The development process includes a continuous exchange of hydrological and meteorological data, preparation of studies, surveys, flood plains, flood areas and risk maps, flood risk assessments. In the support of the Sendai framework for disaster risk reduction 2015-2030 (UN, 2015), the UNECE offering a road map with concrete examples to help address water related disasters, especially in situations where the transboundary context adds to the complexity of risk reduction (UN, 2018). Although during UNECE meeting in the Hague, stated that only human intervention or interference can cause the worst consequences or amplify the damages as the basic principle, recent studies stated that extreme weather, sea level rise, and other climate change impacts with human behaviour are equally to blame for the increasing flood risk (Auliagisni et al., 2022b; Miller and Hutchins, 2017; Tabari, 2020).

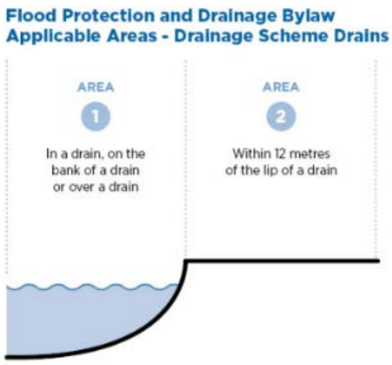
Mehryar and Surminski (2021) stated that national formal legislation system of countries plays an important role in setting out rules and frameworks for flood risk governance. Other popular studies related to the flood management legislation includes national water laws (Hartmann and Albrecht, 2014), environmental laws (Adebayo, 2014; Sholihah et al., 2020), and floodplain and river laws (Shrubsole et al., 1997; Beuchert, 1965; Epstein and Knight, 2004). However, most of the studies are country specific and generalised, lacking on discussing how it locally implemented as flood works are unique in every territory. Generalised law is not providing a great protection in the area at risk. It resulted in many issues due to the noncompliance with the law which has created countless areas subject to flooding, increasing the risks to which its inhabitants are exposed (Amaral and Ross, 2022).

In New Zealand, regulatory framework must developed in the spirit of the Treaty of Waitangi (Hudson and Russell, 2009). Signed in 1840, The Treaty of Waitangi signifies a partnership between Māori and the British Crown and requires the partners to act reasonably and with the utmost good faith (Orange, 2015). Today the Treaty is widely accepted to be a constitutional document that establishes and guides the relationship between the Crown in New Zealand (embodied by government) and Māori. For the flood management context, it translates to the inclusion of Māori representation in developing policy and the understanding indigenous knowledge and wisdom in the national and local flood management law.

2.2 Local law for flood protection and drainage

The International Panel on Climate Change (IPCC) Fourth Assessment Report (IPCC, 2014), on impacts adaptation and vulnerability to climate change concluded with high confidence climate change has already occurred in New Zealand (The Royal Society of New Zealand, 2016) with Northland is one of the most impacted region (NIWA, 2016). Future projections indicate with virtual certainty that there will be noticeable changes in extreme events causing floods, landslides, and storm surges. As management of floods requires the contribution of flood-prone households and their local community, New Zealand use the bottom-up approach for its flood protections governance (Blakeley, 2016). This mean that local council will have more power in decision making and tailor the response specified by the degree of impact and characteristic of community to reach the flood resiliency. For example, there is flood protection and drainage bylaw in some of the region such as Bay of Plenty Region area, Christchurch Region area, and Otago Region area. Similar to the mentioned bylaw, Northland Region's local laws for flood developed into the infrastructure plan, drainage scheme, flood protection scheme, and river management plans (Northland Regional Council, 2022; Northland Regional Council, 2018b).

Local laws provide protection from damage and misuse to flood protection and drainage infrastructure assets managed by or under the control of regional councils (Lawrence and Quade, 2011; Brennan, 2015). Flood protection assets were built to increase productivity of land, and prevent damage, danger, and distress to the community from flooding, and problems associated with a lack of drainage (Archie et al., 2018). There will be no restrictions or prohibitions on people working on their land under these laws, but they will ensure that any work done does not inadvertently affect the integrity of our flood protection infrastructure and drainage infrastructure assets. For example, in the Bay of Plenty areas, any works should be within 12 metres of the lips of a drain (see figure 1), and specified distance required for earthworks for the defence against water (see figure 2)(Bay of Plenty Regional Council, 2020).



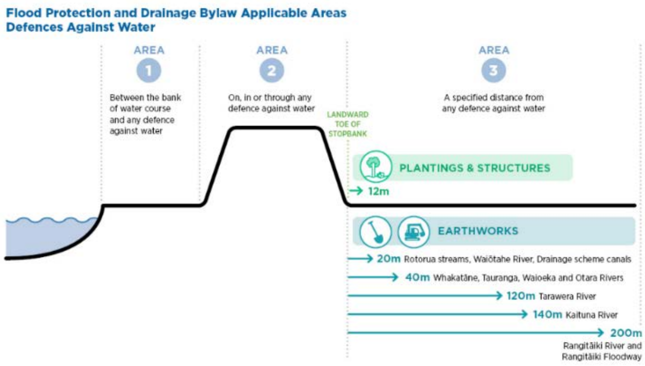


Figure 1. Local law for drainage scheme drains
Source: Bay of Plenty Regional Council (2020)

Figure 2. Local law for defence against water
Source: Bay of Plenty Regional Council (2020)

To support the local law in regional area, there are also a common law, or the responsibility of property owners. The common law requires the people to be responsible to use the property or land in a way that does not increase the risk of flooding to a neighbouring property. Basically, it is to make the drain always clean inside the property, and maintain the property level flood defence, as failure to do this, could make the property owner face a claim in negligence. Therefore, living in or near the floodplain comes with the rights and duties that is liable to individual.

3 Research Methods

This research analyses key issues of uncoordinated community flood protection and local knowledge inclusion in flood management with analysing the documents related to the flood risk management legislation in New Zealand mainly on the local law. Northland regions (Picture 3) were chosen as the area were one of the most prone to recurring flood and well representation of a flood resilience that led by local community looking through the active community engagement, regular flood work meeting, and the practice of transparency of information.

Figure 3. Area of study, Northland Region, New Zealand
Source: modified from Northland Regional Council (2022)

The review of the documents including New Zealand major statutes for flood management, framework from international organisation, and local government bylaw including Northland Regional Council flood protection strategy. The flood risk statutes in New Zealand includes New Zealand major statutes for flood management, Resource Management Act 1991, Building Act 2004 (and Building Code 1992), Local Government Act 2002, Land Drainage Act 1908, Soil Conservation and Rovers Control Act 1941, Rivers Board Act 1908, and Civil Defence Emergency Management Act 2002 (McSweeney, 2006).

Other relevant statues such as Public Works Act 1981, Local Government Official Information and Meetings Act 1987, Earthquake Commission Act 1993, the Environment Act 1986, and the Local Government Act 2002 also reviewed although it had not majorly talk about flood risk. Documents from organisations such as United Nations, NIWA, Zurich flood Resilience Alliance, Red Cross, NEMA, and Ministry for the Environment were studied. Further, documents from Northland Regional Council such as the long-term plan, civil defence group plan, infrastructure plan, and flood schemes work plan were considered for supporting the analysis.

The academic literature and the government documents were critically analysed, and the summary were drawn upon the flood management theme. The legislations mentioned in the data collection were thematically grouped specifically to address the issues of uncoordinated flood management in community level and the inclusion of indigenous community to develop a culturally sound and integrated local law.

4 Findings and Discussion

New Zealand is exposed to coastal and river flooding, and it is the costliest natural hazard related cause of disaster when both tangible and intangible losses are taken into account. Being one of the most prone areas to the recuing flood Northland regional area has experienced major devastating flood during the last decades. Northland’s three districts’ councils (Whangarei, Kaipara, and Far North district councils) developed planning laws and then implemented by the local council. Northland region is slowly moving to a more sustainable, community-based, and risk aware flood management.

4.1 New Zealand legislation for flood management and the inclusion of indigenous and local knowledge

New Zealand has two main pieces of legislation that regulate climate change and flood risk management: the Resource Management Act 1991 (RMA) and the Civil Defence Emergency Management (CDEM) Act 2002. According to the RMA, regional authorities must control the use of land in order to avoid or mitigate natural hazards. In addition to controlling the effects of land use, development, or protection, territorial authorities have a responsibility to prevent or mitigate natural hazards. Moreover, under the Resource Management (Energy and Climate Change) Amendment Act 2004, local authorities are required to consider the effects of climate change when managing resources.

Another key piece of flood risk management legislation is the CDEM Act. Specifically, the Act aims to promote the sustainable management of hazards, the resilience of communities, and the safety of people, property, and infrastructure in an emergency. Based on the CDEM Act, an approach based on risk reduction, readiness, response, and recovery is recommended (CDEM Act, 2002). Despite the fact that the RMA and CDEM Act mandate proactive planning as a means of reducing risk, there are other relevant laws for managing flood risk and climate change, including the Building Act 2004, the Local Government Act 2002, and the Soil Conservation and Rivers Control Act 1941.

In 2019, with the spirit of the Sendai Framework (UN, 2015), the Ministry for the Environment established a national approach recognising that a coordinated and cooperative effort is needed to withstand and recover from disasters. Subsequently, the National Disaster Resilience Strategy (NDRS), and Community Resiliency towards disaster was adopted by the regional councils including in the Northland Region Long Term Plan 2021-2031 and the Northland Civil Defence Emergency Management Group Plan 2021-2026. New Zealand's central government, regional councils, district councils, businesses, community leaders and non-profit sectors rely on the NDRS for disaster management guidance. Through the strategy, governments are able to move away from traditional approaches to emergency management and focus on risk management readiness and reduction rather than response and recovery. In addition, it acknowledges that disaster resilience is a shared responsibility between government levels (central, regional, and territorial), industries and businesses, non-governmental organizations (NGOs) like the Red Cross, NIWA, volunteer organizations in emergency management, and community groups (MCDEM, 2019).

However, climate change presents challenges that no one knowledge system can meet on its own. The solution to this problem requires a combination of different ideas and systems. By the fact that Māori has occupied Aotearoa for generations, it resulted in layers of knowledge that have been accrued through observation, analysis, and the necessity to survive (Proctor, 2010; Doyle, 2022). As Māori words are often used to explain the environment, and so mātauranga (knowledges) needs to be seen through the lens of *te reo*. As a result of following this concept of a resilient nation, the NDRS recommends building resilient communities (MCDEM, 2019):

1. *Manaakitanga*: The respect and care for others such as in wellbeing and hospitality.
2. *Whanaungatanga, kotahitanga*: Nurture positive relationships and partnerships by active engagement, acting inclusively, and collaboration actions.
3. *Kaitiakitanga, tūrangawaewae*: Guard and protect the places that are special to people by protecting and enhancing our cultural, historic, and natural environment; Intergenerational equity; and effort for people to feel enabled and connected.
4. *Matauranga*: Value knowledge and understanding by using scientific, historic, local, and traditional knowledge; and striving for a common understanding.
5. *Tikanga*: customs and cultural practices that central to the community's identity by encouraging cultural identity and expression; ethical and values-based; and accountability and transparency.
6. *Rangatiratanga*: Lead by example such as values-based leadership and self-determination, principle of subsidiarity.

In terms of flood resiliency practices, the application of *Manaakitanga* in the Northland community translated to the voluntary actions during the emergency situation and *Whanaungatanga* applied in the flood mitigation as community collaborating with multiple stakeholders to work on flood protection and in post flood action when community working together to clean up after flood (Auliagisni et al., 2022a; Haley, 2021). The *Kaitiakitanga* translated in community works together to protect their land natural environment by managing the riparian, ecosystem, and improving the state of the river and the quality of the water. The *Tikanga* in community guides to moral behaviour to respect leaders (follow the instruction during emergency, ensure the continued security and wellbeing of the group after the flood, and protect nature (e.g., use no harming material during cleaning up after flood)(Proctor, 2010; Auliagisni et al., 2022a). And the *Rangatiratanga* in actioning leadership during the emergency by reducing the chaos and facilitate the safe evacuation (Kenney and Phibbs, 2015; Wevers, 2011).

The practice of respect and collaboration can also be found in the other community from different country, for example local community in Indonesia, *Sundaneese* believes in *Silih Asah* (improve knowledge and teach others), *Silih Asih* (respect each other), *Silih Asuh* (care with each other) to face any difficulties (Mulyaningsih, 2018). While Indonesian *Dayaknese* believes in respecting the nature guardian by performing ceremony such as *Mamapas Lewu* performed by *Dayak Ngaju* tribe (ceremony to avoid disaster happen to community) and *Nyuwuk Jumpun* performed by *Dayak Maanyan* tribe (ceremony to open a new land for new purpose of use) (Usop and Rajiani, 2021; Souisa, 2021). Local community in Indonesia believes to only take what they need from nature in response to flood caused by land use change and overharvesting in the area. Therefore, indigenous knowledge is many things brought together as a body of knowledge, handed down from previous generations and built on by the generations of today.

In New Zealand, indigenous knowledge of Māori community should be included in climate change responses, primarily due to obligations under the Treaty of Waitangi. Hapū (clans or descent groups) and iwi (tribe) have a role to play in the management of natural resources especially when it comes to providing solutions that will ensure community resilience (Kenney and Phibbs, 2015; Doyle, 2022; Proctor, 2010). Oftentimes the solutions for climate adaptation and climate resilience come from more localised types of approaches. It can be good at a national level for providing guidance but lacking when applied to specific regions. For example, specific flood protection strategies for the Kaitaia and Kaeo in Far North District would look different to those for Whangarei CBD and Dargaville given things like geographic differences and causes of flooding.

Māori already had legal customs in the form of *tikanga*, a set of rules and principles which governed daily life. Indigenous communities living in flood-prone areas extensively use their traditional knowledge for forecasting floods and other natural disasters. The knowledge is based on whakapapa and on connections between everything. That includes how people are connected to the earth and all living and non-living things. Therefore, in solving the flood problem, the inclusion of indigenous representation in the flood meetings is important so that they can comment and provide advice on the best approach to deal with floods as per their traditions and cultural dealings.

4.2 Local laws in promoting community flood resilience

Increasing floods and flood-affected communities, despite the implementation of flood management practices, clearly indicates a gap between practice and policy. Using the information from the domain of indigenous knowledge and local coping capacities, this gap can be bridged, offering not only better flood management (reducing, among others, the costs), but also strengthened participation of the communities. For example, the development in the floodplain impacting the reoccurring flood's flow. Northland community dealt with the problem commonly by building the stopbank and floodwall to protect the property. However, if this was done in the upstream, it will creates bigger problem in the downstream areas and people in the low lying areas will be get double treats, one is the flood with the possibility of land slips from the highlands and two is from the downstream inundation as there are no outlet for water in the low lying areas especially for areas that surrounded by hills made the town inundated with water blocking the access and damaging the infrastructure, house, and nature.

To control this issue, all regional councils in New Zealand have some form of asset management system in line with the requirements of the Local Government Act 2002. Having a local law for flood protection and drainage is important in manage, regulate, and protect these assets, or those under our control, from inappropriate modification, damage, or destruction. It is vital for local authorities to keep up maintenance across our flooding and erosion control and drainage schemes to prevent damage or danger to nearby communities and keep people and properties safe (Fournier et al., 2016; Hegger et al., 2016). However, performance across local government is likely to be variable, reflecting the resources available to councils. Although there are no uniform standards for construction, and maintenance of assets, some infrastructure protected by local law an activity that required approval before the works stared listed in table 1.

Table 1. Infrastructure and activities protected by local law (Source: Authors)

Infrastructures protected by local law	Activities that require approval from authorities
Drains and small watercourses	Widening deepening and infilling any drain or small watercourse
Floodway	Altering, damaging or otherwise interfering with any drain or small watercourse, defences against water, flood protection vegetation, hydrological equipment and survey benchmarks
Defences against water including stopbanks, rock protection and groynes	Placing any material or structure in, on or near a drain or small water course or defence against water

Floodgates and culverts	Connecting any pipe, channel or other flow conduit to a drain or small watercourse
Flood protection vegetation	Allowing stock to damage drains or small watercourses, defences against water and flood protection vegetation
Hydrological devices and equipment	Growing, damaging or removing flood protection vegetation
Survey benchmarks	

Local governments operate under a variety of principles outlined in legislation described in 4.1 that have developed through established practice and case law. Planning and decision making at the local level should incorporate a precautionary approach as one principle for managing future flood risk. A regional council should consider existing knowledge as well as uncertainties when assessing risk. For example, depending on the level of risk, there will be different bylaws designed to meet the needs of communities in urban and rural areas (see figure 2).

Table 2. Flood related local law in urban and rural (Source: Authors)

Local law/ Regional bylaw required	**Urban**	**Rural**
Riparian plantings		✓
Horticultural development		✓
Dairy effluent system upgrades		✓
Digging a new drain or upgrading a culvert		✓
Water intake structures		✓
Subdividing a property	✓	✓
Geotechnical investigations	✓	✓
Planting/removing trees or shrubs	✓	✓
Landscaping involving earthworks		✓
Building/removing fences, garden sheds	✓	✓
Building/extending a house, shed or adding a deck	✓	✓
Constructing/removing a retaining wall	✓	
Constructing/removing an in-ground swimming pool	✓	

However, the process, administration, and timeframe are not suitable for responding in emergency. The community will take any measures to protect the property regardless the policy. Therefore, Northland Regional Council undertook a comprehensive engagement and consultation process with the affected communities for the review of any flood related policy including for new flood works or maintenance. In developing local laws, Northland Regional Council held information sessions, catchment-based flood meeting, publication, *Hui* (meeting) with *Iwi* and *Hapū*; and a formal consultation process under the Local Government Act 2002.

Reaching agreement on the minimum level of service for between the community and local government want from infrastructure is important. Many local authorities define minimum level of service for new development, and some define it as interventional for existing development. The flood risk assessment process in the Northland allows the authorities to decide whether a minimum level of service can still be maintained under future flooding scenarios. Alternatively, it allows them to decide whether it will be acceptable to reduce such level of service. If a reduction in service is contemplated, inter-generational equity should be considered to ensure that future generations are not burdened by excessive flooding risks.

5 Conclusion and Further Research

The formal legislation system of countries plays an important role in setting out rules and frameworks for flood risk governance. New Zealand flood related legislation framework are a strength and weakness to the FRM. As the responsibility for flood mitigation are devolved to local council, Northland Regional Council (NRC) and the district councils are to enable local approach and allowing the FRM to be integrated with NRC's other responsibilities including land use planning and asset management. However, the level of support provided to the district councils and communities varies across the region based on the territorial jurisdiction such as more funding needed for flood protection infrastructure works. In conclusion:

1. New Zealand the direction of flood risk management is more into the responsibility of local council so that the regional and territorial authorities can fit the best practice fit the community and local environment characteristic.
2. The solutions for flood resilience and sustainable development come from more localised types of approaches. Integrating local and indigenous knowledge with science and technology are recommended to create a comprehensive local law.
3. Inclusion of indigenous representation in the flood meetings is important so that they can comment and provide advice on the best approach to deal with floods as per their traditions and cultural dealings.
4. Changes in policy is part of the Northland region's flood recovery phase. Aftermath a disaster is the best situation to evaluate if certain policy is working or needed to improve. The policy needed to accommodate the need of today and the future as whatever decision done today will have the impact to the future.

6 Acknowledgement

This research was funded by Massey University Doctoral Scholarship. This research is part of the wider project for PhD program at the School of Built Environment, Massey University, NZ.

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Comparative Response Spectrum Analysis on 15 Storey Reinforced Concrete Buildings Having Shear Walls With and Without Openings as Per EN1998-1 Seismic Code

Mistreselasie S. Abate[1*], Ana Catarina Jorge Evangelista[1] Vivian W.Y. Tam[2]

[1]Engineering Institute of Technology, 1031 Wellington St, West Perth, WA 6005, AUSTRALIA
[2]School of Engineering Design & Built Environment, Western Sydney University, Locked Bag 1797 Penrith NSW 2751, AUSTRALIA

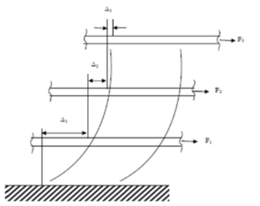
12536@student.eit.edu.au; ana.evangelista@eit.edu.au; v.tam@westernsydney.edu.au
* Corresponding author

Abstract:
In Ethiopia's major cities, medium-rise Reinforced Concrete (RC) framed apartment complexes with stories ranging from 4 to 15 are becoming more popular. Shear walls are supplied for lateral load resistance in medium-rise RC framed structures. Because apertures are often supplied in shear walls, it is vital to investigate their impact on storey drift, storey stiffness, shear and moments, and stress inside the shear walls. For the examination of the effect of openings in a building's shear wall, a 3-D analysis is performed. The consequences of the size and position of these apertures are examined in this research. On the basis of this investigation, detailed data have been gathered, and helpful conclusions have been reached that will be of service to practicing engineers. The seismic parameter for RS analysis was used Building Code of Ethiopia ES8-15 corresponds to Eurocode 8-2004 standards (based on EN1998-1) seismic code recommendations with target response spectrum parameter Ground Acceleration, ag/g=0.1, Spectrum Type=I, Ground Type=B, Soil Factor, S= 1.35, Spectrum Period, Tb, =0.05 sec, Spectrum, Tc= 0.25 sec, Spectrum Period, Td=1.2 sec, Lower Bound Factor, Beta=0.2, Behaviour Factor=1, and Damping ratio =5% was used. The results are compared based on different parameters such as Displacement, Storey Drift, Base Shear, Storey Shear, and Storey Moment for both with and without shear wall opening case This study will give tremendous insight on the effect of shear wall openings on the performance of the structure. In this study the analysis was performed on linear model which might not capture the full local response of the structure; hence it is highly advisable for future researchers to perform nonlinear analysis based on performance-based design. From this paper we concluded that the performance of the structure greatly improved by introducing shear wall than that of framed structures. Shear wall openings provided in a structure tremendously impact the performance of the building. For seismic hazard areas, it is highly recommended to use shear wall structure due to its high resistivity to the earthquake forces.

Keywords:
Response Spectrum, Storey Displacement, Storey Drift, Storey Moment, and Storey Shear

1 Introduction

A shear wall is a form of the structural system used in structural engineering to counteract the effects of lateral loads occurring on a tall building caused by wind or earthquakes. The primary purpose of a shear wall is to provide stiffness for lateral load resistance. If lateral loadings for inter-Storey deflections have to be managed, shear walls or their equivalents are utilized in some high-rise constructions. The shear wall is equipped with apertures to meet the functional need. In certain cases, wall apertures for windows, doors, and other sorts of openings in the shear wall are unavoidable. The size and position of openings may vary based on architectural and functional needs, and this can have a significant influence on a structure's seismic performance. Shear walls are vertically reinforced concrete beams that are quite deep and thin. They are often employed in constructions to withstand gravity loads and Storey shears. Shear walls are vertical components of the lateral force restraining system that convey lateral forces from the diaphragm above to the diaphragm below or the foundation. Shear walls may be bearing walls in a gravity load system or components in a dual system built to withstand solely lateral stresses(Borra, Nanduri and Raju, 2015). Wall deflections: The force needed to cause a unit deflection is often used to describe the stiffness of a wall. The sum of the shear (Figure 1) and flexural deflections determines the deflection of a concrete shear wall (Figure. 2). The calculations of deflection are fairly straightforward in the case of a solid wall with no holes. When the shear contains openings, such as doors and windows, the deflection (Figure 3) and rigidity estimates become significantly more complicated. It takes a long time to do a precise study that considers the angular rotation of parts, rib shortening, and other factors. As a result, various estimated short-cut approaches have been created. These may not always provide consistent or acceptable outcomes. It is necessary to take a cautious approach and utilize good judgment.



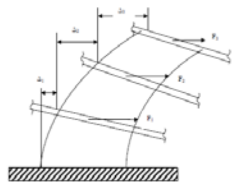


Figure 1. Shear Deformation(Borra, Nanduri and Raju, 2015) **Figure 1.**Flexural Deformation (Borra, Nanduri and Raju, 2015)

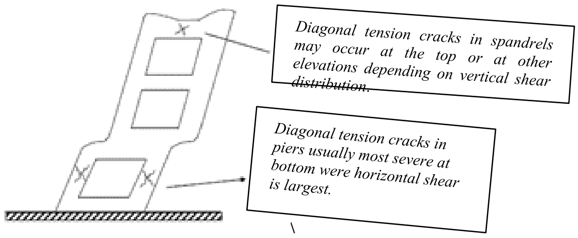


Figure 2. Deformation shear wall with opening(Borra, Nanduri and Raju, 2015)

Shear walls in the key site of multi-Storey reinforced concrete (RC) structures are one of the most prevalent procedures for increasing their lateral stiffness against earthquakes. Rectangular, T-Shape, L-Shape, and C-Shape are some of the most frequent forms used for shear walls (Khan, Ahmad,Tahir, 2016).

Hence in this paper, it is presented the design of G+15 reinforced concrete structure with and without shear wall opening at different locations. The RS analysis was used with the Building Code of Ethiopia ES8-15 corresponds to Eurocode 8-2004 standards (based on EN1998-1) seismic code recommendations and the expected out come would be building with shear wall without opening perform well in the process of resisting earth quake forces.

2 Literature Review

A 10-Storey RC shear wall construction with and without opening under seismic loading time history and pushover was investigated (Satpute and Kulkarni, 2013). The study showed that a structure with varying degrees of openness found a significant displacement increase with an opening size(Satpute and Kulkarni, 2013). Using the capacity spectrum technique, the structure's plastic hinge remained stable when the demand curve crossed the capacity curve at immediate occupancy(Ram, Az and Mohit, 2021). Different level buildings, shear walls with and without openings, and box and L-shaped shear walls were studied(Ram, Az and Mohit, 2021). Results show that box-type shear wall models have lower design base shear. Displacement and design base shear increase with apertures and floor height (Ram, Az and Mohit, 2021).

In addition to that another study investigated high-rise structures with varied designs and shear wall positions and discovered that the building's centre of mass and centre of rigidity (CM and CR) are closer to shear walls than without shear wall, Shear wall shape and placement affect time duration(A Murali Krishna, 2014). In another study multistorey shear wall installation shear walls reduce transverse and longitudinal top deflection(Harne, 2014). In addition to that shear apertures affect a building's seismic reaction. STAAD pro simulated aperture sizes and shear wall locations were investigated (RezaChowdhury *et al.*, 2012). A static equivalent analysis is used. The highest displacement of buildings with two different-sized apertures was 14%. Apertures smaller than 20% aren't as relevant for shear wall stiffness as opening arrangement (RezaChowdhury *et al.*, 2012). Window layout affects a building's stiffness. Kankuntla Seven in seismic zone V, a 15-Storey shear wall and aperture construction were studied. Finite element modelling is used to examine how a structure responds to lateral member loads (RezaChowdhury *et al.*, 2012). The SAP structural analysis findings are contrasted with the seismic coefficient technique and the response spectrum methodology. Shear walls diminish column moment and axial forces (RezaChowdhury *et al.*, 2012). The seismic coefficient forecasts stronger pressures than the response spectrum (RezaChowdhury *et al.*, 2012). Regular structures with staggered openings had better displacement, Storey drift, and Storey shear results than irregular structures with staggered openings in both the X and Y directions (H shaped and T shaped) (Gupta and Bano, 2019). L-shaped irregular structures with vertical openings had code compliant Y displacement and base shear (Gupta and Bano, 2019). As per the result several shear wall shapes using Response Spectrum Analysis and found that the I-shaped shear wall performs best. Shear wall model IV outperforms all others(Gupta and Bano, 2019). The size and form of shear wall gaps affect their strength and stiffness. The column moment and axial forces rise as the hole size decreases along the building height (Gupta and Bano, 2019). The authors studied the impact of vertical or staggered apertures of various sizes in regular-shaped structures. Different shear walls were built in unevenly shaped buildings(Gupta and Bano, 2019).

Additionally, another study presented the seismic study and evaluated the shear wall impact on a multi-Storey RC frame. Seismic Analysis shows that the RC-framed structure with a Shear wall has significant earthquake resistance(Babu, 2022).

Khan, Ahmad, Tahir (2016) investigated the effects of shear walls to provide lateral stiffness to multi-Storey buildings and withstand seismic pressures. This study compared rectangular, C-shaped, L-shaped, and T-shaped shear walls. A 20-Storey RC building with a regular plan is utilized for studies(Khan1, Ahmad, Tahir, 2016). The structure is represented using columns and the reference model lacks a shear wall. In each independent model, all of the compared shear wall shapes were introduced and evaluated. Analytical results include Storey drifts, displacements, and shears. Rectangular and L-shaped walls endure earthquakes better than H and T-shaped walls.

Shear barriers withstand horizontal pressures while preserving gravity forces application (Sanjivan Mahadik and Bhagat, 2022). High-rise buildings use shear barriers to withstand seismic stresses. This paper provides a Response spectrum-based strategy for monitoring high-altitude seismic activity. The G+25 project uses ETABS to examine shear wall impacts on the high-rise building. Comparing shear-walled and non-shear-walled constructions. Results revealed the study shows that the shear wall construction has less drift. The difference in deflection between shear and non-shear walls is measured. Shear wall construction is stiffer than non-shear wall construction. The structure was evaluated using IS:1893-2002(Sanjivan Mahadik and Bhagat, 2022).

Altouhami *et al.*, (2020) evaluated a reinforced concrete (RC) shear wall effect that withstands horizontal winds and earthquakes effect. Long (slender, l/b > 2) and short (squat, l/b 2) shear walls are classified by their aspect ratio. Even if buildings are constructed with shear walls and designed to code, they may still be demolished. To overcome the problem of squat shear wall failure, concealed diagonal reinforced concrete stiffeners, and diagonal steel tube stiffeners were tested to enhance shear wall performance. This research compared squat RC solid shear walls with conventional reinforcement, inbuilt RC stiffeners, and steel tube stiffeners. Shear walls using RC stiffeners and steel tube stiffeners have higher load-carrying capacities than conventionally reinforced shear walls. Shear walls with RC and steel tube stiffeners have a 34.34 percent and 9.04 percent greater deformation capacity than conventionally reinforced shear walls. Similar to RC stiffeners, steel tube stiffeners increased strain by 209% compared to conventionally reinforced shear walls (Altouhami *et al.*, 2020).

Shear barriers protect tall structures against wind and seismic forces(Yadav and Rai, 2020). Shear wall installation must be precise or it will fail. Distance between a shear wall and mass canter affects shear contribution when mass canter and hardness canter are aligned(Yadav and Rai, 2020). Building codes may indicate a part's true performance and cannot forecast the overall structure's performance under large forces(Yadav and Rai, 2020). In this work, the arrangement of shear walls was radically changed to produce a multi-storey building structure (Yadav and Rai, 2020). The effect of installing a shear wall at different locations and configurations in constructions with and without a shear wall using the ETABS software was investigated(Yadav and Rai, 2020). In square and rectangular structures, perimeter shear walls have 5.85% and 1.54% larger displacement than canter shear walls(Yadav and Rai, 2020). External shear walls feature the biggest square and rectangular base shear. Rectangular structures with core walls had 3.23 percent more stress than square ones(Yadav and Rai, 2020).

The lateral stress resistance of a tall RC frame structure without a shear wall and the ideal shear wall design were investigated and buildings must withstand lateral loads(Wei, Chen and Xie, 2022). The G+31 high RC frame architecture's design and attributes are studied. This RC frame construction is subject to lateral stress at 50 m/sec. This frame structure is evaluated using IS 875: 2015 Part III. Unique shear walls protect the building from wind loads. Natural time, narrative drift, and tale displacement results were collected. After data analysis, the optimal shear wall location is chosen. A normal frame exposed to wind has the longest duration because it has no shear walls(Wei, Chen and Xie, 2022). A corner shear wall adds rigidity quickly. The normal frame drift is 12.761mm, followed by the outer canter shear wall (5.88mm) and core shear wall (5.88mm) & (5.744mm). Corner shear walls have less drift (4.609mm). Despite its increased mass, a corner shear wall lowers the model's natural period (sec). Due to stiffening, corner shear walls have the least displacement (108.508mm) and conventional frames have the most (303.339mm).

3 Research Gap

As per the literature review; there has been a significant amount of research done on the effect of the shear wall on the overall seismic performance of structures in different parts of the world. However, to our knowledge, there is no comprehensive research work done on the comparison of shear walls with or without opening and RS analysis for 15 stories reinforced concrete in the selected design location of Addis Ababa, with Type I response spectrum as recommended by the building code of Ethiopia ES8-15 adheres to Eurocode 8-2004 regulations ES EN 1989-1:2015 and based on different parameters such as Displacement, Storey Drift, Base Shear, Storey Shear and Storey Moment.

4 Research Methodology

4.1 Project Description

For this study, a regular reinforced concrete building is considered as shown in Figure 1. The floor area of the structure is 900 sqm (30m x 30m) with 5 bays along each side (each span 6m). The structure is modelled with two 15-Storey structures with each Storey height of 3 m with and without a shear wall as shown in Figure 4.

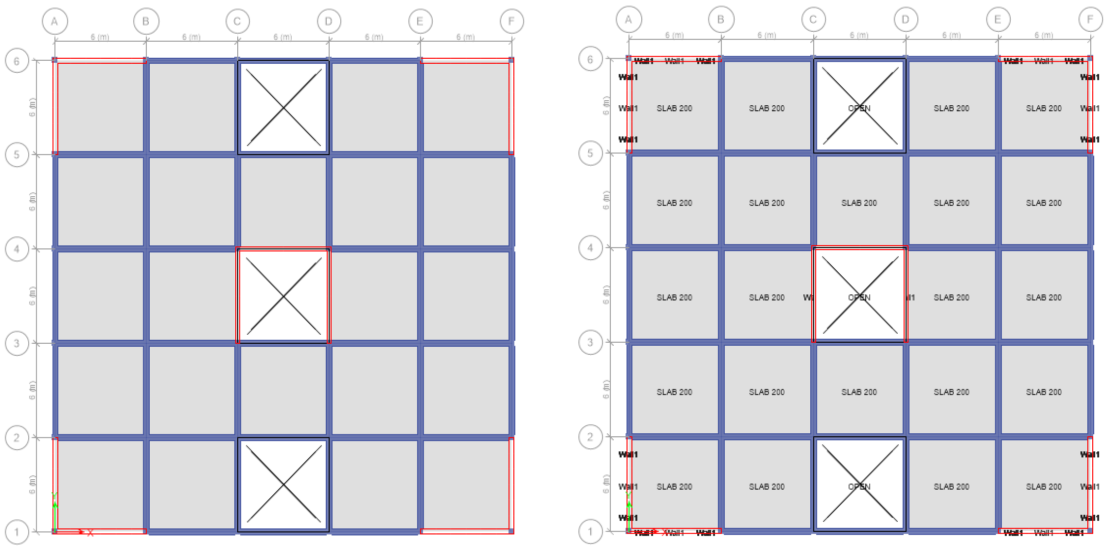


Figure 3. Plan View of Sample RC Structure

Table 1. Sample15 Storey RC buildings Detail

Height 15 Storey RC	45 m
Structure's type	Multi-Storey Moment resisting Frame (15 Storey)
Floor to Floor Height	3.2 m
Soil type	B
Damping	5%
Support	Fixed support
Importance Factor	1
R Factor	1
Beam Section	0.50x0.35 m
Column Section	0.4x0.40 m
Wall Section	0.300 m
Slab section	0.20 m

Seismic Zone	III (Addis Ababa)
Concrete quality	C-30
Steel	G-60

Table 2. Loading Detail

Dead load	2.1 KN/m2
Live load	3.1 KN/m2
Wall load on Beam	14 KN/m2
RS procedure	ES8-15 corresponds to Eurocode 8-2004 standards (based on EN1998-1)

4.2 Modelling

Both the structures with the same heights are modelled and analysed by ETABS 2019 using Response Spectrum Procedure (RS) as dynamic analysis according to ES8-15 corresponds to Eurocode 8-2004 standards (based on EN1998-1). The models are created in ETABS; shear walls are supplied at corners, and in instance 1 openings are provided in the X-Y Direction in the canter, however, in case 2 openings are not provided in both the X and Y-Directions, as seen in Figure 5.

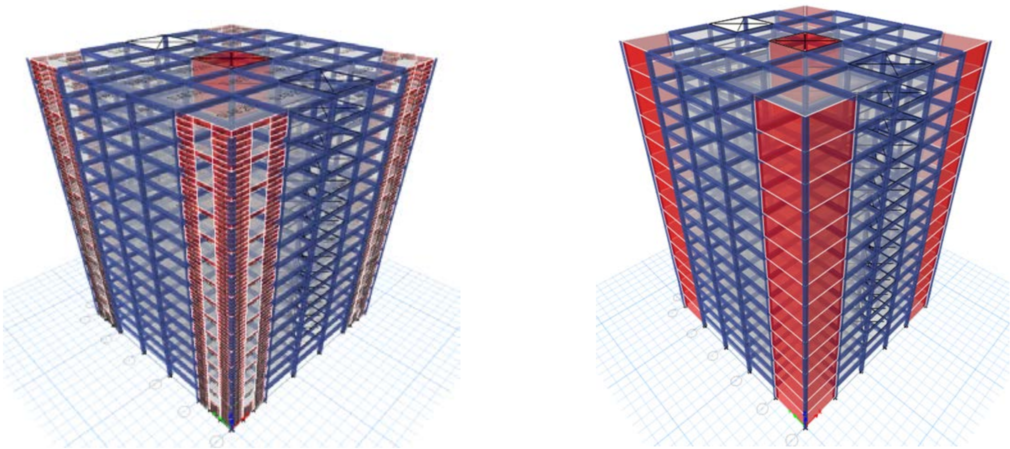


Figure 4. 15 Storey -3D model of case-1 & case 2.

5 Findings and Discussion

After performing dynamic analysis for both structures with case 1 & 2 shear wall opening type, the obtained results were compared based on five factors i.e., Displacement, Storey Drift, Base Shear, Storey Shear and Storey Moment.

Table 3. Comparison of with and without shear wall opening dynamic analysis results centre of mass (CM)Displacement for Diaphragm D1 for 15 Storey structures.

			G+15 RC with Opening		**G+15 RC Without Opening**		X-Y Axis Output	
			CM Displacement for Diaphragm D1		**CM Displacement for Diaphragm D1**		CM Displacement for Diaphragm D1	
Storey	**Elevation**	**Location**	**X-Dir**	**Y-Dir**	**X-Dir**	**Y-Dir**	**With vs Without Shear wall X-direction**	**With vs Without Shear wall Y-direction**
	m		**mm**	**mm**	**mm**	**mm**	%	%
Storey15	45	Top	45.115	47.205	42.18	43.798	106.9582741	107.778894
Storey14	42	Top	41.768	43.579	38.734	40.163	107.8329117	108.5053407
Storey13	39	Top	38.332	39.882	35.263	36.503	108.7031733	109.2567734
Storey12	36	Top	34.83	36.141	31.785	32.844	109.5799906	110.0383632
Storey11	33	Top	31.292	32.38	28.324	29.21	110.4787459	110.8524478
Storey10	30	Top	27.752	28.625	24.907	25.625	111.4224917	111.7073171
Storey9	27	Top	24.237	24.901	21.557	22.114	112.4321566	112.602876
Storey8	24	Top	20.771	21.231	18.296	18.698	113.527547	113.5469034
Storey7	21	Top	17.378	17.641	15.145	15.403	114.74414	114.5296371
Storey6	18	Top	14.079	14.162	12.128	12.258	116.0867414	115.5327133
Storey5	15	Top	10.905	10.837	9.28	9.302	117.5107759	116.5018276
Storey4	12	Top	7.899	7.727	6.648	6.59	118.8176895	117.2534143
Storey3	9	Top	5.123	4.916	4.297	4.195	119.2227135	117.1871275
Storey2	6	Top	2.687	2.529	2.318	2.212	115.9188956	114.3309222
Storey1	3	Top	0.823	0.772	0.826	0.76	99.63680387	101.5789474
Base	0	Top	0	0	0	0	0	0

Table 3, Figure 6 and 13 show the CM Displacement for Diaphragm D1 for 15-Storey structure with and without shear wall opening RS dynamic analysis. From the results, it can be observed that the CM Displacement for Diaphragm D1 obtained by the shear wall with the opening is higher than that obtained by the shear wall without opening for all stories. Shear wall with opening analysis gives 6.95 % in X and 7.77 % in Y direction higher result. It can be also noticed that the difference in CM Displacement for Diaphragm D1 calculated with and without shear wall increases with the increase of height of the structure in both directions. Figures 7 and 14 show the Drifts for Diaphragm D1 for 15-Storey structure with and without shear wall opening RS dynamic analysis. From the results, it can be observed that the Drifts for Diaphragm D1 obtained by a shear wall with an opening is higher than that obtained by a shear wall without an opening for all stories. Shear wall with opening analysis gives 33.39 % in X and 22.44 % in Y direction higher result. It can be also noticed that the difference in Drifts for Diaphragm D1 calculated with and without shear wall decreases with the increase of height of the structure in both directions.

Figure 8 and 15 show the Max Storey Displacement for 15-Storey structure with and without shear wall opening RS dynamic analysis. From the results, it can be observed that the Max Storey Displacement obtained by shear wall with opening is higher than that obtained by shear wall without opening for all stories. Shear wall with opening analysis gives 27.44 % in X and 18.99 % in Y direction higher result. It can be also noticed that the difference in Max Storey Displacement calculated by with and without shear wall decreases with the increase of height of the structure in both directions. Figures 9 and 16 show the Max. Storey Drifts for 15-Storey structure with and without shear wall opening RS dynamic analysis. From the results, it can be observed that the Max. Storey Drifts obtained by shear wall with opening is higher than that obtained by shear wall without opening for all stories. Shear wall with opening analysis gives 33.39 % in X and 22.85 % in Y direction higher result. It can be also noticed that the difference in Max. Storey Drifts calculated by with and without shear wall decrease with the increase of height of the structure in both directions.

Figures 11 and 18 show the Max. Storey Shear for 15-Storey structure with and without shear wall opening RS dynamic analysis. From the results, it can be observed that the Max. Storey Shear obtained by shear wall with opening is lower than that obtained by shear wall without opening for all stories. Shear wall with opening analysis gives 20 % in X and 16 % in Y direction lower result. It can be also noticed that the difference in Max. Storey Shear calculated by with and without shear wall increases with the increase of height of the structure in both directions. Figure 10 and 17 show the Overturning Moment for 15-Storey structure with and without shear wall opening RS dynamic analysis. From the results, it can be observed that the Overturning Moment obtained by shear wall with an opening is lower than that obtained by a shear wall without opening for all stories. Shear wall with opening analysis gives 14 % in X and 20 % in Y direction lower result. It can be also noticed that the difference in Overturning Moment calculated by with and without shear wall decrease with the increase of height of the structure in both directions. Figures 12 and 19 show the Storey Stiffness for 15-Storey structure with and without shear wall opening RS dynamic analysis. From the results, it can be observed that the Storey Stiffness obtained by shear wall with opening is lower than that obtained by shear wall without opening for all stories. Shear wall with opening analysis gives 28 % in X and 23 % in Y direction lower result. It can be also noticed that the difference in Storey Stiffness calculated by with and without shear wall varies with the increase of height of the structure in both directions.

ETABS Output Result for Shear Wall Without Opening:

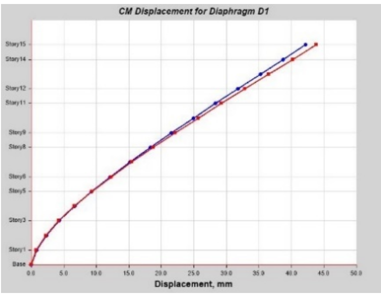


Figure 6.CM Disp. for Diaphragm D1

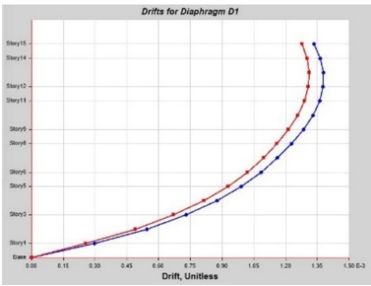


Figure 7. Drift for Diaphragm D1

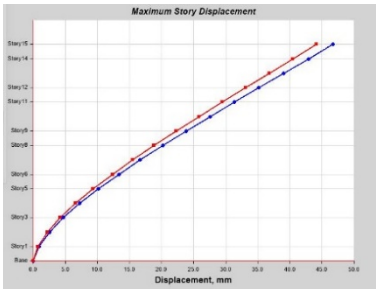


Figure 8.Max. Storey Displacement

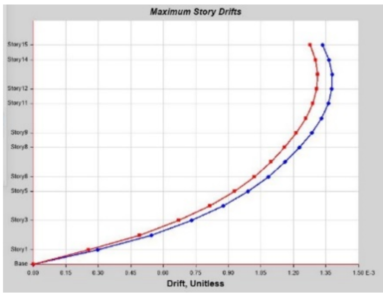


Figure 9. Max. Storey Drifts

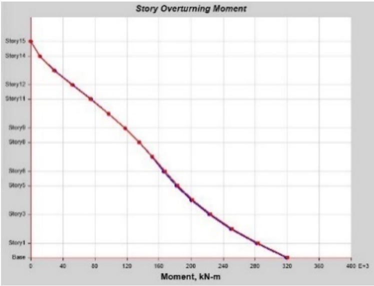


Figure 10. Storey Overturning Moment

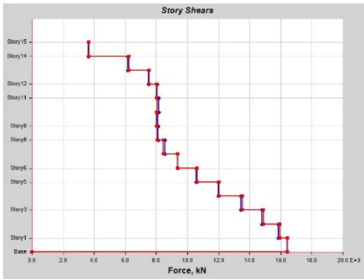


Figure 11.Storey Shears

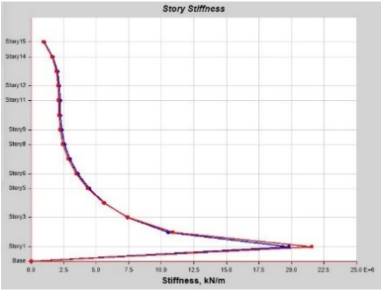


Figure 12. Storey Stiffness

ETABS Output Result for Shear wall With Opening

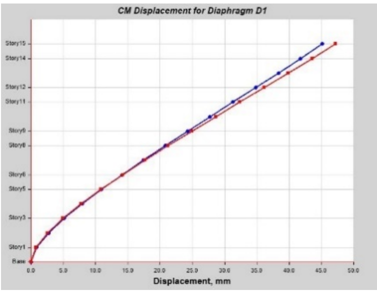


Figure 13. CM Disp. for Diaphragm D1

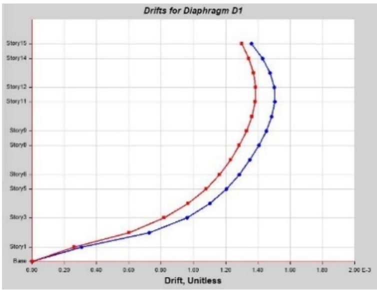


Figure 14. Drift for Diaphragm D1

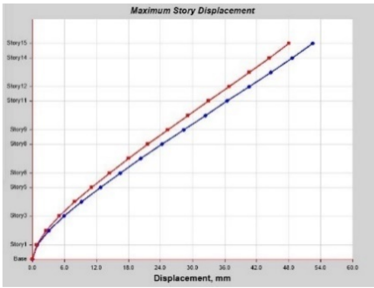


Figure 15. Max. Storey Displacement

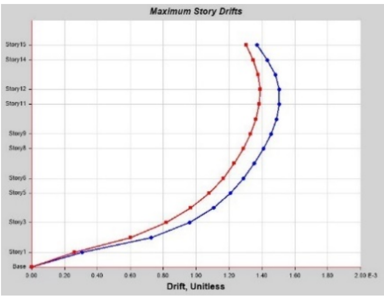


Figure 16. Max. Storey Drift

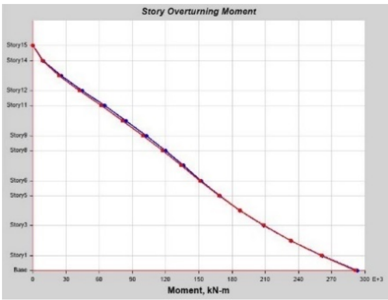


Figure 17. Storey Overturning Moment

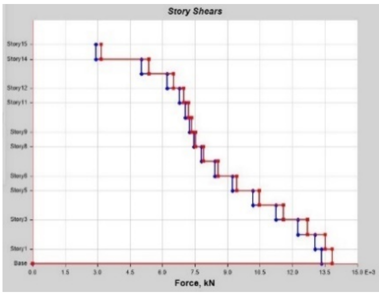


Figure 18. Storey Shears

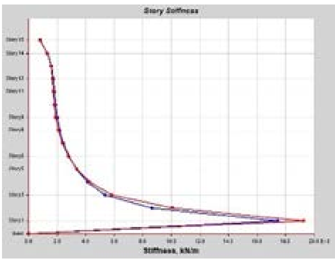


Figure 19. Storey Stiffness

6 Conclusion and Further Research

From the results and analysis of this paper these points were observed: The centre of mass (CM) displacement diaphragm D1 deflection for RC G+15 building with shear wall opening was found higher than that of G+15 with shear without opening results. It can be also noticed that the difference in displacement calculated by with and without shear wall opening decreases with the increase of height of the building in both X-Y directions. The Drifts for Diaphragm D1 deflection for RC G+15 building without shear wall was found higher than that of G+15 with shear wall opening results. It can be also noticed that the difference in Drifts for Diaphragm D1 calculated by with and without shear wall opening decreases with the increase of height of the building in both X-Y directions. The Max Storey Displacement deflection for RC G+15 building with shear wall opening was found higher than that of G+15 without shear wall opening results. It can be also noticed that the difference in displacement calculated by with and without shear wall decreases with the increase of height of the building in both X-Y directions. The Max. Storey Drifts deflection for RC G+15 building with shear wall opening was found higher than that of G+15 without shear wall opening results. It can be also noticed that the difference in Max. Storey Drifts calculated by with and without shear wall opening decrease with the increase of height of the structure in both directions. Structures with shear walls without openings are more resistive to the earthquake. The size of opening plays an important role than the height of structure. The Storey displacement is less when shear walls are introduced to the structure. When openings were introduced on higher floors than at the lower floor deflection dramatically decreased. The Max. Storey Shear for RC G+15 building with shear wall opening was found lower than that of G+15 without shear wall opening results. It can be also noticed that the difference in Max. Storey Shear calculated by with and without shear wall decreases with the increase of height of the building in both X-Y directions. The Overturning Moment for RC G+15 building with shear wall opening was found lower than that of G+15 without shear wall opening results. It can be also noticed that the difference in Overturning Moment calculated by with and without shear wall decreases with the increase of height of the building in both X-Y directions. The Storey Stiffness for RC G+15 building with shear wall opening was found lower than that of G+15 without shear wall opening results. It can be also noticed that the difference in Storey Stiffness calculated by with and without shear wall decreases with the increase of height of the building in both X-Y directions. The Storey stiffness is more for structure without shear wall opening. The Storey drift is more for structures shear wall with opening than with shear wall without opening. The limitation of this study is that the analysis was performed on linear analysis which might not capture the full local response of the structure, hence it is highly advisable for future researchers to perform nonlinear analysis based on performance-based design. This study will give tremendous insight on the effect of shear wall openings on the performance of the structure. From this paper we concluded that the performance of the structure greatly improved by introducing shear wall than that of framed structures. Shear wall without opening provided at the corner of a structure gives better results than shear wall with opening provided at the corner of a structure as a shaft for a lift. For seismic hazard areas, it is highly recommended to use shear wall structure due to its high resistivity to the earthquake forces.

7 Acknowledgment

We acknowledge there is no conflict of interest.

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Resilience of Post-Resource Landscapes

Sarvin Elahi[1]*, Penny Allan[1] and James Melsom[1]

[1]Faculty of Design, Architecture and Building, University of Technology Sydney
15 Broadway, Ultimo NSW 2007, AUSTRALIA

sarvin.elahi@student.uts.edu.au; penny.allan@uts.edu.au; james.melsom@uts.edu.au
* Corresponding author

Abstract:
This research investigates the resilience of post-resource landscapes with a focus on Broken Hill in NSW. Extraction practices have made these landscapes and the communities who live there vulnerable, and more so in the face of major disturbances such as land degradation, drought and water scarcity, loss of native vegetation cover, contamination of natural resources, climate change, political disturbance, and social disorganisation. Because individual responses to each social-ecological hazard are not adequate or within the scope of local infrastructure, broader resilience during everyday life becomes critical to effective adaptations in the face of evolving risks. Although rehabilitation of post-resource landscapes is typically considered independently of local communities, the research considers how a coupled system of social networks, inextricably interwoven with landscape renewal can strengthen the collective capacity of a city. This research undertakes a comparative analysis of two sites, Broken Hill in NSW, Australia, and Sarcheshmeh Copper city in Kerman Province, Iran, where mining activities have caused industry-related environmental pollution, a reduction in the capacity of the land, and an increase in the vulnerability of local communities. The research illustrates how the adaptation of existing infrastructures and the integration of regional interspecies logics that have proven their capacity to withstand and recover from hazards can offer a broader, regenerative ecological and social infrastructure, as well as a culture of knowledge and care for land. Developing collective capacities in this way can strengthen everyday activity, which makes both communities and landscapes more resilient while enhancing adaptation potentials to cope better with the sudden and unpredictable shocks.

Keywords:
Urban resilience, Social-ecological system, Everyday resilience, Post-mining landscapes

1 Introduction

Landscape is an integration of ecosystems and society (Xu et al, 2021). While natural resource extraction contributes to the economic development aims of many countries, resource landscapes, due to long-term extraction practices, are less resilient and more vulnerable. Although rehabilitation of post-resource landscapes is mostly considered with respect to ecological networks, the broader concept of resilience thinking can improve opportunities to reassess the current situation, promote social cohesion, recombine sources of experience to develop knowledge, and actively identify new kinds of adaptability at multiple scales (Walker, 2004; Folke *et al*., 2010).

This research intends to investigate and stimulate interdisciplinary discussion concerning the social-ecological resilience of post-resource landscapes. Three key questions are raised to provide a systematic framework for enquiry to challenge thinking about the dual regeneration of degraded post-resource landscapes: How do extraction practices make landscapes and local communities who live there vulnerable?; Is the ecological response to post-resource-induced challenges adequate for recovery? and c) How can local communities adapt to changes and contribute to the recovery of degraded post-mining landscapes?

This research paper compares two post-resource desert landscapes— the city of Broken Hill in Australia and Sarcheshmeh Copper city in Iran — through the lens of resilience to understand how mining practices can create surprisingly similar environmental and social challenges. Applying an analytical research method focused on a 1930s landscape regeneration project in Broken Hill, it then considers how the development of ecological networks and local social networks in everyday urban life might enhance recovery from long-term extraction-induced degradation. It illustrates the importance of strengthening the capacities of post-resource landscapes, ecologies, and local communities simultaneously, so that they may better cope with sudden and unpredictable shocks.

2 Literature Review

2.1 Post-resource landscapes

All human communities critically depend on the natural environment. In recent years, the resource landscape has long been the focus of attention of environmental activists and researchers. The post-resource landscape is a common phenomenon of developed and developing countries. Post-resource landscapes are territories whose structural and functional characteristics, while directly and indirectly reshaped by past industrial practices, have not retained their industrial function.

Resource dependency refers to communities whose social order, livelihood, and stability are defined by the heavy reliance on limited natural resources and localised economies (Machlis *et al*., 1990). Post-resource communities face complicated challenges due to social, demographic, ecological, and economic decline. Resource dependency deleteriously impacts the environment through ecological alterations and biodiversity damage and can cause social and economic changes in local communities (Cashen, 2007, Shahid and Nabeshima, 2005). Resource-dependent communities experience broad social cleavages and ecological, economic, demographic, and structural changes after periods of economic growth, leading to long-term decline (Bluestone *et al.*, 2017).

Although natural resource extraction and related businesses improve employment and income opportunities in local and remote regions for a limited period, rapid market integration and degradation as a consequence of industrial activities can reduce resilience (Freudenburg, 1992). The financial benefits of resource extraction can accelerate growth in a short period of time but in the long term can depress economic growth and development in local communities (Hajad, 2021; Taguchi and Lar, 2016). Resource-dependent communities need innovative approaches to assist in their multi-phase transitions from resource-dependent settlements to sustainable urban systems (Campbell and Maclaren, 2021).

2.2 Resilience

The landscape is a living system that interacts with ecological, social, cultural, and economic systems (Lu and Guozeng, 2022). Therefore, in order to promote landscape resilience, moving beyond a human scale and opening up multiscale approaches are essential (Kwak et al., 2021). The concept of landscape resilience focuses on a human-in-ecosystem perspective to understand the interactions between ecological and social systems and their dynamics (Kuldkepp, 2022; Berkes et al., 2003). Landscape resilience refers to the landscape’s capacity to adapt (Mallick, 2021). Resilient landscapes can help to mitigate environmental and social hazards in urban environments and promote inclusive and sustainable growth. There are many definitions of resilience. From an ecological perspective, Holling (1973) defined resilience as the ability of the ecology to absorb disturbance and maintain the same relationships between populations and variables to persist through time (Holling, 1973). Tilman and Downing (1994) defined resilience as an ecological system's resistance and recovery ability to reach a single equilibrium point after a disruption (Tilman and Downing, 1994). Holling later expanded his approach to focus on the definition of a system and its capacity to adapt, suggesting that resilience was the capacity of a system to control behavior and absorb disturbance in order to maintain the same organisation, function, identity, and feedback (Holling and Gunderson, 2002; Walker, 2004).

Resilience has more recently been associated with urban environments: with the recovery, adaptation, and transformation of landscapes (Amirzadeh, et al, 2022); with the capacity of an urban system to allocate resources efficiently and to deliver essential services in the face of market perturbations and environmental shocks (Brock *et al.*, 2002; Perrings, 2006); and with the ability of regions to allocate resources productively and rebound from economic shocks without losing functionality (Hill *et al.*, 2008) Resilience is also a useful way of framing adaptive responses to natural disasters. Gunderson (2010) defines resilience as the capacity of coupled systems of humans and nature to deal with uncertainties and risks (Gunderson, 2010). Allan and Bryant (2011) focus on the potential of enhanced adaptive response and recovery in the event of disasters to enhance the quality of everyday urban life (Allan and Bryant, 2011). For Cutter et al. (2008), community resilience is the ability of the community to recover from hazards and cope with shocks in order to create adaptive responses based on the existing built environment and the interplay between social and spatial behaviour and natural processes (Cutter et al, 2008). Resilient landscapes are characterised by their capacity to adapt to a broad range of complex problems, across different aspects and scales (Kwak, et al, 2021) in a holistic and integrated way (Woodruff et al, 2021; Ribeiro & Gonçalves, 2019).

2.3 Post-mining resilience

Mining, by changing the nature of the landscape, clearing vegetation cover, and polluting the air, soil, and water can cause environmental contamination and land degradation (Moore, 2018; Krishnamurthy *et al*., 2020). Landscapes that have experienced extraction face a severe threat of land degradation and environmental challenges due to the decline in the capacity of land, loss of its biological, chemical, and economic productivity, and environmental degradation and climate change (Xie *et al*., 2020; Yang *et al*., 2018). Mezzadra and Adger (2000) investigated the relationship between social resilience and the ecological resilience of resource-dependent communities and found that resource endowment creates constraints on the social development of post- resource communities (Mezzadra & Adger, 2000). In such a situation, local people face climate change impacts and severe livelihood problems and are forced to flee their homes and find themselves displaced. (Carr 2018; Yang *et al*. 2018).

This research defines post-mining landscapes as weakened sites where mining activities have caused severe problems for both landscape and local communities. It looks at landscape as a complex Social-Ecological System (SES) regulated by dynamic interactions and feedback between community and nature. A system possesses a relatively stable state distinguished by its identity, function, and structure. When external stresses and shocks are incrementally threatening the state of the system, and the system cannot cope with external shocks, it reaches a tipping point, and after that, abruptly shifts from a stable state to a state of change (Saito *et al*., 2020).

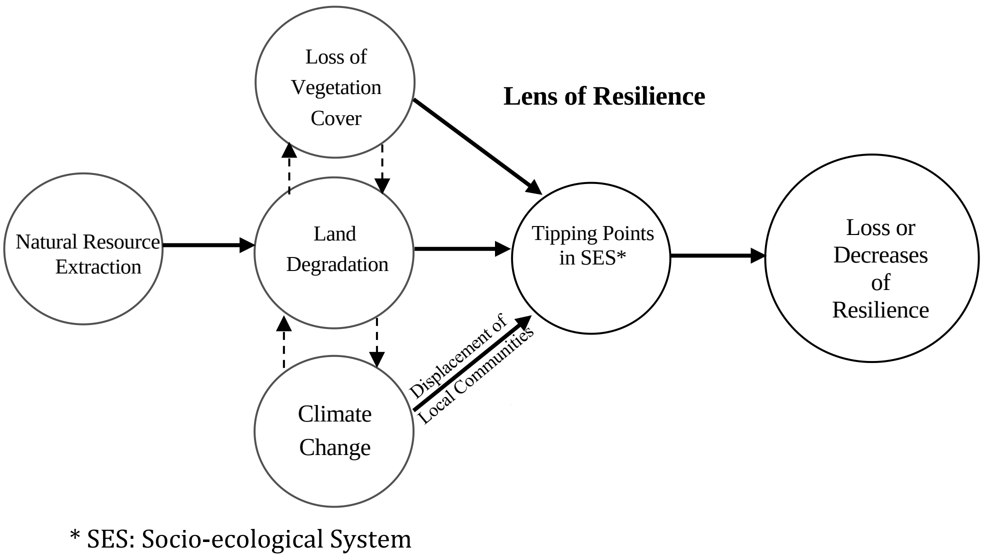

Figure 1. Interconnections between the main concepts of the research

While it is commonly assumed that increasing pervasive gradual pressure does not affect ecosystem functioning significantly, large and long-lasting pressures such as mining can force a socio-ecological system across a tipping point, which may eventually lead to its collapse (Cochard, 2017; Saito *et al*., 2020). Once a system crosses a tipping point, there are often severe impacts on ecological components, and loss of substantial and immediate ecological feedback can affect the social sustainability of the system. In most systems that have crossed a tipping point, the new state is characterised by uncertainty, with a high cost for a reversion back to its prior state (Yletyinen *et al*., 2019). Regarding the relationship between ecological and social networks, enhancing the social life of post-resource landscapes can affect a post-resource landscapes' capacities to recover.

3 Research Methodology

To develop a framework for resilience in post-resource landscapes, this research undertook a comparative analysis of two sites, Sarcheshmeh Copper city in Kerman Province, Iran and Broken Hill in NSW, Australia, where mining activities have caused industry-related environmental pollution, a reduction in the capacity of the land and an increase in the vulnerability of local communities. Documents, strategic and master plans of the cities of Broken Hill and Sarcheshmeh, historical documents, local newspapers, and related research projects were reviewed to identify the local communities' main ecological challenges and social problems. Focusing systematically on both post-mining case studies by using a social-ecological resilience lens and providing the event history analysis clarified how resilience can act as a useful frame to develop appropriate approaches to the rehabilitation of degraded post-resources landscapes.

4 Case Studies

4.1 First Case Study, Sarcheshmeh Copper city in Kerman Province, Iran

The Sarcheshmeh copper deposit is one of the world's largest Oligo-Miocene porphyry copper deposits. It is located in the central Iranian volcano-plutonic belt and 65 km southwest of Kerman Province, Iran (Atapour and Aftabi 2007). Exploration work and basic investigations of the mineralisation of ore deposits were carried out in 1967. Sarcheshmeh Copper city was planned and built according to the housing programs for personnel and engineers working in the Copper Complex in 1973, and it covers 534 acres (Ministry of Roads and Urban Development of Iran, 2013). During the mining boom, the mining industry impacted significantly on local communities, and more people looking for jobs were hired in the mining complex. At its peak in 1995, the number of people living in Sarcheshmeh increased by 9,070, the city council was established, and Sarcheshmeh was recorded as an independent city in Kerman Province.

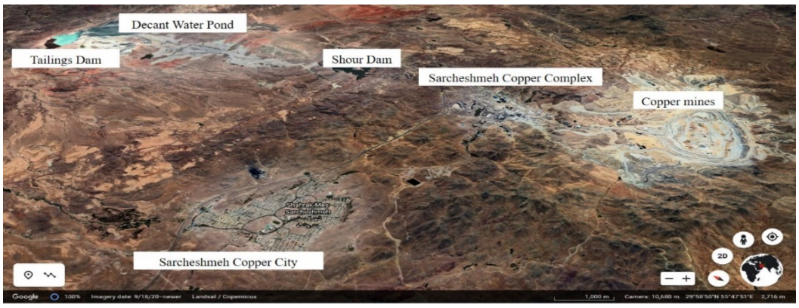

Figure 2. Locations of city of Sarcheshmeh copper, copper mine, and tailing dam, (Edit by Author, Source: https://earth.google.com/).

Figure 3. Loss of vegetation cover in Sarcheshmeh copper city between 2016 and 2021 (Source: https://earth.google.com/).

Due to intensive exploitation, technological advances in extraction techniques in other mining sites in the world, and competitiveness in global markets, the mining industry was caught in turmoil, and signs of a gradual decline began to emerge in 2005 (Ministry of Roads and Urban Development of Iran, 2013; Shamsaddin *et al*. 2020). One of the main challenges of Sarcheshmeh Copper city is drought and lack of access to water. A project for transferring water from the Persian Gulf to mine has been under implementation, with about 86% of the project developed since 2020 (Sazesazan, 2020). Comparing historical and recent aerial photographs indicates a loss of vegetation cover in the region between 2016 and 2021. Land degradation, climate change, and environmental problems caused by mining have had severe consequences on locals' livelihoods and social health. Internal migration data of Sarcheshmeh city indicates that because of ecological, social, health, and economic issues more than of 5 percent of residents are displaced annually (Ministry of Roads and Urban Development of Iran, 2013).

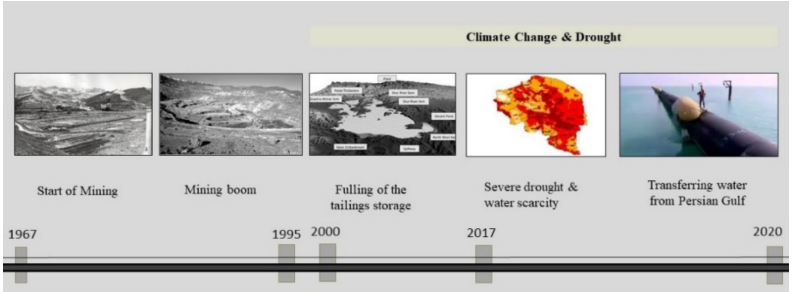

Figure 4. History timeline of Sarcheshmeh Copper City
(Source of images: https://scico.ir/ & farsnews.ir/)

4.2. Second Case Study, Broken Hill in NSW, Australia

Broken Hill, located in the far west of outback New South Wales, is approximately 935 km northwest of Sydney, and 511 km from Adelaide (Broken Hill City Council, 2020). The Broken Hill Ore Deposit is one of the world's largest deposits of silver, zinc, and lead (Schatz, 2017). Founded in 1883, in response to the inter-regional effect of the mining boom in the late 19th century in Australia (Solomon, 1959), it was originally built as a temporary settlement to house mine workers and service the mining company (Solomon, 1959; Broken Hill City Council, 2020). During its mining boom period in 1952, flows of workers to this city exceeded 6,500 people, and the population of Broken Hill increased to 30,000 (Solomon, 1959; Broken Hill City Council, 2020). By the 1920s, due to a decrease in the price of minerals, mining activities were suspended in Broken Hill for several months, and finally in 1939 BHP, the first and the biggest mining company in Broken Hill, after exhausting the largest part of mineral deposit in Broken Hill estimated to be worth 180 million British pounds, closed its operations (Solomon, 1959; Broken Hill City Council, 2020). Since the 1970s, the town has experienced a long-term sustained decline due to deregulation of international markets, trade liberalisation, and gradual deterioration of resources (Fernández-Raga *et al.* 2017; Schatz, 2017; Battellino, 2010).

Figure 5. City of Broken Hill,1883,
(Source: https://nla.gov.au/)

A review and analysis of historical documents, local newspapers, and research about Broken Hill indicate that land degradation, soil erosion, dust storms, reduction in biodiversity, loss of native vegetation, water scarcity, and floods have been historically severe in this region. Roots of the abovementioned issues can be traced back to heavy overgrazing, foraging of commercial stock and rabbits, and timber felling for fuel and building construction in the region between 1900 and 1927 (Ardill, 2017; Jones, 2011). Mining activities also have exacerbated the situation, which has had negative impacts on the surrounding communities and environment at both local and regional scales (Entwistle *et al.*, 2019; Schatz, 2017).

Widespread destruction of flora and fauna and exposed fragile soils to wind caused dust storms, threatened the town's existence, and obliged Albert Morris, a resident of Broken Hill, self-taught botanist, and mining company senior assayer, to find fresh perspectives and come up with an innovative solution (Ardill, 2017; Jones, 2011). Morris witnessed the extinction crisis and turning of the landscape into a desert and took the view that establishing regeneration reserves could overcome the growing dust storms, soil erosion, and environmental problem which were threatening Broken Hill. Morris pursued his research in the local flora to regenerate the degraded landscape of Broken Hill. He had the dream of creating a green belt around the city to minimise dust storms and sand-drift, protect native flora and fauna and improve the standard of living of local people (Ardill, 2017).

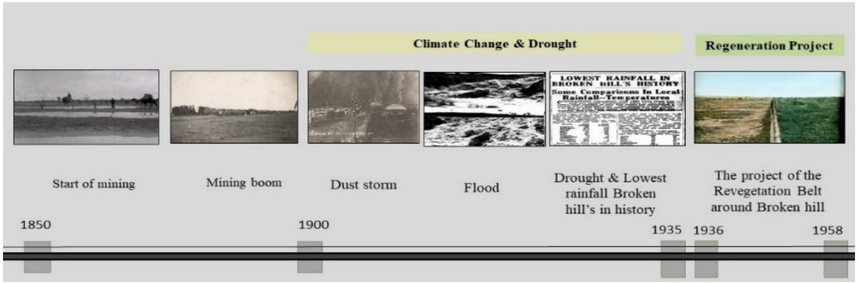

Figure 6. History timeline of Broken Hill,
(Source of images: https://nla.gov.au/& https://trove.nla.gov.au/)

By 1936, Morris, with the co-operation of Margaret Morris (his wife), the Barrier Field Naturalists Club, mining corporations, and the government, initiated a regeneration project to restore ecological function by surrounding the city with a green belt of native vegetation (Ardill, 2017; Jones, 2011). Morris travelled to different regions in pursuit of botanical specimens. His project involved two major phases, including regeneration of the vegetation in a relatively quick timeframe and fencing of regeneration areas to enable natural regeneration of existing species and the restoration of native vegetation. Despite the limitation of resource material, he developed an expert knowledge of the local vegetation and provided seedlings of (*Eucalyptus*) gum trees and (*Atriplex nummularia*) old man saltbush, the disappeared local species, and native grasses for this project. This project is one of the first documented attempts in Australia to restore degraded landscapes using naturally occurring resources (Ardill, 2017).

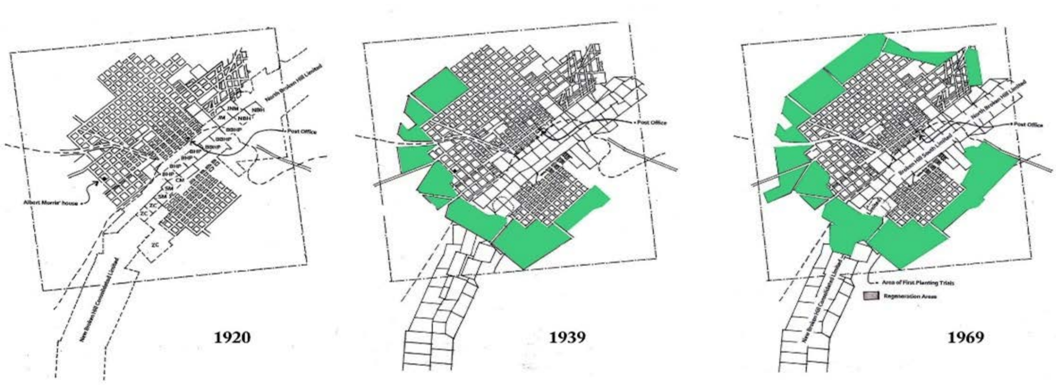

Figure 7. Project of Revegetation Belt around the Broken Hill, 1936 –1958,
(Source: Jones, 2011).

Studies show that this project faced local communities' resistance to change. Local residents were heavily reliant on the enclosed common land around the town to collect their required firewood and keep their animals after the great financial depression; therefore, the aims of the project were not well received by some local communities at first (Volkofsky, 2017). Additionally, due to the project's connection to the mining corporation, there was some resistance. Within two years however, due to the reduction of dust storms in the region, the benefits of the reserve were clarified to local communities, and the concept was accepted and promoted by local groups (Volkofsky, 2017) and the Barrier Naturalists Club was established to maintain the green belt and does so to this day.

The applied approach to ecological regeneration, with its ongoing integration of community engagement promoted the social-ecological resilience of Broken Hill and can be considered a milestone in the history of the region.

5 Findings and Discussion

Analysis of two post-mining landscapes revealed some important relationships between ecological recovery, social resilience, community engagement, and everyday resilience. The following key finding suggest ways to enhance the resilience of post-resource landscapes.

First, the decline in post-mining landscapes not only leads to economic problems; it can also cause the loss of local community identity (Kim et al., 2020). Vulnerable landscapes and environmentally displaced people are the major victims of resource extraction practices. Severe environmental and economic impacts experienced by mining in post resource landscape encourage communities to leave, weakening both their social cohesion and social resilience. So, any regeneration plan for increasing resilience of the post-resource landscapes should include both ecological and social dimensions simultaneously.

Second, an event history analysis of post resource landscapes can clarify the complex factors that make post resource landscapes vulnerable, thereby suggesting where the most impactful rehabilitation work might occur. Projects that address multiple factors have the potential to become mutually reinforcing, with benefits that extend beyond a project’s life.

Third, community engagement at the beginning of a rehabilitation project can help to clarify the needs of local people while also building a project’s credibility. Community engagement is an essential part of long-term regeneration projects (Kim et al., 2020). It is worth noting that community engagement not only builds credibility and develops local supporters for the project but also can clarify the needs of local people as the major users in first steps of decision-making process, implementation and integration process, as well as project delivery.

Fourth, if a plan to rehabilitate post-resource landscapes does not receive attention at the right time, both social and ecological systems can experience exponential decline that is mostly irreversible, resulting in serious ecological issues in and beyond the region. This continued decline may pose a threat to the collective capacity of the post-resource landscape to regenerate and in particular, may weaken the identity and values of landscape and related local communities.

6 Conclusion

Although the application of ecological resilience concepts in regeneration of post-mining landscape is common, applying an approach incorporating social engagement and ecological recovery is rare. This research paper showed how mining-induced degradation could cause similar environmental problems in two very different post resource landscapes such as drought, soil erosion, land degradation, and contamination of natural resources, as well as severe social problems for local communities. However, this small case study review suggests that building trust with local communities in post resource landscapes may have significant implications. It improves community participation, encouraging local residents to collaborate on rehabilitation and environmental projects and in this way strengthens the robustness of everyday urban socio-ecological networks while enhancing the adaptive potential of vulnerable people and places to cope with sudden and unpredictable shocks.

Future research into the application of social-ecological resilience in the regeneration of the post-resource landscape is critical. Social-ecological resilience is a complex subject and involves many disciplines. This study covers the social, ecological and economic factors which contribute to post-resource landscape vulnerability of two case studies from a landscape perspective. Future research will be much more extensive, comparing the vulnerability of a number of post resource communities in Australia with similar histories ecological, social, cultural, and economic backgrounds to better understand how to improve a local communities post resource resilience.

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Evolutionary Designed Building Skins with Embedded Biomimetic Adaptation Lessons

Saam Kaviani[1*], Yamuna Kaluarachchi[2], Federico Rossi[1] and George Ofori[1]

[1] School of Architecture & Built Environment, London South Bank University,
103 Borough Rd, London, SE1 0AA, UK
[2] Manchester School of Architecture, Manchester Metropolitan University,
Chatham Building, Cavendish St, Manchester M15 6BR

kavianis@lsbu.ac.uk*; y.kaluarachchi@mmu.ac.uk; federico.rossi@lsbu.ac.uk; oforig3@lsbu.ac.uk
* Corresponding author

Abstract:
The ambition of this study is to create a computational design engine that develops testable simulated models that can adapt to various situations or environments by abstracting some adoption lessons from biology and their relationship to the evolutionary growth of natural systems. With an emphasis on the optimisation of thermal and visual comfort across specific floor areas, the abstracted principles of biology are used to develop building skin tissues. These designs, evaluations, and implementation principles are conceptualised and computationally simulated. The idea of nature as a repository of interconnected dynamic processes that are open to investigation and simulation has changed from a formal metaphor to credible applications that can be implemented to improve the built environment. Environmental catastrophes during the past 20 years have accelerated efforts to gain a deeper understanding of natural systems and processes. A greater congruence between architecture and nature is believed to be possible with the help of applying the principles of natural systems and processes to the construction of buildings. Examining and reflecting on the interrelations of forms, processes, and behaviours can yield useful strategies to develop architectural morphologies that require significant environmental performance enhancements. This paper aims to propose an evolutionary design process with embedded biomimetic principles to generate building skins with morphological characteristics that can be applied in the context of excessive solar radiation e.g. the Persian Gulf region, to maximise thermal comfort by blocking unwanted the solar radiation while simultaneously increasing the visual comfort by increasing the view of the users to the outside.

Keywords:
Adaptation, Architecture, Biomimicry, Building Skin, Evolutionary Computation

1 Introduction

The number of people that are going to live in urban areas is projected to increase by up to 70 % by the year 2050 (United Nations, 2018). The exponential growth of population not only reflects the necessity of having more habitable spaces in the near future but also illustrates an urgent need for a proposal of a design system at which one of its core missions is to inhibit the exhaustion of environmental resources and, at best enhance environmental conditions by lowering greenhouse emission.

Building envelope is one of the most vital design elements that define the interior physical environment, influencing how energy is used in buildings (Yilmaz, 2003). Considering this critical role, in the past few years, many studies and research work around the world have been focused on building envelopes in a bid to improve performance and efficiency with regard to structure, comfort, and energy (Lee, 2004, Selkowitz et al., 2003).

Nature, as a repository of forms and processes, has always been a source of inspiration for solving complex real-world problems across different disciplines. Evolution as a mechanism by which all of these processes and behaviours have been evolved is compelling to be investigated and studied in order to infer a design methodology for problems revolving around adaptation to the environment. According to the biologist John S. Torday, ‘Homeostasis as a scale-free biological process plays an important role in the adaptation of species to their environment throughout their evolutionary developments’ (Torday, 2015).

This paper sets the theoretical context and the background to present a design methodology to address the rising issues of increased energy consumption in areas with extreme solar radiation that are intended to neutralise the impacts of extremely hot climates. It also presents a case study in relation to Al-Bahr tower in Abu Dhabi, UAE, to investigate how biological processes and their connections to the adaptive behaviour of species can lead to extracting useful parameters to be utilised in the early stages of design processes. The study aims to put forward a design methodology which highlights the significance of early design explorations in addressing climatic issues by generating building skins with morphological properties embedded into the shadings and geometrical attributes that enable their adaptation to excessive solar radiation.

2 Literature Review

Nature has always been a source of inspiration in the architecture and design discipline. However, the attention has shifted from formal inspirations to simulating processes. According to Steadman’s key literature (1979 & 2008), “systems and processes inherent in nature can play a key role in driving the architecture closer to harmony to the environment” (Steadman, 1979 & 2008). Homeostatic behaviours explained as species, play a crucial role in their evolutionary adaptation and the emergence of their formal characteristics (Torday, 2015). These processes function in a spatial domain of the internal and external environment with boundaries in between them. The existing measures of regulating these external environmental changes have contributed to the loss of significant amounts of energy through implemented heating and cooling mechanisms (Napier, 2015), among which the cooling systems utilise more energy in summer than heating systems in winter. Cooling systems are being utilised extensively in countries with excessive solar radiation, e.g. the Persian Gulf region, and lead to extreme electricity loads (Attia 2018).

Since the late 20th century, evolutionary multi-objective optimisation techniques have been used extensively as problem-solving tools. The earliest use of evolutionary principles as optimisation procedures can be found in the 1930s work of Sewell Wright (Aedas, 2019). In its simplest form, Erns Mayr defined the evolutionary model as a two-step process: the random variation within a phenotype’s genome and then the selection of the phenotype through environmental factors (Mayr, 1982). The majority of evolutionary algorithms that are currently in use, such NSGA-II (Bateson, 2012), were developed using Mayr’s concept. The algorithm starts by generating an initial random population of solutions and then iterates via a primary loop. It continues with alterations of genomes (sets of DNA) via random variations and evaluation of the solutions on their objective performance. A collection of solutions are ultimately chosen using a predetermined selection mechanism. (Turner, 2002) (Figure 1).

In recent years, evolutionary optimisation processes have gained recognition in architecture and design disciplines, both in academia and practice. Research conducted by Ayman Hassaan et al. (2016) investigated the use of evolutionary optimisation in the design phase by exploring geometric formations of the skin at the early stages of design (Steadman, 2008). Yun Kyu Yi implemented NSGA 2 algorithm in his investigations of optimising building facades (Ladybug Tools, 2019).

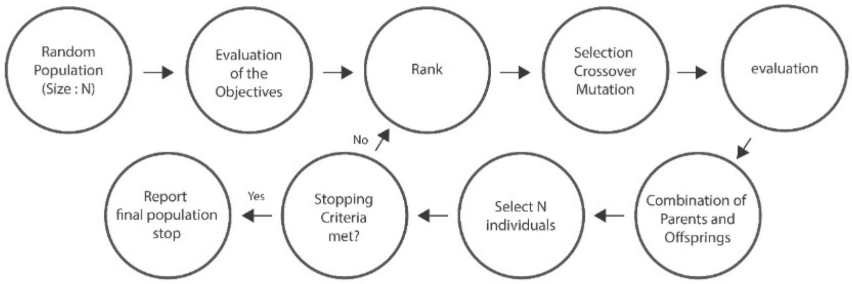

Figure 1. NSAGII algorithm pseudocode.

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In nature, homeostasis occurs through evaluations and responsive feedback mechanisms. The application of homeostatic principles for the development of adaptive architectural skins requires an iterative generative model that includes a mechanism of evaluation and reconfiguration of the generated results. Thus, the experiment presented in this research utilises evolutionary computation as the main framework through which generated design solutions address the predefined environmental pressures via an increase in their fitness (Luke, 2011).

2.1 Experiment Setup

In this context, heat received by solar radiation is the parameter for which homeostasis will be maintained and monitored by inserting the secondary evaluation mechanisms as the algorithmic loops into the evolutionary simulation (Figure 2). With a similar goal but a different algorithmic approach to the experiments presented in the paper (Showkatbakhsh and Kaviani, 2020), this paper investigates the application of homeostatic feedback mechanisms into the evolutionary simulations to generate adaptive building skins.

The main components of a homeostatic process (set point, receptor and effector) are translated as a secondary evaluation mechanism by which the main evolutionary simulation will be directed towards the emergence of a new set of morphological attributes in the phenotype should evolution favour such properties. Building upon Torday's statement of '*a reference point for change'* these secondary evaluation mechanisms create a reference point for morphological changes through the evolutionary simulation (Torday, 2015).

The presented experiment utilises multi-objective Non-Dominated Sorting Genetic Algorithm II (NSGAII) developed by Deb. et al. (Deb et al., 2000) as the base algorithm into which the evolutionary simulation is developed. Rhinoceros3D, Grasshopper3D and its plugin 'Wallacei' (Wallacei, 2018) are used to run the simulation and analyse the results thoroughly. In the conducted experiment, the algorithm parameters within the evolutionary simulation were set to the following values. (Table 1) (for a detailed description of the terminology used in the simulation, see (Makki et al., 2019)).

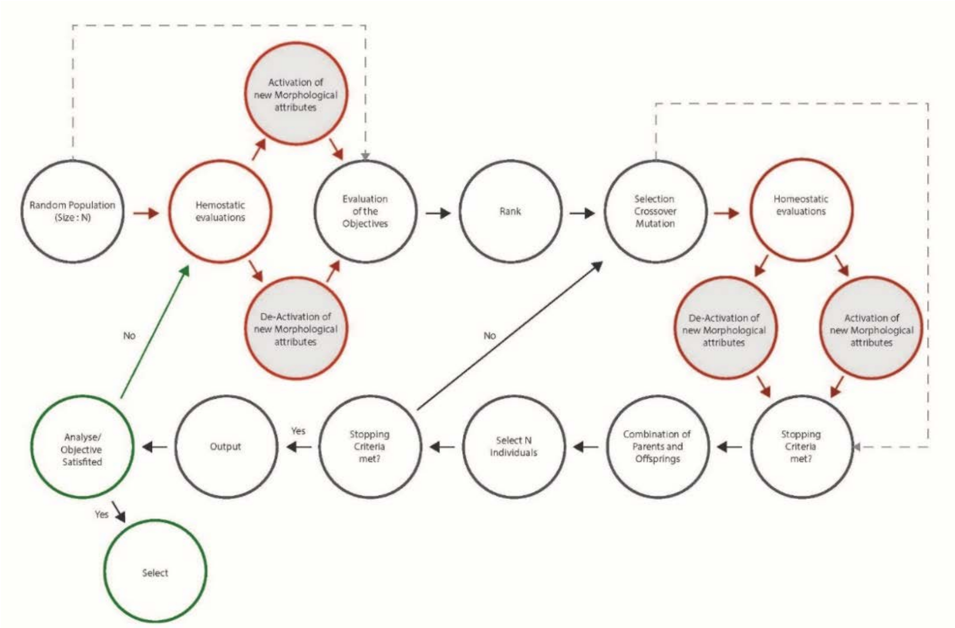

Figure 2. The modified evolutionary simulation workflow with two secondary evaluation mechanisms. The red squares show the modified stages. The green square shows the added step on the application of evolutionary simulation.

Table 1 Detailed description of the terminologies used in the simulation

Term	Short Description
Genotype	All the genes (and the gene groups) that define a single solution/phenotype. The genotype may be considered as the solution's 'blueprint' or DNA. It is also called genome.
Phenotype	The morphological (or otherwise) representation of the solution. The phenotype is the manifestation of the genotype
Extrusion	The ability that shading morphologies have to extrude out their mass in order to increase the self-shading of the façade and by increasing the surface-to-volume ratio.
Rotation	The ability to move the holes created in cells to maximise the view during the simulation
Offset	The thickness of the sides of each cell of the shadings
Density	The number of cells in a specific area over the surface of the skin

The design experiment in this research aims to generate building skins with morphological properties embedded into their shadings and geometry that enable their adaptation to excessive solar radiation. Especially in the Persian Gulf Region, which is one of the areas with increasing interest in building constructions while possessing extreme environmental conditions in summer that, in the next decade or so, the temperature can rise up to 60 degrees in summers (Pal and Eltahir, 2016). In the context of this research, the seasonal solstices (21st of June), September, December and March) are considered the date on which solar radiation is calculated and studied. This research, through comparisons to the original skins implemented in Al-Bahr towers located in the UAE, highlights the significance of adaptation of skin to extreme environmental conditions. Secondary evaluation mechanisms have been hardcoded into the evolutionary simulation to steer the evolutionary process in the direction of generating such formal attributes.

In each case study, the original skin of the building will be precisely modelled, and the skin will be exposed to solar radiation on during 21st of June in order to measure the skin performance in terms of the solar radiation occlusion and to provide visibility (view) to the outside. Then, by utilising each case study skin as the basic geometry component, a primitive geometry will be constructed to enable the changes necessary in the simulation. The experiment will present these behavioural attributes by analysing individual solutions extracted from different generations throughout the simulation.

2.1.1 Selection of the Fitness Criteria

The evolutionary simulation was developed to generate a building skin in Abu-Dhabi and Riyadh for the Albahr towers to optimise for the following fitness objectives:

a) *FO1*: To increase the shadow on the buildings by *self-shading* mechanisms (Figure 3)

b) *FO2*: To increase the view from the inside of the buildings towards the outside (Figure 4)

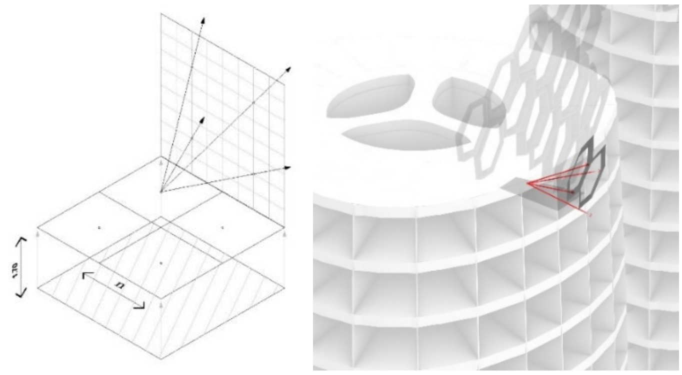

Figure 3. Skin view analysis

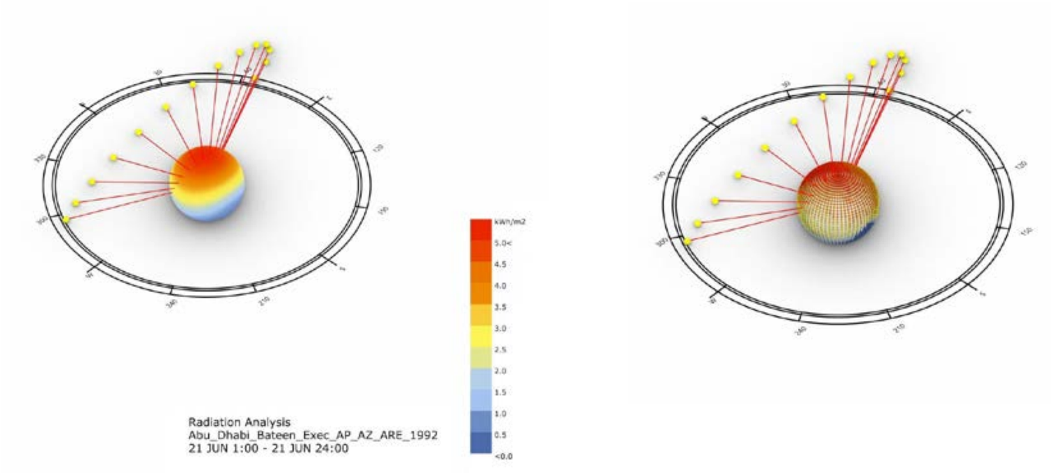

Figure 4. Illustration of sun radiation application over the building

Each of these objectives was formulated to direct the evolutionary simulation toward the emergence of the formal attributes (Table 1 & Figure 6) suitable for the context. Secondary homeostatic mechanisms in the simulation will then steer the simulation towards preferred morphological attributes by creating reference points for change. The architectural application of these fitness objectives, however, holds an equal significance, and they are as follows:

The sample points populate the geometries to calculate the self-shading objective (Pa) efficiently. The volume of the phenotypes is inversely correlated with the number of (Pa). The sun vectors can access some of (Pa), but some are blocked (Ps). Objective 2 is calculated to increase the number of (Ps) in the simulation in order to increase the self-shading on the buildings. The ratio is calculated as the objective since each solution may have a different number of sample points Pa (due to their various volumes).

$$\delta = \sum_{n=0}^{n} P_{an} \qquad \theta = \sum_{n=0}^{n} P_{sn} \qquad FO1 = \left(\frac{\delta}{\theta}\right)$$

Each room on the selected floors (office floors) is divided into four parts, and from each part, vectors are projected to the outside of the building from an elevated point (eye level of 1.7m). The number of vectors that are blocked by the skin will be mapped and shown in percentage to have a clear ratio of blocked and unblocked rays. Vectors (V_a) are drawn outwards, as shown in figure 4. The skin system will block some of them, while some vectors will not hit the skin and pass through (V_p). Fitness objective two is assigned to increase the number of vectors (V_p) from inside to outside.

$$\alpha = \sum_{n=0}^{n} V_{an} \times \mathrm{V} \qquad \beta = \sum_{n=0}^{n} V_{pn} \qquad FO2 = \left(\frac{\alpha}{\beta}\right)$$

Number of vectors (n) = area/x
Number of points to test on window = n
% of view = (β / α)×100
β = Number of blocked Vectors, α = all of the vectors
(Length of blocked vectors < length of vectors)

As a result of the inserted homeostatic mechanisms in the evolutionary system, a new morphological attribute (skin system) will be activated. In order to address the concern regarding the blockage of the view from inside of the buildings towards the outside, the second objective is introduced to the evolutionary simulation to increase the view from inside to outside.

Given the complexity of the design problem, the experiment was limited to 10 (Generation Size) individuals per generation with a total number of 400 generations (in total, 4000 generated solutions). The main purpose of the conducted experiment is to test the success/failure of the implemented homeostatic mechanisms within the evolutionary simulation to generate phenotypes with formal attributes suitable for adaptation to hot climates.

2.1.2 Genotypes and Phenotypes and the development of the skin:

Table 2 Fitness Criteria

Fitness Criteria	**Genes**			
	Offset	Extrusion	Rotation	Density
Increasing Self-Shading				
Maximising the View from Inside to Outside				
	1	2	3	4

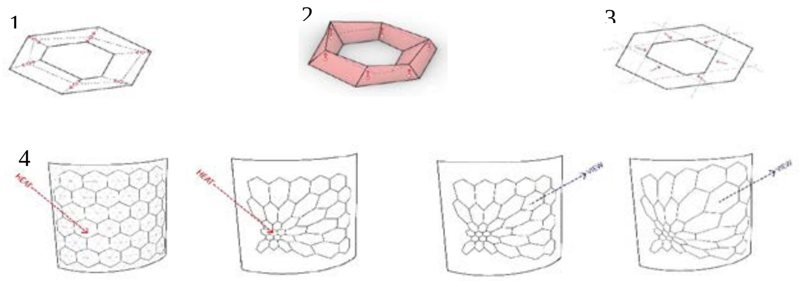

Figure 5. Illustration of an example of genes morphological representation of proposed cellular skin

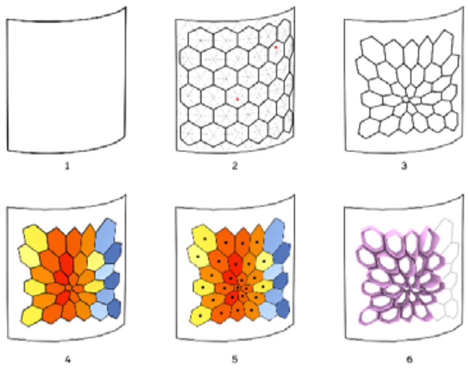

Figure 6. Basic Illustration of the development of each type of skin in the evolutionary design experiment (Cellular Skin with N-gon geometries)

3 Findings and Discussion

In addition to the analysis of the entire simulation for each case study, the best phenotypes were selected among the 4000 phenotypes to study how successful or unsuccessful the simulation was in optimising their objectives and, more importantly, how better or worse they performed relative to the original skin of the buildings in adapting to the excessive solar radiation of the Persian Gulf region. Selecting a set of candidate solutions in the multi-objective evolutionary algorithm while limiting the user's preference is challenging. In order to compare a wide range of solutions with the case studies' original skins, selected solutions are the best option for each of the two fitness objectives. As the visual and the thermal comfort may contradict each other, the selected solution is the relative difference between the best fitness rank of each fitness objective. The fifth one is the solution which addresses the fitness objectives equally. It has the lowest average fitness rank amongst 4000 solutions (for further description of the selection strategies, please refer to (Showkatbakhsh, Kaviani, and Weinstock, 2021; Ladybug Tools, 2019)).

The analysis of each selected solution continues by studying how successful or unsuccessful they performed in the following measurement criteria in comparison to the case studies.

a) What percentage of the building surface area will receive more than the threshold of 3.5 KwH/m2 solar radiation?

b) How much the evolved skin system obstructs the view from the inside to the outside of the buildings?

c) In all case studies and solutions, the only floors selected in terms of function are the office floors.

The selected phenotypes display a wide range of morphological variations. All the selected phenotypes have H-M-A (skin system) activated, while H-M-B (extra skin) was triggered selectively (based on the fitness criteria and solar radiation intensively).

The following pages comprise a series of illustrations of the extended set of selected skin morphologies that evolved in the experiment. The drawings highlight the variations of skin tissues over the case studies (figures 7, 8, 9 and 10).

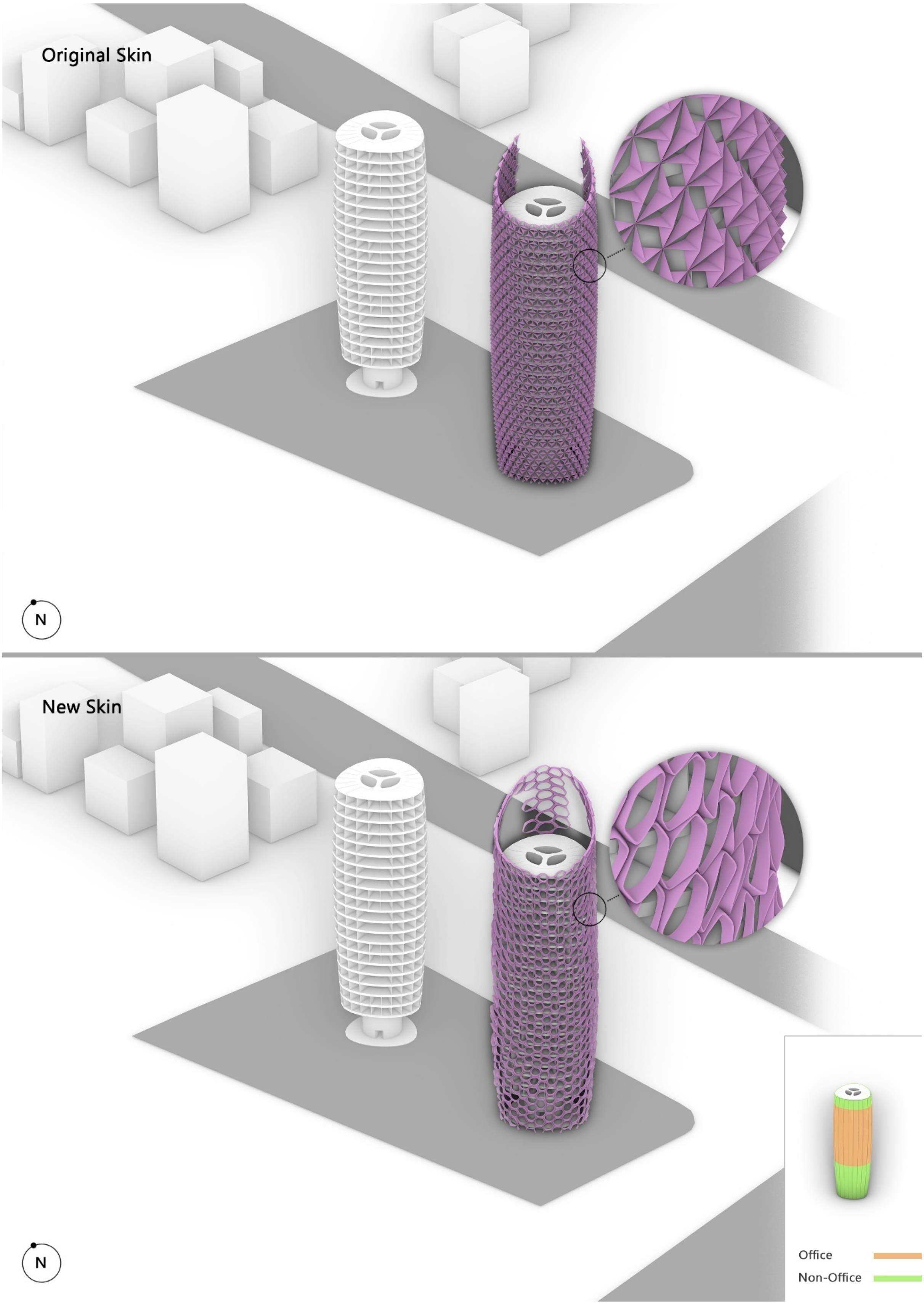

Figure 7. Illustration of Albahr tower before and after applying the biomimetic morphological configuration.

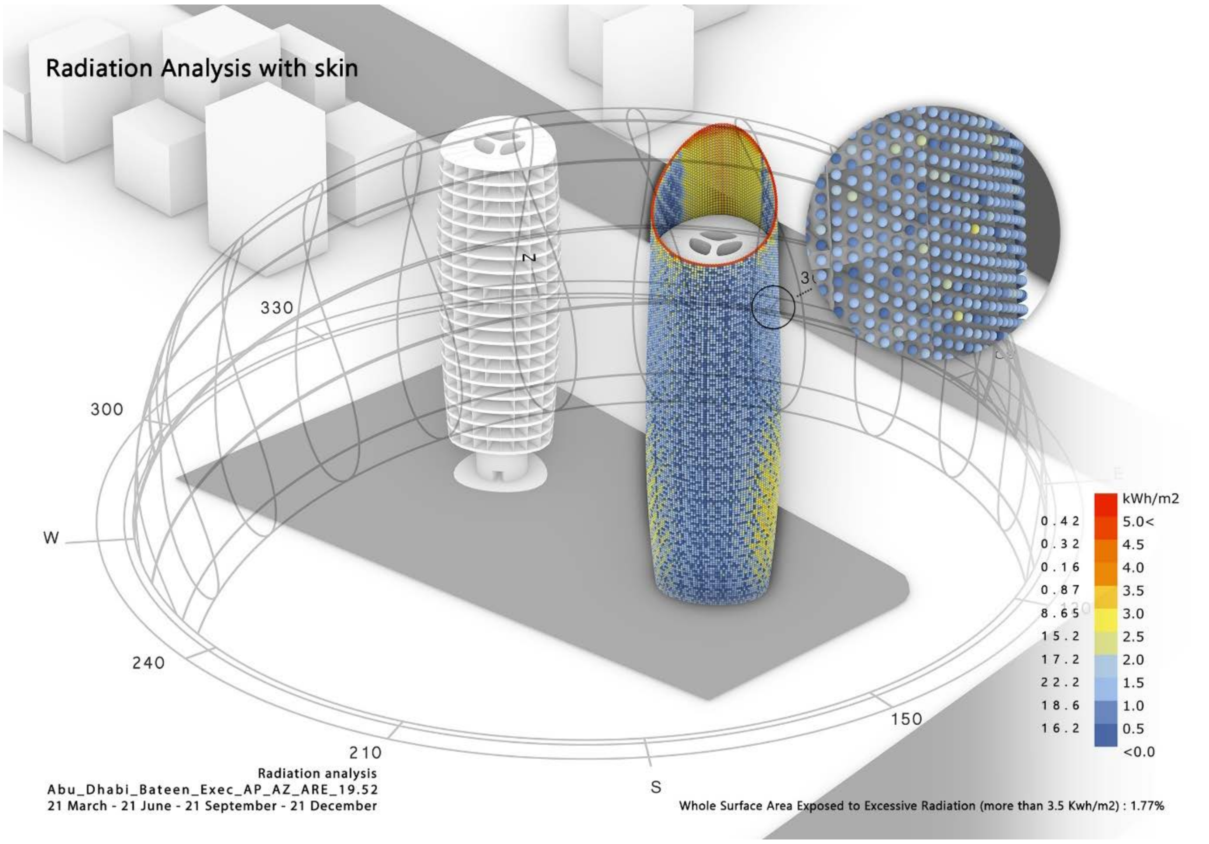

Figure 8. Radiation Analysis of the tower with the original skin

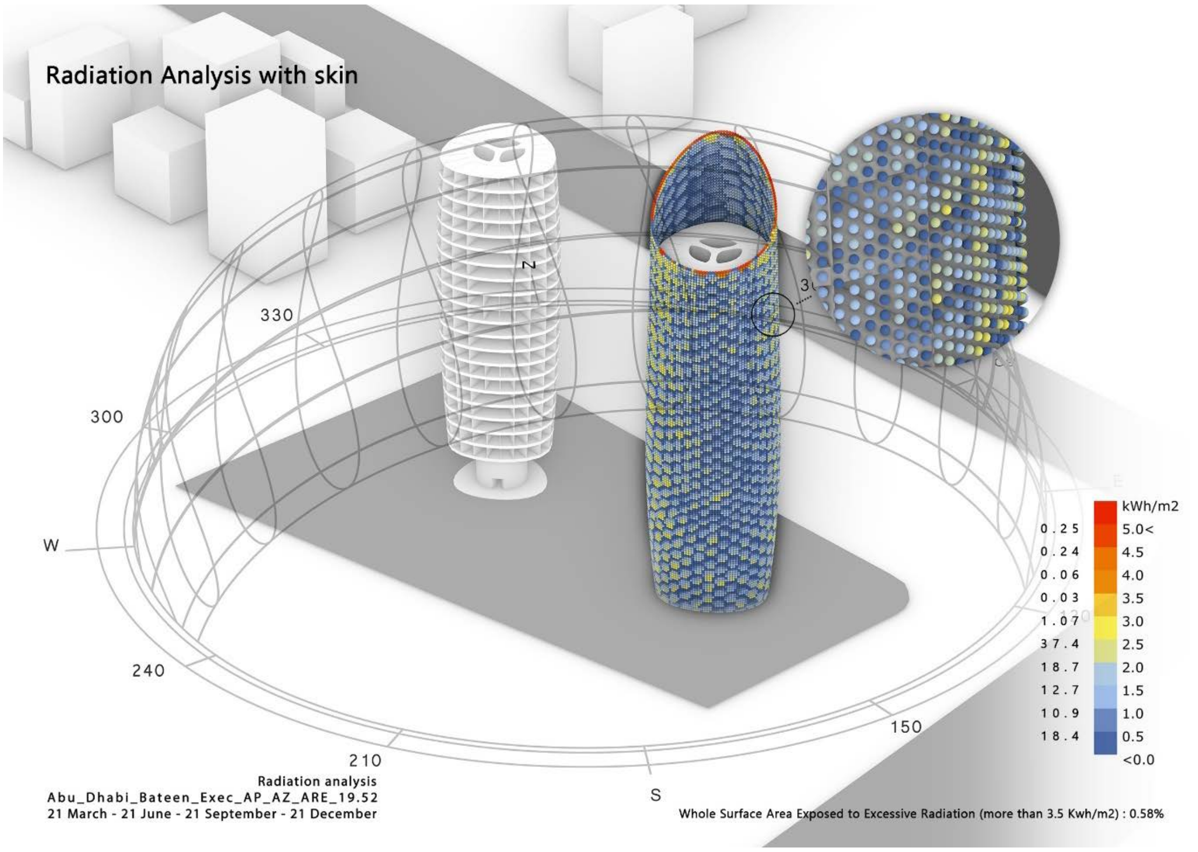

Figure 9. Radiation Analysis of the tower with the new optimised skin (after the simulation)

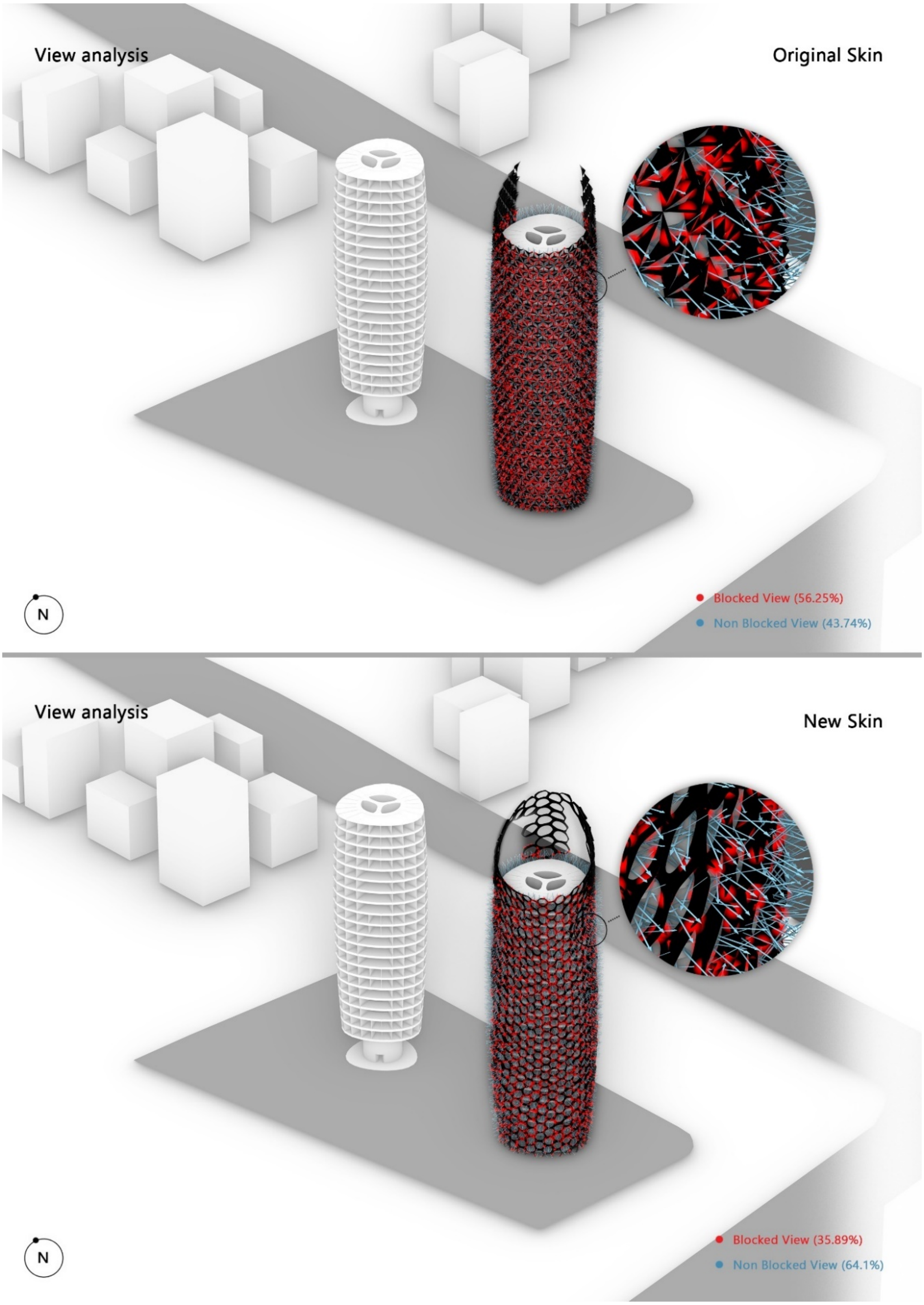

Figure 10. View Analysis of the original and newly optimised skin of the Al-Bahr tower

4 Conclusion and Further Research

This research contributed to two primary fields: building skin design and evolutionary computation through computational experimentation of biologically driven evolutionary design simulations. It highlighted the significance of biomimetic skin morphologies in adaptation of buildings to excessive solar radiation through a variety of changes across the length, width and density of the geometries of the skin. The crucial biological process of homeostasis, which ensures the adaptation of species through their interactions with their local context, was investigated. Through a series of computational experimentations, the abstracted genotypic and phenotypic attributes derived from biological homeostatic mechanisms were applied to a set of evolutionary models to form a novel generative engine that evolves skin morphologies with embedded homeostatic characteristics suitable for their context.

The proposed skin design system of this paper has provided a comprehensive workflow to implement a set of biological principles of evolution and homeostasis in an architectural generative design process, to evaluate and select the results. The contribution of the research to the analysis and improvement of visual and thermal comfort in design can be highlighted below.

Thermal comfort: The algorithmic implementation of a homeostatic process's regulatory mechanism to keep the solar radiation variable in a steady state (less than 3.5 kWh/m2) throughout the repeated evolution process. Throughout all selected results of the skin proposals, the amount of solar radiation exposure on the building surface (especially office floors) reduced significantly to below 3.5 kWh/m2.

Visual comfort: As a result of the inserted homeostatic mechanisms in the evolutionary system, a new morphological attribute is activated in the new proposed skin on selected buildings in order to address the concern regarding the blockage of the view from the inside of the building to the outside. This process has been introduced to evolutionary simulation as the second objective to increase the visual comfort of the users.

The main obstacle to this was the computational load required to include these variables within the experiments. The computational setups required for design experiments must be optimised to avoid slow calculations and simulations. Since the intention is to develop a design system to be utilised in a consumer-specification computational platform, the evolutionary design models need to be reformulated to reduce the computational calculations. The materials of the building's skin and the function and specificities of each floor space were considered constant values across all experiments. This was done to ensure the results only reflect the impact of skin morphology on solar radiation intake of office spaces at the selected buildings. The complexity of the solutions and the amount of data produced by the simulations were two disadvantages of adding more factors to the solar radiation analyses. Therefore, another potential path to expand this research is to incorporate variables such as energy flow, room temperature and material studies by developing prototypes and adopting digital twin techniques.

5 Acknowledgement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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Unrecognised Ramifications of Base Isolators in Buildings

Ronwyn Coulson[1], Eric Scheepbouwer[1*] and Daniel Van Der Walt[1]

Department of Civil and Natural Resources Engineering, University of Canterbury, Private Bag 4800 Christchurch 8140, NEW ZEALAND

ronwyn.coulson@pg.canterbury.ac.nz; eric.scheepbouwer@canterbury.ac.nz; daniel.vanderwalt@canterbury.ac.nz

* Corresponding author

Abstract:

Base Isolation is a proven method for safeguarding people and property in an earthquake event. It has been used in some rudimentary form or other for over a century and with its modern steel plate and rubber bearing form for over 40 years. While the technology is well understood by earthquake engineers, base-isolated buildings are designed by multi-disciplinary teams, and owned, operated, and maintained by stakeholders who are not typically trained in earthquake engineering. The aim of this research was to identify the consequences of base isolation on the overall building from a lifecycle perspective and test whether current design practice (and legislation) provides for safety for the whole design life of a building. Through an integrative literature review of international academic research and base isolator manufacturer literature, New Zealand engineering guidance notes and building legislation, this research highlighted key risks and issues that need to be considered and accommodated by Architects, Engineers, Contractors, and Building Owners when a base-isolated solution is proposed. Risks discovered included the broader implications of displacement, pounding of adjacent buildings, soft-soil and near-fault earthquake sensitivity, base isolator failure (both temporary and permanent), construction safety prior to the release of isolators, durability concerns, and spatial provision for access for regular inspections and replacement during the design life of the building.

Keywords:
Architecture, Asset Management, Base Isolation, Construction, Services Engineering

1 Introduction

The February 2011 M6.3 earthquake in Christchurch resulted in over 70% of buildings in the central business district being demolished. (Chang et al., 2014). After the earthquakes, there was a sentiment for "building back strong", and many new buildings were rebuilt or retrofitted with a base isolation structural solution, a system that has been widely embraced in seismic regions around the world for over 40 years in its modern form.

Base Isolation (BI) is essentially a mechanism for separating the foundations from the superstructure, allowing for movement and energy dissipation at the isolation level, thereby protecting the superstructure above (Kelly, 1998). The primary drivers for base isolation are the safety of occupants and the protection of property "*to provide life safety during the earthquake and a high seismic resilience and business continuity following the earthquake*"(Carr, 2021).

Base isolators have a dual function (Nakazawa et al., 1991):

1. To isolate the superstructure from the foundations and ground motions
2. To function as supportive structural materials for the building superstructure

In respect of a structural engineering solution, base isolation can achieve both of the above criteria when used on good soil, not subjected to near-fault earthquakes (Carr, 2021) and while the isolators remain functional. If base isolators do not remain functional in both respects (isolation and support) for the design life of the building, the structural performance of the building will be compromised (Coulson et al., 2022).

The history of base isolation is long. There is wide acknowledgement of a Japanese system of base isolation in practice going back to the late 19th century. The Imperial Hotel in Tokyo by Architect Frank Lloyd Wright was completed in 1921 using soft mud as an isolation layer to separate the building from the effects of ground motion. (Kelly, 1988). The hotel survived the M7.9 Great Kanto earthquake of 1923.

The earliest building using engineered rubber bearings dates as far back as 1959 in the Soviet Union, known to have survived the 1966 M4 and 1973 M6 Askhabad earthquakes. (Buckle & Mayes, 1990). Another building frequently cited as the first BI structure in the world, namely the Pestalozzi School Building in Skopje, Macedonia, was built in 1965. It too survived numerous large earthquake events.(Gjorgjiev & Garevski, 2012). Modern rubber and steel base isolators were first developed in 1982 (Robinson, 2000) and by 1990, modern base-isolated structures had been built in at least 17 countries. (Buckle & Mayes, 1990). By 2003, there were over 400 base-isolated buildings in China (Zhou et al., 2004).

Base isolation is far from new. Yet, despite the very long history of structural and mechanical engineering advances in the design and use of base isolation in multi-storey buildings, design implications outside of the structural/earthquake engineering profession, remain poorly documented. There are important architectural and services engineering implications of a base isolated solution that must be resolved, which, if not satisfactorily managed, can create risks of structural building failure as well as a failure to "*provide life safety*" (Carr, 2021).

In the words of Edmund Booth, "*Seismic engineering should be practiced as if people mattered*" (Booth, 2018).

2 Aims and Objectives

This paper aims to identify the consequences of base isolation on the overall building from a lifecycle perspective. It draws attention to the issues and risks that need to be addressed by Architects and Services Engineers during design, and by Asset Managers during the operational phase of the building after construction.

It is intended as a preliminary review, creating a conceptual framework for more in-depth research, with the intention of improving the safety of base-isolated buildings and structures for the whole design life of the building.

The following objectives have been identified:

1. Undertake an integrative literature review
    - Academic publication review
    - Legislative and Design Standards review
    - Base Isolator Manufacturer literature

2. Develop a preliminary log of issues and risks associated with base isolation, providing a conceptual framework for further research

3 Research Methodology

A literature review as a research method was considered an appropriate approach to provide a sound basis for an overview of existing research in the field of base isolation, identifying gaps in research from a multi-disciplinary perspective, and creating a framework for further research to advance knowledge in the field of base isolation.

Most research on base isolation focuses on base isolation design rather than the broader implications of base isolation from a multi-disciplinary and whole-building lifecycle perspective. Undertaking a systematic literature review of all articles ever published on base isolation in respect of structural engineering design would not address the specific research question, namely identifying existing research and research gaps beyond the lens of structural/earthquake engineering design.

The integrative (or critical review) model, as defined by Snyder, allowed for a broader approach to data selection, combining insights from disciplines outside of structural engineering design and providing the framework for a new way of looking at base isolation from a multi-disciplinary, whole design life perspective. This more innovative approach allowed the authors "*to assess, critique and synthesise the literature*" on base isolation "*in a way that enables new theoretical frameworks and perspectives to emerge*."(Snyder, 2019).

4 Findings and Discussion

4.1 Literature review overview

The academic literature search was limited to peer-reviewed journal articles in the discipline of engineering, subject terms engineering and written in English. Research and publications on base isolation have been increasingly prolific since the 1980s, and there are now over 94,000 peer-reviewed articles on base isolation. Base isolation can therefore be considered a mature topic. A multi-search exercise demonstrated the resounding prominence of structural engineering design articles and the lack of research /gaps in base isolation research and knowledge beyond engineering design.

Table 1. Academic Literature review results

Search identifier	Search terms	Field	Number of search results
1	(base isolation)	engineering	94,583
2	(base isolation) AND design	engineering	19,765
3	(base isolation) AND architect*	architecture	750
4	(base isolation) AND (fire protection)	engineering	150
5	(base isolation) AND construction	construction	1,125
6	(base isolation) AND (asset management)	Asset management	17

In the first instance, the search was conducted using academic databases such as Scopus and Science Direct for academic literature about base isolation, looking specifically for research conducted into base isolation beyond the field of structural engineering design, focusing on architectural design, services engineering design, fire engineering, legislation, construction, and asset management. Further searches were conducted using multi-search and Google Scholar and cross-checked with Scopus. Both recent and older literature were included in the search to ensure that earlier valuable work was not excluded.

Of the returned results for design (search identifier#2 in table 1), none of the articles addressed base isolation design from a multi-disciplinary perspective i.e., architectural spatial considerations, services engineering, or fire design. Even the results for search #3 returned articles that were about structural engineering design of base-isolated buildings with a very minor reference to architecture rather than architectural design. Of the results returned for construction and asset management, none of the articles addressed construction methodology for base-isolated buildings or asset management of base-isolated buildings in respect of base isolator maintenance or replacement.

The lack of research into the implications of base isolation from a perspective other than structural engineering design, considering that academic research about base isolation has been prolific for over 50 years, could point to a lack of understanding (knowledge transfer), interest or training in earthquake engineering outside of the structural engineering discipline over a long period of time. It does indicate that little research has been done into the consequences of base-isolation in respect of design (architectural, services, fire), construction (and demolition) safety, and design life maintenance of base isolated buildings.

The review of the collated literature was conducted through the lens of assessing knowledge that addresses the whole building design life of 50+ years, ordered into the research objectives of design, construction, and asset management. The research was collated, and the final sample was shortlisted according to the identified research objectives, namely design, construction, and asset management of base-isolated buildings. Also collated into the database were articles that focused on earthquake engineering design but that also highlighted important issues for consideration in respect of multi-disciplinary design, construction, or asset management.

A search was also conducted into literature published by the New Zealand Central government, Local government, and Crown Entities, including earthquake engineering guidance notes by the NZ Society of Earthquake Engineering (NZSEE). A thorough investigation of legislative requirements (MBIE, 2021) was also carried out to assess current legislation covering base-isolated buildings. Manufacturer technical specifications and warranty conditions from various international base isolator manufacturers were reviewed to gather information on both design implications (specifically in respect of spatial requirements) and maintenance or warranty implications.

Although most of the academic literature on base isolation is structural engineering design focused, a final sample was collated of articles, shortlisted initially by abstracts, and then reviewed in detail. The sample articles indirectly provided valuable insight into some of the issues of base isolation that impact other designers, construction, or design life implications.

Focusing on the core issues, published engineering design guidelines and base isolator manufacturer literature were also valuable for informing the development of a framework to address the deficiencies and omissions identified in the existing knowledge base. The findings from the literature review process are presented below as high-level issues or risks to be addressed by the multi-disciplinary design team during design, building contractors during construction or building owners during the operations phase of the design life.

4.2 Results

The following risks and issues were discovered through the literature review:

4.2.1 Displacement (implications of)

Specific areas of movement in the building in the event of an earthquake may be as much as 700mm. Seismic flooring and gaps require signage to warn occupants (Whittaker, 2019). Suspended lift shafts and stairwells free of the isolated foundations are some of the factors that need to be accommodated, as well as a seismic isolation flooring system. Displacement at the isolation level (typically at the basement level) leading to structural collisions with the surrounding moat wall (Mavronicola et al., 2020) requires clearance between the base-isolated building and adjacent structures.

Special care needs to be taken to ensure that fire egress routes are safe in an earthquake event. Design for access is addressed in the NZSEE report (Whittaker, 2019), which specifically addresses the fact that movement joints pass across circulation routes, including stairs and lifts. Further, fire protection is required for base isolators where they could be exposed to fire risk, and both the Architect and the Fire Engineer need to be across this.

4.2.2 Pounding of adjacent buildings

Pounding of base-isolated buildings with aligned slabs was a risk identified when buildings, although individually compliant, were positioned too close together, and in the study, this was found to be a common issue. (López-Almansa & Kharazian, 2019). Architects need to be aware of this at the front-end design and development feasibility stage owing to the impact of the net lettable building area.

4.2.3 Soft soils and near-fault earthquakes

Several researchers have identified that base isolation may not perform as designed in soft soil conditions, soils of varying conditions and earthquakes with long periods and duration (Kuang et al., 2016; Liu et al., 2021; Patil & Reddy, 2012).

4.2.4 Base Isolation Failure – temporary post-earthquake and permanent

Various researchers have identified that base isolation can be vulnerable to failure in near-fault earthquakes (Chanda & Debbarma, 2020; Jangid, 2007; Jangid & Kelly, 2001; Pan et al., 2005; Patil & Reddy, 2012), but it appears that this issue has not been fully resolved, and that more research is required.

A few articles address base isolator failure in displacement or increased superstructure acceleration, identified through seismic monitoring devices in real earthquake events, notably in the 2011 Christchurch and Great East Japan earthquakes (Kuang et al., 2016; Siringoringo & Fujino, 2015a, 2015b). Siringoringo notes that base isolators do not perform as designed for two months after an earthquake owing to cyclic straining history on the rubber, and this has implications for pre-earthquake and aftershock events.

Investigation into the reason for these failures would advance earthquake engineering design practice, but no research addressing these failures have been found. Further, no evidence has been found that the failures were addressed in those buildings after the events.

4.2.5 Construction safety

Construction methodology and phasing for the release of the base isolators can be complex and dangerous to workers, especially in relation to work around the rattle zone, and accepting that construction work is being carried out in a seismically active place. After the base isolators are released, the building will move freely in an earthquake, making work near the isolators or rattle zone very risky

No existing literature was identified, and research and guidelines are needed to ensure worker safety on site, and the correct installation of base isolators to ensure that they perform as designed for the life of the building. A good example is the lack of guidance around the safe construction of base-isolated buildings. Guo et al. identified New Zealand as rating worst out of nine Economic Cooperation and Development (OECD) countries in 2017 for safety performance in the construction industry. They concluded that there was an urgent need to develop Safety in Design capability across the construction industry. (Guo et al., 2021).

4.2.6 The durability base isolators vs a 50-year design life

According to the New Zealand Society for Earthquake Engineering (NZSEE) Guidelines for the Design of Seismic Isolation Systems for Buildings (Whittaker, 2019) “Isolators and their attachments should have adequate durability to meet the relevant performance requirements of Building Code Clause B2 Durability”. As B2 requires 50-year durability, base isolators should be procured to meet this. A review of base isolator literature, academic literature, and industry durability testing (to 30 years) has revealed uncertainty around whether base isolators meet the 50-year durability requirement. (Gheryani et al., 2015; Hamaguchi et al., 2009; Mazza, 2019; Pan et al., 2005; Papadrakakis & Fragiadakis; Van Engelen & Kelly, 2015)

In 2019, Mazza also identified a need for changes to the US, Italian and Japanese codes to address durability. A gap was identified in the NZ Building Code B2 Durability (MBIE, 2019). The current NZ legislation does not require the engineer to certify the durability of base isolators, and buildings may have been built that do not meet, or have not been proven to meet, the 50-year durability requirement in respect of the structural system.

4.2.7 Base isolator inspection and replacement

The building needs to be designed to provide for the safe and regular inspection of base isolators (typically annually). The building should also make provision for the replacement of base isolators during the 50-year design life of the building. Apart from replacement through degradation, base isolators may also need to be replaced after an earthquake event or fire.

Spatial requirements include sufficient head room to be able to manoeuvre moving equipment for the heavy isolators and an exit point to the basement or sub-floor where new isolators can be brought in, and old ones removed. Safety in Design considerations for the maintenance and replacement aspects may include lighting, ventilation, and fire safety of the confined work-space. A complete understanding is needed of the extent of movement in an earthquake event during replacement, the impact on service runs and connections across the rattle zone, as well as the fire sprinkler system and retention of water supply during replacement.

4.2.8 Operations (asset management) and LCA

The base isolator manufacturer literature brings into sharp focus an understanding that a base isolator is essentially a piece of mechanical equipment. It requires regular inspections (typically every two years), replacement of parts after an unstipulated period, and wholesale replacement of the base isolator after an earthquake, potentially after a fire, or through natural deterioration (noting durability concerns above).

NZSEE guidelines recommend that base isolator inspection and maintenance is added to the compliance schedule for Building Warrant of Fitness (BWoF) (Whittaker, 2019). A failure to inspect and maintain base isolators will void the warranty, and in the case of BI failure, will result in extensive structural repairs to the building, or even demolition and rebuild. Conditions under which base isolators will need to be replaced include ageing, earthquakes, and fire. This is likely to occur at least once in the 50-year design life of a building, and asset management plans and budgets should reflect this.

Despite the numerous base-isolated buildings that are now over 50 years old, no literature could be found on the inspection, maintenance and/or replacement of base isolators. Given that most large buildings are retained well beyond the 50-year design life, base isolator replacement could feasibly occur more than once. Asset management plans should allow for both base isolator maintenance and replacement costs.

The estimated maintenance and/or replacement of base isolators within the design life of the building should be considered in Life Cycle Assessments (LCA) and carbon footprint calculations.

5 Risk and Issues Log

The lifecycle of a building can be represented in Figure 1 below:

Figure 1. Typical building lifecycle

The risks and issues identified through the literature review have been collated into a matrix that demonstrates the risk/issue as it correlates with or impacts stages of the building lifecycle. The resultant matrix is represented in Table 2.

Table 2. Unresolved Issues and/or Risks (and research gaps) identified

Issue / Risk description	Design	Construction	Asset Management	Demolition
Durability of BI's to match the 50-year design life of the building	●		●	
Base isolation not suited to soft soils	●		●	
Base isolation not appropriate for near-fault earthquakes	●		●	
BI failure – investigation into the causes and capturing learning	●		●	
Access for BI inspection and replacement within 50 years	●		●	
Displacement at isolation level	●	●	●	
Pounding risk in respect of building set-out	●	●	●	
Movement joints and seismic gaps impacting stairs, lifts, access	●	●	●	
Displacement and seismic gaps impacting services & fire	●		●	
Construction methodology and phasing for BI buildings – Health &Safety	●	●		●
BI inspection and maintenance: provisions for access	●		●	
BI inspection and maintenance: budgeting and insurance			●	
BI replacement - conditions, design provision and budgeting	●	●	●	
Maintenance of seismic floors, gaps, and signage			●	

6 Conclusion

The research aim was to investigate the issues and risks associated with base isolation from a whole design life, multi-disciplinary perspective in respect of the design, construction, and asset management of buildings, and to assess any gaps in knowledge which give rise to unmitigated critical risks to the safety of people and property in base isolated buildings.

A broad literature review of base isolation revealed issues and risks with a base isolation solution that have not previously been recognised in research and not well-known in the construction industry. They included the broader implications of superstructure displacement, pounding of adjacent buildings, soft-soil and near-fault earthquake sensitivity, base isolator failure (both temporary and permanent), construction safety, durability concerns, and spatial provision for access for regular inspections and replacement during the design life of the building.

The scarcity of research into base isolation in respect of design (architectural, service engineering, fire engineering), construction safety, asset management and the safe demolition of a base isolated building has, as it pertains to unmitigated risk, been captured in a matrix which provides a conceptual framework for further research in the interests of plugging the knowledge gaps and leading ultimately to the safer design of base isolated buildings.

The resultant high-level issues and risks identified serve a dual purpose:

1. To draw urgent attention to some critical issues or risks in respect of base isolation that need to be addressed by designers, consenting authorities, contractors, building owners and insurers, and
2. To formulate a research agenda for further important work in base isolation research.

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Inefficient Regulations that Worsen the Housing Crisis

Christian van der Pump[1*] and Eric Scheepbouwer[1]

[1]Department of Civil and Natural Resources, University of Canterbury, Private Bag 4800, Christchurch 8140, NEW ZEALAND

christian.vanderpump@pg.canterbury.ac.nz; eric.scheepbouwer@canterbury.ac.nz
* Corresponding author

Abstract:
Performance-based design (PBD) has been available in Australia and New Zealand's building legislation for over 25 years. A central feature of PBD has been the availability of horizontal spread of fire (HSF) PBD solutions to address spread of fire between buildings and to other property, whereby fire protection engineers could adopt more efficient solutions than under previous prescriptive rules. However, both countries adopt different regulatory approaches to HSF. For example, in New Zealand, 'other property' is defined as property under a different legal title, whereas in Australia 'other property' can include property under the same title. Moreover, and as this paper argues, neither countries' approach is consistent with the common law approach the courts adopt to address HSF, nor the economic theory where HSF that affects third parties is a negative externality. This paper reviews the economic efficiency of each country's existing HSF PBD regulations. It then argues Coasean bargaining has the potential as a more efficient solution to HSF, increase land utilization, and therefore assist in alleviating the housing crisis.

Keywords:
National Construction Code, New Zealand Building Code, Coase Theorem, Horizontal Spread of Fire

1 Introduction

Performance-based design (PBD) laws for fire protection engineering form a relatively new regulatory pathway. It was passed into New Zealand law in 1993 under the Building Act 1991 (BA91), and in Australia in 1997 under the Building Code of Australia – now the National Construction Code (NCC). These new laws allowed designers such as fire protection engineers (FPEs) to adopt first-principles analysis methods rather than prescriptive methods which had historically been the only means of design. These PBD laws enabled FPEs to address horizontal spread of fire (HSF) via first principles (e.g., radiation calculations) rather than prescriptive methods, the latter which typically involved prescriptive limits of non-fire rated vertical external areas (commonly referred to as 'unprotected areas' and abbreviated here as 'UAs') for specified distances to other property. As addressing HSF is achieved via limits of land use and/or restrictions on non-fire-rated elements, efficient solution to HSF is of particular importance, since if there are alternative means to address HSF that allow increased land use and/or greater levels of unprotected areas (the latter in turn can affect the degree of land use or habitability if natural lighting and/or ventilation is restricted due to the need for fire rated external walls etc), then land utilization increases. With Australia (Mizen, 2022) and New Zealand (Hunt, 2021) both experiencing a crisis in housing supply which shows no sign of being alleviated, the importance of having efficient HSF laws cannot be understated.

Legally, each state and territory in Australia is permitted to administer building laws via their own statutory laws, as the Australian Constitution does not grant the Australian Federal Government powers to have a national building Act, and therefore HSF is addressed via state and territory building Acts. However, by agreement, each state and territory adopt the National

Construction Code (NCC) into their respective state territory building Acts, essentially as a disallowable instrument (Dal Pont, 2021) (disallowable instruments are laws below that of an Act which can be ruled invalid by the Judiciary if found to be incorrect: refer van der Pump and Scheepbouwer (2022) for further discussion). The NCC prescribes various substantiative and procedural requirements that, if complied with, the building's design is deemed to comply with the NCC. For example, under the NCC, designs can adopt any of the following methods to demonstrate compliance with the NCC:

1. Comply with the prescriptive requirements, known as Deemed-to-Satisfy or DtS:
2. Comply with the performance requirements of the NCC, known as PBD:
3. Demonstrate a design that is equivalent to the DtS; known as equivalency:
4. Comply with a Verification Method (optional calculations methods specified by the NCC that are considered means of demonstrating compliance with relevant performance requirements).

How the NCC requires HSF to be addressed is affected by the definition of *other property* and performance clause CP2, namely:

1. *Other property*: means all or any of the following:
   a. any building on the same or an adjoining allotment; and
   b. any adjoining allotment; and
   c. a road.
2. CP2 Spread of fire:
   a. A building must have elements which will, to the degree necessary, avoid the spread of fire:
      i. Between buildings;
   b. Avoidance of the spread of fire referred to in (a) must be appropriate to:
      i. Its proximity to *other property*

Also, the NCC's verification methods CV1 and CV2 (which if complied with then CP2 is deemed complied with) specify not-to-exceed heat flux thresholds requirements to address spread of fire between buildings:

CV1:

Compliance with CP2 to avoid the spread of fire between buildings on adjoining allotments is verified when it is calculated that –

(a) A building will not cause heat flux in excess of those set out in column 2 at locations within the boundaries of an adjoining property set out in column 1 where another building may be constructed; and
(b) When located at the distances from the allotment boundary set out in column 1, a building can withstand the heat flux set out in column 2 of without ignition

CV2:

Compliance with CP2 to avoid the spread of fire between buildings on the same allotment is verified when it is calculated that a building –

(a) Can withstand the heat flux set out in column 4 without ignition; and
(b) Will not cause heat flux in excess of those set out in column 4

Table 1. NCC CV1 & CV2

CV1		**CV2**	
Location	**Heat Flux (kW/m^2)**	**Distance between buildings**	**Heat Flux (kW/m^2)**
On boundary	80	0 m	80
1 m from the boundary	40	2 m	40
3 m from the boundary	20	6 m	20
6 m from the boundary	10	12 m	10

Thus, the intent of the NCC is for buildings to be designed to resist HSF for the following scenarios:

1. From the proposed building to another building on a different allotment.
2. From a building on a different allotment to the proposed building.
3. From the proposed building to another building on the same allotment.
4. From a building on the same allotment to the proposed building.

In New Zealand the building code mandates how HSF is addressed. HSF requirements are stated in the Objectives, Functional Requirements, and Performance Criteria in Schedule 1 of the Building Regulations 1992 (BR92), namely:

1. Objective C1(b): Protect *other property* from damage caused by fire
2. Functional Requirement C3.3: Buildings must be designed and constructed so that there is a low probability of fire spread to *other property* vertically or horizontally across a relevant boundary.
3. Performance Criteria:
   a. C3.6: Buildings must be designed and constructed so that in the event of fire in the building the received radiation at the relevant boundary of the property does not exceed 30 kW/m^2 and at a distance of 1 m beyond the relevant boundary of the property does not exceed 16 kW/m^2.
   b. C3.7: External walls of buildings that are located closer than 1 m to the relevant boundary of the property on which the building stands must either:
      i. Be constructed from non-combustible building materials, or
      ii. Be constructed from materials that, when subjected to a radiant flux of 30 kW/m^2, do not ignite for 15 minutes.
4. *Other property* means any land or buildings or part thereof which are –
   a. Not held under the same allotment; or
   b. Not held under the same ownership

Thus, the New Zealand Building Code mandates buildings not on the same land title or not owned by the same building owner to be designed to mitigate against HSF.

Looking at the differences between the NCC and the BR92, there is a clear distinction between the goals of the NCC and the BR92 by way of their effect on design requirements, as summarized below in Table 2:

Table 2. HSF Objectives – NCC (Australia) vs BR92 (New Zealand)

HSF Objectives	Australia NCC	New Zealand BR92
Addresses HSF to other property across a legal boundary:	Yes – All UAs must be addressed.	Yes – All UAs must be addressed.
Addresses HSF from other property across a legal boundary:	Yes – All UAs within the same distances as the case for spread of fire to other property (above).	No.
Addresses HSF from the proposed building to another building, both under same title and on the same allotment:	Yes.	No.
Addresses HSF from another building to the proposed building, both under same title and on the same allotment:	Yes.	No (except for household units and residential units).

Clearly, there will be a cost difference between each country's approach because of the differing HSF mitigation measures, subsequently having one or more of the following characteristics:

1. Reduced quantities of UAs.
2. Increased distances between buildings.
3. Increased distances between the proposed building and other property.
4. Reduced quantities of combustible materials as façade materials.

These all come with considerable costs, whether it be reduced flexibility of building use (e.g., habitable spaces) because of lower quantities of UAs (e.g., reduced window area), reduced land utilization to meet minimum separation distances (which clearly reduce the available land to build on), restricted building material choices due to combustible material constraints, or higher costs due to fire rating requirements (walls, etc.).

The questions that arise from differences between the NCC and BR92 is which is the most efficient, and is there a more efficient way to address HSF other than the NCC or BR92? By efficiency, this must not only take into the costs associated with items 1 – 4 above but the cost of not doing so – i.e., the cost of unconstrained HSF and associated damage – if one were to consider no precautions at all. Such questions, of which the purpose is to determine the soundness and efficiency regulations regarding HSF, have (by the authors investigations) received no attention in the academic literature.

These questions are not formally answered here, however, this paper will introduce the principles that have been applied in a draft paper that argues Coasean bargaining can offer (under certain circumstances which are detailed in the draft paper) a more efficient means than either the NCC or BR92 to address HSF is better able to increase land utilization, and therefore assist with alleviating problems such as the housing crisis. Such issues raised in this paper are consistent with Coase's original work on issues such as HSF, where Coase states "But the real danger that extensive Government intervention in the economic system may lead to the protection of those responsible for harmful effects being carried too far."

2 Background to HSF

Since before The Great Fire of London in 1666, the legal system treated the issue of liability from HSF in a straightforward manner. The courts created the common law doctrine of *ignis suss* to HSF (Latin for ‘his fire’ (Ogus, 1969)), whereby the occupier of the land which fire escapes from causes damage to another property, the occupier was fully liable for the damage (the common law of nuisance). This changed in 1868, wherein *Rylands v Fletcher* the UK House of Lords incorporated exceptions with negligence-based qualities (Todd et al, 2019). However, in either common law setting of nuisance or negligence, unless the damage occurred from HSF, landowners were free to manage the risk of HSF using whatever means that was most effective for their circumstances. Landowners did not have to work to prescriptive rules (such as the DtS), but if the fire spread to the neighbour’s property, they would be liable for damages, i.e., there is a financial deterrent against irresponsible behaviour for failing to prevent HSF. The courts still use the same principles today where HSF results in losses.

Statutory law supersedes the common law (Gifford, 1990), and in the case of HSF caused by building fires, building Acts across Australasia now restrict building owners to using legal instruments such as the NCC, BR92, and prescriptive regulatory instruments to address HSF. As Table 2 indicates, this reduces flexibility and increases cost, issues which have received no attention in the academic literature (by way of the authors’ investigation) to determine if the issue of nuisance (regarding HSF) has been correctly addressed at regulation level. The following section discusses these issues from an economic perspective.

3 The Economic Nature of HSF & Negative Externalities

Negative externalities have the characteristics of a third-party incurring (at least) some of the costs of another party without agreeing to incur that cost (Nicholson and Snyder, 2010). Negative externalities are often a by-product of economic activity e.g., neighbours who have noisy dogs, pollution from factories, consumption of cigarettes and the corresponding increase in demand on social healthcare systems to treat smoking-related illnesses.

In the case of HSF, whilst an unwanted structural fire in a building is not a building owner’s choice (i.e., excluding situations of arson for the purposes of a fraudulent insurance claim), the unwanted structural fire is a possible consequence of the economic activity of the person who builds on their land and near other property. Such economic activity, whilst it may cause loss for the building owner, may also cause losses to third parties via HSF, and thus HSF to third parties is a negative externality. Negative externalities can be treated via three mechanisms (Rosen and Gayer, 2014), namely:

1. **Regulation:** This entails third-party intervention by way of the Government to place restrictions on the extent one party can produce negative externalities, e.g., noise control laws, or in the case of HSF, restrictions on land use and/or restrictions on the quantity of UAs permitted.
2. **Pigouvian Taxes:** This entails a tax imposed on the party producing negative externalities. That is, by increasing the cost of production of the good that is causing negative externalities, producers have an incentive to find more efficient means of lowering the production of negative externalities. Also, the tax revenue collected often goes toward remedying the cost of the negative externality, e.g., tobacco excise taxes go towards the cost of treating smoking-related illnesses where the healthcare system is socialized. Pigouvian

taxes are founded on English Economist Arthur Pigou's treatment of externalities in the Economics of Welfare (Pigou, 1932).

3. **Coase Theorem:** 1991 Nobel Laureate Ronald Coase proposed that where property rights are defined and transactions costs are low, parties can negotiate a solution to address externalities (Coase, 1960). For example, if 'Party A' wishes to produce a good that results in a negative externality that affects 'Party B' and Party A has the property right to produce negative externalities, Party B can negotiate a price with Party A not to produce (or reduce in quantity) negative externalities. Alternatively, if Party A does not have the property right to produce a negative externality that, if produced, would affect Party B (that is, Party B has the property right to be free of negative externalities), Party A could negotiate a price with Party B for the right to produce negative externalities that affect Party A. Such negotiations are often referred to as Coasean bargaining, and their success is often largely dependent on the number of people who must be negotiated with (i.e., transaction costs must be low and usually work best when only two parties need to negotiate).

The next section discusses the viability of each approach to HSF as a negative externality.

4 Pigouvian Taxes, Regulations, and Coasean Bargaining

We begin with reviewing Pigouvian taxes as a solution to HSF externalities, as it will be shown that such taxes are not feasible, and therefore can be dismissed for the remainder of this paper. After Pigouvian taxes are shown to be unsuitable, the other two approaches to negative externalities, namely regulations and Coasean bargaining are discussed for the purposes of establishing their characteristics and viability.

4.1 Pigouvian Taxes

Pigouvian taxes are commonly used where the quantity of negative externalities can be determined along with their cost. One of the best examples is tobacco excise taxes. Pigouvian taxes on tobacco consumption works for the following reasons:

1. Taxes can be collected at the point of sale via an excise tax that is in proportion to the quantity of tobacco sold, with only those who consume tobacco paying the excise tax.
2. The harm that tobacco causes is statistically predictable, both in terms of probability of health-related complications and their severity, thus the cost on public health facilities to treat tobacco related harm can be determined *ex-ante* in proportion to the quantity of tobacco consumed.
3. The excise tax revenue collected can be directly channelled to public health facilities who bear most of the healthcare cost of treating tobacco-related illnesses, as some of the harm that tobacco smoking causes is socialized.

Thus, information costs such as identifying those whose activities will cost the public healthcare system at some time and knowing the extent of the harm by way of cost to the healthcare system, is not an obstacle to the effectiveness of a Pigouvian tax. Furthermore, transaction costs are not prohibitive, since a levy can be applied, e.g., tobacco at the point of sale.

A Pigouvian tax is not suitable for HSF. Firstly, it is not possible to know with any degree of certainty which buildings will have fires, as fire is caused by human activity, much of which is not easily observable e.g., leaving cooking unguarded, disposing of cigarettes inappropriately, electrical failures caused by defective wiring. Understanding what the probability of fire is, for any specific building does not come with any reasonable degree of certainty (insurance companies have this kind of information but it is proprietary and used to determine the price of insurance premiums).

Secondly, fire severity also comes with significant degrees of uncertainty. For example, the likelihood of HSF is dependent on factors such as distance to other property, presence or absence of fences that can block radiative heat, construction materials, fuel loads within buildings, fire brigade response times, effect of sprinkler systems, cost of damage to neighbouring property, etc.

Therefore, a Pigouvian taxation model to address HSF suffers from information costs such as identifying those activities which alter both the probability and severity of potential damage. Furthermore, any Pigouvian tax that is collected would, by necessity, need to be *ex-ante*, and if damage occurred that was greater than the tax collected, this opens the potential for litigation against the Government for failing to correctly estimate potential damage.

Concluding, Pigouvian taxes are not a suitable means of responding to the negative externalities of HSF.

4.2 Regulation

Regulation is currently the adopted method of addressing HSF. These regulations specify combinations of minimum levels of fire ratings to external vertical elements (walls and windows) and separation distances between a building and other buildings or other property. This methodology is easy to administer for the following reasons:

1. By specifying minimum levels of fire ratings to external vertical elements and/or separation distances, all building designs incorporate mitigation measures for HSF.
2. The producer of the negative externality incurs the cost of mitigation.

This regulation approach is seen in the NCC and the BR92, including the prescriptive compliance instruments for the NCC and the BR92. Starting with Australia's NCC, the prescriptive method for compliance with the NCC is the Deemed-to-Satisfy (DtS) which specifies fire ratings for various building elements, depending on the building's use and its distance from other property. And for New Zealand's compliance instruments: the Acceptable Solution and the Verification Method both prescribe combinations of vertical external fire rated areas applied to the building and separation distances.

The issue with this regulation approach, whether it be via prescriptive or performance pathway, is it assumes a fire will occur, and the party that produces the negative externality must pay for HSF reduction measures that can only be placed on their property. But it may be that the most efficient solution is that the building owner's best option is to pay for HSF mitigation measures to be provided on the neighbour's property together with some quantity of remuneration that both parties agree to. Such solutions are not possible under the NCC, BR92, nor any prescriptive compliant documents such as the DtS or Acceptable Solution. It is only via Coasean bargaining that the potential for solutions that allow the building owner to pay for HSF mitigation measures to be provided on their neighbouring property, which is explored in the next subsection.

4.3 Coasean Bargaining

In 1960 Ronald Coase published *The Problem of Social Cost* (Coase, 1960), in which he proposed that under certain circumstances, namely where property rights are defined and transaction costs are low, Pigouvian taxes or regulations were not necessary to remedy negative externalities and that a solution could be found between parties without the need for government intervention. Coase made a notable point about the treatment of negative externalities via Pigouvian taxes or regulations, namely:

The traditional approach has tended to obscure the nature of the choice that has to be made. The question is commonly thought of as one in which A inflicts harm on B and what has to be decided is: how should we restrain A? But this is wrong. We are dealing with a problem of a reciprocal nature. To avoid the harm to B would inflict harm on A. The real question that has to be decided is: should A be allowed to harm B or should B be allowed to harm A? The problem is to avoid the more serious harm.

Neither Pigouvian taxes nor regulations consider whether the party causing loss via negative externalities via HSF is in a better position to mitigate against it or the party receiving the negative externality is. And due to government intervention by way of current regulations, parties cannot apply Coasean bargaining to resolve HSF externalities.

In the case of HSF, property rights are defined by legal boundaries. Where there is a building on each side of a legal boundary ('Building A' and 'Building B') and, say, Building A capable of causing HSF to Building B, under Coasean bargaining conditions the owner of Building A can either pay to design their building to have features which mitigate the effects of HSF (e.g., reduced UAs, increased distances to the relevant boundary, or combinations thereof), or negotiate a price with the owner of Building B ('Owner B'), whereby the price negotiated can be used to either mitigate the effects of HSF from building A (e.g., external radiative shading instruments such as a masonry wall), or pay an increased insurance premium. The point is that Coasean bargaining does not restrict building owners to regulation-based solutions, and that other solutions can be explored without government intervention which may be more efficient, taking into consideration the full range of market options available, i.e., turn the tort-based adversarial issue of HSF into a cooperative contractual issue.

5 Discussion

Examples of Coasean bargaining to negative externalities are found in statutory laws such as New Zealand's Resource Management Act 1991 (RMA91). An example can be found in s 87BA of the RMA91:

87BA Boundary activities approved by neighbours on infringed boundaries are permitted activities

(1) A boundary activity is a permitted activity if—

(a) the person proposing to undertake the activity provides to the consent authority—

(i) a description of the activity; and

(ii) a plan (drawn to scale) of the site at which the activity is to occur, showing the height, shape, and location on the site of the proposed activity; and

(iii) the full name and address of each owner of the site; and

(iv) the full name and address of each owner of an allotment with an infringed boundary; and

(b) each owner of an allotment with an infringed boundary—
(i) gives written approval for the activity; and
(ii) signs the plan referred to in paragraph (a)(ii); and
(c) the consent authority notifies the person proposing to undertake the activity that the activity is a permitted activity.

Section 87BA of the RMA91 allows the right to negotiate (and agree) with neighbours on boundary activities such as buildings built closer to the boundary than local regulations permit (e.g., the neighbour agreeing to reduced sunlight caused by a building built closer than permitted under local laws). Whether some type of remuneration was exchanged between parties is not a relevant factor in terms of what the consent authority must consider, and in this instance Coasean bargaining is permitted by law. And in the case of, say, the reduction in sunlight from a proposed development that affects another, Coasean bargaining may cover the cost of any loss in value of the neighbouring property, and/or may provide for the cost of substitute solutions such as a skylight, or relocation of a room. Solutions to an economic problem of this nature could not be imposed by the legislature since to do so would result in an extension of eminent domain (where Government takes private property rights without the owner's consent with compensation), which comes with the consequences of the neighbour having to either accept the government's terms and conditions, or challenge them via the courts.

6 Conclusion and Further Research

This paper has argued how Coasean bargaining can substantially widen the choices available to address the negative externality characteristics of HSF and without the need to rely on prescriptive instruments such as the DtS or Acceptable Solutions, the latter of which can come at the cost of restrictive land use and/or restrictive building design. The authors have formally proven in their draft paper via ordinal mathematical methods that Coasean bargaining can be a viable and more efficient solution (and are seeking to have the work published); that is, the most efficient solution is found to mitigate against the effects of HSF can be via voluntary means, with the beneficial effect of increasing land utilization (wherever feasible). This latter potential increase in land utilization can assist in reducing the shortage of supply of affordable housing across Australia and New Zealand without any need to change land zoning rules – a leading cause of unaffordable housing.

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Contractor Bankruptcies in the Australian Construction Industry: Causes and Impacts

Matt Stevens[1*] and Awais Piracha[1]

[1]Western Sydney University, Locked Bag 1797 Penrith NSW 2751, AUSTRALIA

Matt.Stevens@westernsydney.edu.au; A.Piracha@westernsydney.edu.au
* Corresponding author

Abstract
The construction industry has one of the highest rates of organisational bankruptcy in Australia. Recently, several building firms have sought legal protection from creditors. This paper examines the impacts of construction company failures, including the economic and societal costs. Several studies conclude that entrepreneurs who suffer from business liquidation have an elevated rate of personal problems than the general population. Additionally, these bankruptcies have significant effects on their families and communities. In the long term, a robust construction industry is required to meet the construction needs of rapid urbanisation and climate-change-related repair and expand the built environment. A better understanding of construction organisations' strategic and operational dynamics should lead to effective initiatives and create a less arbitrary and capricious system that currently causes unnecessary contractor insolvencies. This paper argues that Australia has not paid enough attention to the problem of declining construction capacity despite the predicted fast-growing demand for construction from rapid urbanisation and climate change.

Keywords:
Business default, Company liquidation, Corporate foreclosure, Project failure, Socio-economic harm

1 Introduction

Contractor insolvency is when a contractor cannot repay its creditors or is unable to pay its employees their salaries and wages. An increasing number of construction contractor bankruptcies can deprive a nation's economy of the vitality needed to be productive and ready for quick provision of shelter repair in emergencies that are becoming more frequent due to climate change. Additionally, there is a social cost of individual and community disruption. Bankruptcies are adverse social and personal events that can cause unwanted outcomes.

This paper discusses the causes and impacts of construction contractor bankruptcy in Australia. It employs secondary material for its exploration. It explains the overall construction industry dynamics, the current Australian construction industry situation, the growing need for more construction in Australia, impacts of bankruptcies.

2 Methodology

This paper uses narrative review, a qualitative method that requires collecting and interpreting studies on a theme or topic and summarising evidence. This paper's literature search was for two key research questions: (1) what are the contributing factors to the involuntary exit of construction contracting firms, and (2) what are the impacts of those exits? SCOPUS was used for conducting this search. In addition, the references of selected articles were skimmed to find more papers relevant to this review.

Articles related to contractor bankruptcy's social, personal and economic impacts were searched for and reviewed using a set of keywords. This article's literature collection and filtering technique is a comprehensive, top-down strategy that gathers articles using broad phrases.

A narrative review does not have a strict protocol to be followed. This approach can address one or more questions with a broad scope. The efficacy of narrative reviews is irreplaceable in tracking the development of a principle or a concept. The preferred structure is the Introduction, Methods, Results, and Discussion (Green et al. 2006)

2.1 Bankruptcy and Its Effects

Rawls (1971) suggested that the social contract that governments and citizens agree on protects all, regardless of their majority or minority status. Keeping enterprises viable, even when run by a minority, results in tremendous economic and societal benefits (Beraho 2008). However, scepticism in society about enterprises remains because of the provision of bankruptcy as a strategy to limit the liability resulting from court-imposed penalties (Kliestik 2018). It is important to note that bankruptcy systems help the economy by protecting businesses and individuals from excessive suffering (Beraho 2008).

For-profit organisational failures have a ricochet effect throughout the entire value chain and have adverse economic impacts, specifically higher unemployment rates (Quach et al., 2021). Business failures significantly affect employment and entrepreneurial mobility (Brüderl et al., 1992; Shepherd et al., 2014). Many intangible costs are related to bankruptcy, including difficulty obtaining credit for future business endeavours and emotional strain (Miller 2015). Moreover, involuntary exits arising from a business bankruptcy may significantly deteriorate small business owners' physical and emotional states (Nikolova et al., 2020). Under normal circumstances, they are already highly susceptible to mental health issues, e.g., 30% of entrepreneurs experience depression compared to only 16.6% of the general population (Orendorff 2018).

Bankruptcies often result in significant social impacts. Social impacts are "the net effect of an activity on a community and the wellbeing of individuals and families." Negative social impacts result from any intervention or event that adversely impacts individuals' or community's wellbeing. The trigger of negative social impacts is often unemployment and financial losses. In the case of business failures or bankruptcies, economic losses are accompanied by a loss of self-worth and reputation. In addition, bankruptcies can manifest in poor physical or mental health, substance abuse, gambling addiction, family violence and breakdown, and even suicides (Ramsay, 2001).

The Australian Financial Security Authority provides a long list of consequences of a bankruptcy for the company owners. Some of them include loss of control over financial matters, restrictions on travel overseas, and permanent listing of the name(s) National Personal Insolvency Index (NPII). Such limits can result in significant negative social impacts for the company owners.

Gururaj et. al (2004) discovered through their research in India a sevenfold increased risk of suicide among people who had become bankrupt. Vanclay (2002) reported high levels of debt problems among people who self-harm by exploring several cross-sectional studies. Weyerer and Wiedenmann (1995) investigated the causes of suicides in Germany over a 110-year period. They discovered a strong association between unemployment and the frequency of bankruptcy and suicide. It was reported in the Indian parliament that more than 16,000 people committed suicide due to bankruptcy or indebtedness in India between 2018 and 20204. Philips et al.

(2020) discovered that in the USA, there is a higher level of susceptibility to suicide under bankruptcy conditions.

A study by Addo (2017) explored the effects of consumer bankruptcy on health. Results showed a negative impact of self-reported bankruptcy on physical and mental health. The author concluded that poor health is an unintended consequence of seeking financial relief from bankruptcy. Grant et al. (2010) found a strong association between bankruptcy and pathological gambling.

2.2 Construction Industry Dynamics

Robust construction and repair services of residential and commercial buildings are essential for a vibrant economy and good quality of life. Construction is one of the world's most essential and sophisticated economic sectors. The Built Environment is crucial to improving quality of life (QOL) (Gregory 2009). With improved QOL comes higher levels of prosperity and increased chances of sustainability adoption (U.N. Habitat 2012).

Constructing the built environment involves many complicated tasks that must be carried out with extreme care while economising on costs. Many functions in a construction project are very high cost. Even a minor mistake can cause significant financial liabilities. Therefore, a steady and careful management process is required in this area (Lu et al. 2013).

Construction organisations are more vulnerable to bankruptcy than other economic sectors because of project variability and tight completion deadlines (Cheng et al. 2021). Gerber and Ong (2013) note that price competitiveness is accentuated among construction tenderers by owners. They often view price as the most decisive criterion for awarding contracts and sometimes encourage many contractors to tender for a project, particularly in the case of government projects, due to the accountability for public funds. Sometimes, contractors try to win a tender by submitting an abnormally low bid, notwithstanding any inherent complexities the project may face. As a result, Australian building and construction firms have an increased probability of adverse financial effects either from insolvency for themselves or insolvency further up the contracting hierarchy (ETUA 2015). Contributing factors include firms sometimes underbidding on one project to obtain cash flow to meet payments on another project (Creighton, Handford and Mclure, 1995).

The Australian Tax Office's (ATO) latest filings report that 78% of Business Owning Households (BHO) hold some form of debt and pay its interest and principal monthly. Additionally, 54% of Australian companies declared a loss and thus paid no taxes. Further demonstrating risk, a bankruptcy study sponsored by Australia's Construction Forestry Maritime Mining Energy Union (CFMEU 2014) concluded that the construction industry outscored all other industries for each deficiency category and whose average default was more than $500,000.

Small businesses account for 35% of Australia's gross domestic product (GDP) and employ 44% of the country's workforce (The Australian Small Business and Family Enterprise Ombudsman 2019). In addition, 98.5% of construction contracting organisations employ 20 persons or less and fall under the category of small business (ABS 2021).

A survey conducted by Palmer-Derrien (2018) revealed that 55% of Australians working in small businesses fall into the "at-risk" category (compared to 37% of the general population). The survey further revealed that 9.5% fall in the "severe" risk and 10.1% at the "extremely severe" risk categories. Data submitted by the Australian Securities and Investment

Commission (ASIC) to the Senate Economic References Committee (SERC) (2015) shows that over the period 2009-10 to 2013-14, the construction industry accounted for 23% of all external administrations in Australia. These include sole traders, of which construction's workforce contains 37% contract employees (the highest of all sectors). The next highest percentage sector of insolvencies was retail trade at 10%.

2.3 Australia Construction Industry Situation

Just before Christmas 2021, the construction contracting firm BA Murphy was liquidated, leaving 50 unfinished building projects, while bankrupted Privum had 831 incomplete contracts around Australia. In addition, there were other notable, voluntary bankruptcies in the last two years, such as ABD, Probuild, Tasmanian Construction, Blint, Besse and Caydon, and others. Each of these saddled creditors with at least $1 million. This has resulted in substantial financial losses for sub-contractors and loss of employment for thousands of employees. This has also caused economic losses for individuals and families investing in building or buying homes. This calamity has been widely reported in the Australian print and broadcast media. Currently, the outlook is bleak, predicting a higher rate of bankruptcies. For example, Bleby of the Australian Financial Review (AFR) warns, "the latest data from regulator ASIC shows – construction industry insolvencies jumped nearly 40 per cent in the three months to December (2021) compared to the September quarter – and were up almost 30 per cent on a year earlier".

Overall, the exit rate for Australian companies was 12.0% in 2021, while the construction industry recorded a 12.8% rate. However, it is noteworthy that construction firms are 17.1% of all companies, representing the largest sector of the economy (ABS 2021). Specifically, the industry is burdened by around $3 billion in unpaid debts annually. In addition, the sector was consistently ranked as having one of the highest rates of insolvencies in Australia (EUTA 2015).

Insolvency is seen as endemic in the Australian construction industry. The scale of the problem has reached such proportions that both the NSW Parliament and the Senate have recently commissioned inquiries into construction insolvency (Coggins et al. 2016). The Australian construction organisation exit rate, pre-COVID averaged from 2016 to 2020, was approximately 14.0% versus 11.1% for manufacturing (ABS 2021). The causes of bankruptcy are numerous, but deficiencies in critical operational practices such as payment, procurement and costing, which can add unnecessary financial stress or unfair outcomes, should be examined. Patel et al. (2022) assert, "Every insolvency is a unique story of financial wrecking, but a rightful and ethical approach would either avoid the disaster or lessen the harm for the project and all the stakeholders".

Table 1. Rankings of Five Highest Contributors to Construction Company Insolvency 2009-2014 (ETUA 2015)

Five Highest Contributors by Rank	**Percentage of 25,701 Cases**
1 - Inadequate cash flow or high cash use	17.1%
2 - Poor strategic management of business	17.0%
3 - Poor financial control, including lack of records	12.7%
4 - Trading losses	12.1%
5 - Poor economic conditions	11.9%
Total	**70.8%**

The Final Report of the 2012 Independent Inquiry into Construction Industry Insolvency in New South Wales (the Collins Inquiry) mirrored ATO's statistics. However, category labels differed, and general causes but their proportion were the same.

Unfortunately, Australia's Senate Economics References Committee (SERC) has offered little in the way of recommendations, probably because it was concerned about being perceived to make a limited incursion into free market economics (Coggins et al. 2016).

The Electrical Trade Union of Australia (ETUA) Report (2015) states, "While market forces play a part, there are other factors at play—the structure of the commercial construction sector, serious imbalances of power in contractual relationships, harsh, oppressive and unconscionable conduct, unlawful and criminal conduct and a growing culture of sharp business practices" Add to this the new causes that are primarily COVID-related such as disrupted supply chains, increased costs of shipping, and skilled labour shortages (Biswas 2021).

The Australia Construction industry suffers from the highest number of business bankruptcies and the most follow-on personal insolvencies. For the 2016-2017 financial year, the most common occupational category for debtors entering business-related insolvencies was construction trades workers (O'Brien et al. 2018). Murray and Harris (2016) found that business-related personal bankruptcies vary within different sectors of the economy, with construction workers representing the highest number of debtors entering business-related personal insolvency. Sadly, this group was more likely than others in the personal bankruptcy sample to have spouses (O'Brien et al. 2018).

2.4 Scoping Review

This research and a review of academic works on construction company insolvency utilised a search of specific keywords, titles or abstracts of documents was conducted. The following Boolean search string was used in surveying the SCOPUS database:

(Construction) AND (bankruptcy OR liquidation) AND (*contractor OR corporation) AND (effect* OR precursor OR caus* OR cost)

Figure 1. Worldwide search results using targeted keywords

The results showed 90 papers from these keywords. See Figure 1. Research activity did not increase in this general area over time.

Table 2. Analysis of 90 Articles from CIMO Search Strategy Concerning Construction Bankruptcy Articles

Characteristic of Paper	**Abstract, keyword or title**	**Comments**
Year	2018, 2020, & 2017 were the top three years for the number of papers	Ten papers were published in 2018, eight in 2020, and eight in 2017. There has not been a noticeable rise in concern in construction insolvency.
Origin by Country	Australia is third amoung western countries	The United States published the most with 24 papers, the U.K. was second with 9, and Australia was third with 5.
Cost*	45 contain "cost*"	Under-bidding or tendering error was the most significant reason for bankruptcy, so cost is a logical link.
Qualif*	6 contain "qualif*"	Qualifying or qualification of construction firms by project owners is not a top interest in bankruptcy research.
Schedul*	14 contain "schedul*"	Paper cited delays in achieving milestones and completing the project leads to financial penalties as a problematic area.
Quality	18 contain "quality"	The project owner's lack of acceptance of work is the second highest cited factor.

Keyword search analysis of the original 90 papers from 2012 to 2022 shows ten articles published in 2018, eight in 2020, and eight in 2017. Categorising by nations, the United States generated 24 papers, the U.K. was second with 9, and Australia was third with 5. For the search words, the cost had the most research interest with 45 articles. An under-bidding or tendering error was the most significant reason for bankruptcy, and the search word cost reflected that. The project owner's lack of acceptance of work or quality is the second highest cited factor. Finally, papers cited delays or late project completion that led to financial penalties as a problematic area. Qualification of construction firms by project owners is a lesser interest in bankruptcy research.

2.5 Increased Construction Needs

Urbanisation is an important symbol of human society and economic development and is inevitable for social and economic development (Gong 2022). The 21st is the century of urbanisation. Along with this phenomenon, the world's population is the most significant increase in this century (White et al. 2010). Lifestyles are also changing in the 21st century. As a result, people demand larger dwellings and other facilities. The three phenomena together point to a very high need for construction.

The frequency, duration, and severity of heat waves have increased recently due to changes in climatic conditions and Urban Heat Island effect. Australia is highly vulnerable to this hazard. A growing number of studies are being conducted in Australia related to the heatwave phenomena (Pörtner et al. 2022). Dealing with heat would require upgrading the current buildings. That would further increase demand for construction.

Due to climate change, extreme events such as wildfires, storms and floods will increase the destruction of the built environment. Eingrüber and Korres (2022) assert that the speed and intensity of flooding will accelerate with climate change. There is a high probability of increased and erratic rainfalls accompanied by higher winds in many parts of the world (Moradkhani et al. 2010). Climatic causes play a prominent role in the deterioration of building fabric, and climate change is projected to accelerate the built environment deterioration rate (Johns and Fedeski 2001). The International Panel on Climate Change (IPCC) asserts that costs for maintenance and reconstruction of urban infrastructure, including building, transportation, and energy, will increase with global warming (Pörtner et al. 2022)

3 Discussion

Since late 2021, numerous Australian construction companies have collapsed. This is a continuation of financial problems in a critical industry. The current trend has resulted in even larger financial losses for sub-contractors and loss of employment for thousands. The follow-on effect is financial losses for individuals and families investing in building or remodelling homes. This calamity has been widely reported in the Australian print and broadcast media.

Australia needs need a robust and organised construction industry in Australia for many reasons. Insolvency disrupts construction projects and the economy. Many workers and managers have their economic, professional and personal lives impacted. These insolvencies waste time, money and opportunity that can never be recovered. This paper asserts a significant need to improve outcomes for individuals, companies, governments, and society - now and in the future.

A systematic change that leads to less variability will reduce arbitrary bankruptcies. Some may be found information technology such as BIM and Blockchain to minimise underbidding and payment problems. If successful, more predictability facilitates more confidence. Unfortunately, the current chaotic system appears to lead to some unnecessary and preventable defaults. This situation should be countered for everyone, including the ethical contractor and the non-expert citizen.

There is no "creative destruction" (Schumpeter 1943) in the demise of construction firms. The industry or society does not benefit from contractor bankruptcies. Developers and governments are not helped by liquidating their builders or the subcontractors working for them. Suppliers are adversely affected by unpaid invoices. Therefore, significant interest should be in initiatives that can guide the industry to more consistent outcomes.

Most construction contractors must use personal guarantees for their credit lines with partners, such as banks and material suppliers. This is due to the construction industry's risk profile. So, once insolvency occurs, further financial damage to the firm's owner(s) is shown in the data shared. The project margins of average construction contracting firms are single-digit percentages. Cash flow is uncertain, and one poorly planned and administered project will affect others since one organisation is the nexus of a multi-project portfolio.

Insurance is an option in the form of a surety bond, but it appears unavailable in Australia. These bonds guarantee a project owner that the building or infrastructure will be finished without additional cost. The process is well practised in the United States and includes a review of the viability of each project ' 'stakeholder's capacity and capability, i.e., subcontractor, supplier and main contractor.

Climate change will produce more natural disasters and the deterioration of living spaces in the longer term. The construction industry is an essential stopgap to this high-probability future trend. With rapid urbanisation, a stable or increasing number of contracting firms will keep the industry's capacity strong and its prices generally steady.

4 Conclusion and Summary

The construction industry in Australia is facing severe capacity disruption due to COVID and its follow-on effects, such as inflation and supply chain difficulties. These have adverse influences inside and outside of the industry. Therefore, we assert that government, academia, and private company leaders should examine approaches to reduce uncertainty and unfairness in construction processes for a healthier and more predictable industry. As a result, less risk will manifest in a reduced financial contingency in tenders, thus lower prices.

The solution lies in two areas: government-led reform and information technology. Specifically, a) Payment assurance and standardised contracts and Blockchain may rebalance fairness to all stakeholders; b) BIM can standardise quantity takeoff counts as a unit-pricing method to minimise underbidding errors, especially in the residential and commercial building sector.

Construction contracting's poor margins, unpredictable cash flow, and disproportionately high-risk profile make it highly vulnerable. Those risks come from inside and outside the industry. Some are controllable, while others are not. Whatever the cause and its nature, bankruptcy has pernicious effects. Everyone is affected directly or indirectly. Given the size and importance of the industry, more examination should take place to propose improvements in the operations of the industry.

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A Tale of Two Projects

Robert Mulligan[1*], Regan Potangaroa[1*] and Suzanne Wilkinson[1*]

[1]School of Built Environment, Massey University,
Albany, Auckland 0632, NEW ZEALAND

r.mulligan@massey.ac.nz; r.potangaroa@massey.ac.nz; s.wilkinson@massey.ac.nz
* Corresponding author

Abstract:
The New Zealand construction sector faces a challenge delivering on the proposed pipeline of work emerging from 2020 onwards, a situation exacerbated by post-Covid-19 recovery funding initiatives. A smart system is needed to enable shared understanding of horizontal and vertical infrastructure planning and delivery, and the sector's ability to deliver. It focuses on resilience, particularly with regard to systemic shocks and stresses on the construction sector arising from Covid. Two case study projects, designed as complex building typologies, represent political aspirations for achieving sustainability goals and industrial revolution. New Dunedin Hospital, estimated to cost $1.4 billion, is New Zealand's largest healthcare facility and first digital hospital. The Living Pā project, estimated to cost $75 million, redevelops the marae precinct and Te Tumu Herenga Waka wharenui, at Victoria University of Wellington. The vision is to transform how to realise cultural values, drawing together Mātauranga Māori and sustainability in accord with Living Building Challenge Principles. This paper considers the economic focus (Covid recovery grants and their use); social focus (how Covid has affected the workforce, immigration, resources and changes to work patterns): organizational (how Covid has affected organizations/ changes made): supply chain (as above, plus reliance on alternative products): political (legislation changes and their impact, links to Government policies, guidelines and how they have been used): technological (how Covid has changed technological uses in construction). And will address the issues and how the construction sector in New Zealand responded. Research is limited to an initial literature review and qualitative data from interviews.

Keywords:
CanConstructNZ, Capacity, Capability, Infrastructural, Pipeline, Resilience

1 Introduction

The New Zealand construction sector faces a challenge delivering on the proposed pipeline of work emerging from 2020 onwards, a situation exacerbated by post-Covid-19 recovery funding initiatives.

CanConstructNZ is a research project that will deliver a smart system to enable shared understanding of horizontal and vertical infrastructure planning and delivery, and the sector's ability to deliver. Research for this paper contributes to the project. Case studies look for resiliency in the building construction sector, and gaps between capability and capacity. Infrastructure spending has been increased to catch up with under-expenditure and deferred maintenance. However, the sector is under significant stress. Shocks and stresses impacting on the economy were heighted during the Covid-19 (C19) pandemic response from 2020 when borders were closed, and the nation was locked down. Auckland, a major industrial city, was locked down for an extended period that adversely affected manufacturing and supply chains throughout the nation. NZ was isolated and supply chains, both domestic and international, were severely disrupted.

These stresses added to prevalent problems of Boom-and-Bust cycles in the NZ economy. 'Shovel ready' projects were soon overtaken by a booming residential market and new infrastructure projects coming down the pipeline. Investment increased in the residential sector. Supply outstripped by demand was made worse by reduced factory production and international shipping disruption. Shortage of materials and skilled labour, plus increased transport expenses, led to inflation of building costs.

Two case studies represent significant infrastructure projects having similar challenges of design and construction during the pandemic. Both projects are complex building typologies designed for resilience, sustainability and regeneration. Technologically the first of their kind in NZ, one is an innovative educational facility, designed to Living Building Challenge guidelines. The other is a Digital Hospital, that will be the largest healthcare facility in NZ. Both, in similarity and in contrast, they share some attributes, yet are very different in others. Designed, documented, and tendered during the shocks and stresses of the C19 pandemic response, they both represent political aspirations for the implementation of sustainability goals (UN, 2015) and embracing of the fourth industrial revolution (Schwab, 2017). Closely connected with university campuses, their cultural inclusiveness and partnership are of particular interest. Design collaboration by stakeholders throughout both projects, draws together Mātauranga Māori with building science, for resilience and sustainability (SLH, n.d)

The Living Pā Case Study

The Living Pā (TLP) is an educational facility designed for urban sustainability and aims to be one of the most regenerative buildings in the world. Estimated to cost $45 million, construction has commenced. It redevelops the marae precinct and Te Tumu Herenga Waka wharenui, on the Victoria University of Wellington campus in the Capital City. The vision is to transform how we realise cultural values, aligning Mātauranga Māori and sustainability philosophies in accord with Living Building Challenge principles. A 'purpose-built living lab' and 'incubator for innovation' it will be a place for multiple communities and disciplines to discuss together how to build a more equitable, fair, and sustainable society (VUW, n.d).

Figure 1. The Living Pā. Source: Stantial Studio, Victoria University of Wellington web page https://www.wgtn.ac.nz/__data/assets/pdf_file/0012/1876944/living-pa-brochure.pdf

The New Dunedin Hospital Case Study

The New Dunedin Hospital (NDH) will be New Zealand's largest healthcare facility and the first Digital Hospital. Estimated to cost $1.4 billion, construction has commenced. It is located within the CBD adjacent University of Otago campus. The Medical School is integrated with the current hospital. Dunedin, NZ's first city, is now considered a main regional centre, however this new facility will also serve the whole expansive southern region of Otago and Southland, formerly administered by the Southern District Health Board.

Given the size and complexity of the NDH, this paper focuses mainly on the first case study, TLP. Research in more detail for the second and larger case study, the NDH, is ongoing.

Figure 2. The New Dunedin Hospital. Source: MoH web page https://www.newdunedinhospital.nz/

2 Literature Review

Infrastructure

Review of the literature started with various reports, published in both NZ and Australia, that concerned infrastructure and development issues regionally over the past decade. New organisations were established during this period, including Infrastructure New Zealand, and Infrastructure Australia. Various research papers were commissioned, including those for The Treasury. Some papers predated the Covid-19 (C19) pandemic. "*Covid-19 combined with historic underinvestment and record population growth has created a perfect storm for New Zealand infrastructure. This (Priorities for 2020-2023) is what the Government needs to do to address long-standing issues and achieve public outcomes* (INZ, 2020)."

CanConstructNZ Research Project

A partnership between NZ universities and the Building Research Association of NZ (BRANZ), under the banner of CanConstructNZ, will deliver a smart system that enables shared understanding of horizontal and vertical infrastructure planning and delivery, and the sector's ability to deliver. It focuses on resilience, particularly with regard to systemic shocks and stresses on the construction sector arising from C19. This is envisaged to be "… *a system that matches construction needs and the sector's ability to deliver, (that) should help the industry avoid old problems of underperformance at a time when a major pipeline of work kicks off* (Sutrisna et al., 2020)."

Readings then focussed on key web sites, reports and various news updates for the two case studies, TLP and NDH, and the building sector that was becoming increasingly under stress.

Emerging Technologies

Early in the literature review, reports specific to emerging technologies applied to these complex building typologies were accessed. They included Living Building Challenge, considered to be "… *the built environment's most rigorous performance standard. The Living Building Challenge is a certification programme intended to push the marketplace beyond current conceptions of a green building and to transform how we think about our built environment.*" Technologies for seismic design of the highest classification Importance Level 4 (IL4) buildings, and Digital Hospitals (NDH being the first in NZ) were also researched.

Design of these complex building typologies includes emerging technologies of the 'Fourth Industrial Revolution,' as promoted by the World Economic Forum. It was noted that 25 technology trends are transforming 21st century businesses (Marr, 2020). And that UN Agenda 2030 and Sustainability Development Goals balance the three dimensions of sustainable development: Economic, Social and Environmental (UN, 2015).

Changing Design Standards

Building Code Regulations for the NZ construction industry were already changing significantly in response to natural disasters, and regulating compliance with new design standards and guidelines. The C19 pandemic and new legislation added to shocks and stresses on the sector. Natural disasters included the Canterbury Earthquake Sequence 2010-2011, and Kaikoura Earthquake 2016. Awareness by the construction industry was heightened by these events and also predictions for AF8, Alpine Fault Magnitude 8 Hazard Scenario (AF8, 2016).

Design for resilience of critical post-disaster infrastructure such as the NDH, is at Importance Level 4 (IL4), and TLP is at IL3. Clause A3 of the Building Code defines the significance of a building by its importance level (IL), which is related to the consequences of failure. Five levels of importance relate to the importance of the building to society. Levels that apply, are: *"Level 3: Structures that may contain crowds, have contents of high value to the community or pose a risk to large numbers of people in close proximity, such as conference centres, stadiums and airport terminals."*

"Level 4: Buildings that must be operational immediately after an earthquake or other disastrous event, such as emergency shelters and hospital operating theatres, triage centres and other critical post-disaster infrastructure." (MBIE, 2022)

Resilience of the building industry as a whole, includes appropriate design standards, means of procurement, and risk management of supply chains for materials and plant. Supply chain disruptions require closer consideration during design, of alternative materials and sources, and options for local manufacture and prefabrication, favouring modular building elements.

The Market

'Constraint' is a frequently used term in the literature. The market is always the major constraint for the entire supply chain, from provision of raw materials to the end user (Schragenheim et al., 2000). Markets and constraints need to be considered early in design.

Interviews found that serious skilled labour shortages included Engineers, and Architects who are competent with BIM. Production and supply chains of materials are constrained at all levels. The labour market is constraining businesses according to a recent study. The economy and labour market was stronger than expected at the beginning of the pandemic. *"Extraordinary monetary and fiscal stimulus, especially policies like the wage subsidy, have prevented mass layoffs and business closures during lockdowns, and promoted strong economic and employment growth outside of lockdowns."* When employment is at a record high, it is harder to hire people. *"There is record demand for goods and services, but they can't be delivered because of a lack of labour and materials."* And businesses should plan for intensifying labour shortages through 2022 and 2023 (Sense, 2022).

Supply Chain Vulnerability

Global supply chains are at risk of further collapse (FT, 2022). And supply disruption issues for the NZ construction sector are predicted long term. "*Global supply chains issues, major demand for construction work and navigating NZ's alert level boundaries are creating a 'perfect storm' for the construction sector, research shows. Disruptions have a particularly profound impact for remote island nations like New Zealand* (Sachdeva, S. 2021)."

These issues were forecast. Research by the Construction Sector Accord, carried out in May and June 2021 "… found that 53 percent of construction businesses flagged shortages of materials and supplies as affecting their ability to deliver on time and to budget. Shortages of experienced and skilled staff were mentioned by 34 percent, while 13 percent identified increases in the price of materials and supplies (Sachdeva, 2021)." Furthermore, "A boom in housing consents is adding to the pressure on construction businesses caused by supply chain problems (Sachdeva, S., 2021)." Notwithstanding, NZ and Singapore were joined by other nations (Australia, Brunei, Canada, Chile, and Myanmar) in committing to keep supply and trade links open (Beehive, 2022).

Predictions of a worsening of the C19 pandemic on the building system were made by MBIE (Ipsos, 2021). From a survey of End-Users, three aspects anticipated to worsen over the next 2 years were: (1) Ability to get preferred products when required; (2) Overall cost of products; and (3) Availability of suitable tradespeople (Ipsos, 2021, p.27). These have happened and highlight the need for alternative products manufactured locally in order to reduce cost and procurement delays, also availability of suitable tradespeople that suggests more training is necessary. Given the scale and complexity of the two case study projects, time is limited.

Construction sector performance

Lessons learned and opportunities to be identified require performance measurement for the construction sector (Brown et al., 2020). Improving local manufacturing and economic development regionally, with more resilient supply chains nationally is critical for survival.

3 Research Methodology

Research is at an early stage, limited mainly to secondary sources and a small sample of interviews of project managers and architects. The methodology is a mixed-methods study of resiliency in the NZ building construction sector and looks at the gap between capability and capacity. Constraints and supply chain disruption caused by shocks and stresses, were identified.

The two case studies are infrastructural building projects with complex typologies. Their impact on regional and national economies highlight issues for further research. Currently in early stages of construction, one is a special educational facility, smaller but unique in the region. The much larger and more complex 'Digital Hospital' project will take longer to research and analyse. Comparable projects in NZ and Australia, identified in a Cabinet paper and Business Case, and web sites of lead consultants and contractors, will be researched.

Discussions with the project teams commenced with interviews using questionnaires comprising a bank of 53 questions. These were focused under 8 headings:

(1) Economic (Covid recovery grants and their use).

(2) Social (how Covid has affected the workforce, immigration, resources, and changes to work patterns).
(3) Organizational (how Covid has affected organizations/ changes made).
(4) Supply chain (as above, plus reliance on alternative products etc).
(5) Political (legislation changes and their impact, links to Government policies, guidelines and how they have been used).
(6) Technological (how Covid has changed technological uses in construction).
(7) Sector.
(8) Organisation.

Mainly qualitative data came from these interviews. Quantitative data would be collected from closer analysis of an unredacted Cabinet paper with cost estimates, subject to their availability. Due to commercial sensitivity, real project estimates and procurement costs remain confidential. The big questions were *'How have companies managed,'* and *'Are there more effective ways to address and manage these challenges?'* Business Management theories that assist companies and design practices will be considered in ongoing research.

4 Findings and Discussion

The two projects selected as case studies, are of complex building typologies, They require more detailed research when key persons and documents become available. Findings from initial research are discussed as follows, limited mainly to the Living Pā (TLP) case study. Given the size and complexity of the second case study, research with more detail is ongoing for the New Dunedin Hospital (NDH).

The Living Pā Te Herenga Waka—Victoria University of Wellington

The Living Pā (TLP) project redevelops the marae precinct and Te Tumu Herenga Waka wharenui, at Victoria University of Wellington (VUW). The vision is *"…to transform how we realise our cultural values, drawing together Mātauranga Māori and sustainability in accord with Living Building Challenge (LBC) Principles*." Estimated to cost $45 million, construction has commenced (VUW, 2021).

TLP is an ambitious new project for VUW, being constructed beside the existing Te Herenga Waka Marae. This will be the University's first LBC building with a focus on wellbeing and sustainability to match the University's Sustainable Growth initiative. However, indications are that achievement of LBC accreditation may not be financially feasible in the short term. Research has included online participation in various huis with the He Pā Mataora project team, associated with The Living Pā Te Herenga Waka led by an Associate Professor & Assistant Vice-Chancellor (Mātauranga Māori) VUW.

The Living Pā Interviews

The Project Architect (PA) and Project Manager (PM) were interviewed. The PM team included two Co-PMs, the Senior Advisor, Office of the Deputy Vice Chancellor (Māori) VUW who coordinated the interviews, and the Senior PM Campus Development of Property Services VUW. Interviews commenced when the team was under extreme pressure with critical path deadlines during C19 lockdown. Allowing for more reflection, the Senior PM and PA provided written responses to the Questionnaire, summarised as follows.

(1) **Economic focus (Covid recovery grants and their use)**: When asked how they managed economic uncertainty during C19 they just "kept everything running." There was no discussion about recovery grants and their use. They remained very busy. However, and of growing concern, C19 had a significant impact on the project budget that increased 28% from $35m to $45m in 2021. This was due to supply chain issues, sub-contractor resourcing issues and uncertainty of escalation for the next 2 years. The PAs spent more time than their fees allowed, to ensure the TLP design was correct. Time was exceeded on staged consent and delays. On site, the programme was driven by the Contractor during construction, who 'owns' the site and is responsible. Regarding employment diversity, the yearly NZIA remuneration survey provides statistics on diversity. The PA's staff comprised 13% Māori and 13% other ethnicities.

(2) **Social focus (how Covid has affected the workforce, immigration, resources, and changes to work patterns):** Shutting the borders led to resource and supply chain issues. Health and well-being were generally good, but continual anxiety was noticeable with everyone, and of varying intensity under constant pressure.

(3) **Organizational (how Covid has affected organizations/ changes made):** The PM gave consideration to the needs of students, staff, and the public. Operational circumstances were difficult, due primarily to the additional workload C19 has brought with it, higher costs and stretched existing resources. Change in building practices, manufacturing practices and client briefs, are required with more awareness of what can be sourced and produced locally. The PA's remote server allowed more flexibility, however managing the volume of work with slow progress and staff resignations initially was hard. Capacity was generally good, but there was too much work and not enough people, much the same as the construction industry. It took 2-3 months to build the capacity of staff to face shortages. Shortage of people has led to stress and burn out.

(4) **Supply chain (as above, plus reliance on alternative products etc):** The PM said that pretty much everything is imported, except concrete and timber. There are many issues regarding shortages that are still being realised as construction on site commences. Tier 1 contractor leveraging has helped improve capability and capacity to provide material or resources. They try to specify local materials, but not specialised building services plant. Mass timber is purchased from a mill in Rotorua. Regarding C19 impact on supply and value, the PA decided it was best to leave many items open in 'cost plus' mode, on some projects. There were no shortages of materials as yet on TLP, but there are on other projects. To create a more resilient supply chain there should be fewer bulk suppliers, better diversification of materials, and more focus on local production. The only way now is to buy early, and for the contractor to pre-purchase materials.

(5) **Political (legislation changes and their impact, links to Government policies, guidelines and how they have been used):** The PM thought the Government had injected too much money into the market without consideration to supply chain shortages in materials and resources, that resulted in driving prices up and stretching trades across too many tenders and projects. In his view the 'Shovel-Ready' initiative did not genuinely fund innovation and sustainability. It funded scale and region, however. He also does not believe the existing model is sustainable and was an opportunity lost to let the 'dead wood drift.' As above, Government should fund innovation and genuine sustainability, for a step

change. Climate Change impact on building regulations will be addressed through the Living Building Challenge and evaluating every project for opportunities to change construction practices. The Government's housing response is poor on policy regarding investment and taxation, however what Kāinga Ora are doing is good, with broader outcomes, frameworks, and social procurement. Potential staff should be allowed into the country faster. Already accounting for carbon, Property Services have their own targets. Everyone is working hard on supply and price rises are not the Government's fault.

(6) **Technological (how Covid has changed technological uses in construction**): Digital systems ensure project resilience. Most communications are Cloud-based with more meetings online becoming the norm. With more Zooms than before, staff have become more capable. Although beneficial for the company it is isolating for many.

(7) **Sector:** The PM noted that labour shortage, materials inaccessibility, skills inadequacy, and increased workload contributed to work disruption on construction projects. Property Services work at the university has accelerated. Construction sector skill sets internationally, that NZ depends on, include project management, and many trades. The PA lost work during Lockdown #1 that was of concern. Lockdown #2 was good but from November 2020 onwards, when work accelerated, they had a lack of staff. New projects were disrupted by C19. Nationality or ethnicity of workers does not impact on sector capability and capacity. Border and immigration restrictions caused a serious lack of a staff pool to employ. Transition to Zero Carbon will impact on the construction sector's capability and capacity because (1) there is a lot to learn, (2) new skills are required, and (3) increased costs of time and some construction. But it must be done.

(8) **Organisation:** For the PM, the safety protocol mostly practised within the workplace was the requirement for each staff person, compulsorily, to learn how to 'contact-trace.'
Whereas in the PA's office it was practicing 'social distance.' Both the PM and PA provided work-at-home setups including laptops, monitors, cameras, headphones, and chairs. To redirect staff to work remotely was easy. Property Services' operations were interrupted with many delays to projects, and organisational changes were made. They struggled to deal with shortages in the workforce in terms of capacity. PA's staff performance and productivity were enhanced by pay rises, working from home and flexibility of hours. Otherwise there were no significant changes to their work schedule and daily operations to comply with C19 guidelines. Organisational change for the PA included a few redundancies after lockdown. There were no issues with the Contractor and Client. The project remained on track by allowing the contractor to manage the programme. No plans were developed for responses to any future shocks and stresses.

Materials – A strong supply chain

Materials were specified from NZ sources where possible. A good example from the TLP case study is that timber from forestry plantations in Rotorua was sourced from an independent, privately-owned timber company. It was established in 2003 to operate the Waipa Mill originally founded by the Government in 1939 and subsequently privatised in 1996. New Zealand's largest sawmill focusses on producing high-quality structural timber products for markets in New Zealand, Australia, and the Pacific Islands. Subject to shipping, this a positive and viable example of added value to an export product from a sustainable, renewable resource and potentially a resilient, strong supply chain, nationally and regionally in Oceania (Red Stag, 2022).

5 Conclusion and Further Research

This paper reports on early stages of research, limited mainly to secondary sources and a small sample of project managers and architects interviewed. Interviews commenced at a commercially sensitive time during confidential contract negotiations and value management.

Both TLP and NDH projects are rich case studies of highly innovative and complex building typologies. They contribute well to CanConstructNZ research of critical infrastructure.

Resilience requires realistic contingencies and alternative products and services to help mitigate adverse effects of supply chain shocks and stresses.

Collaborative use of Building Information Models (BIM) and who manages and 'owns' it, is important to know. BIM and risk management for the NDH will be researched further.

Procurement and tendering, form of contract and risk management, are present constraints to equitable and economically sustainable development from a regional contractor's perspective.

An Advisian report published by The Treasury, prior to establishing the New Zealand Infrastructure Commission, Te Waihanga, looks at contractual issues including risk management (Treasury, 2019). These issues will be included in ongoing research.

6 Acknowledgement

The researchers gratefully acknowledge funding for this research from the Ministry of Business, Innovation and Employment (MBIE) of the NZ Government, through CanConstructNZ.

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Theme:

Health and Safety in Construction

Modelling Stressor Interconnectivities and Mental Wellbeing among Construction Workers

Imriyas Kamardeen[1*], Abid Hasan[1] and Anthony Mills[1]

[1]School of Architecture and Built Environment, Deakin University, Locked Bag 20001, Geelong Waterfront Campus, Geelong VIC 3220, AUSTRALIA

imriyas.kamardeen@deakin.edu.au; abid.hasan@deakin.edu.au; anthony.mills@deakin.edu.au
* Corresponding author

Abstract:
Recent research claims that construction workers endure poor mental health globally, which causes diminished work ability and quality of life for workers and productivity and profit losses for construction organisations. This study aims to understand the work stressors facing construction workers and their relationship with workers' mental health. A systematic literature review approach was adopted in which 35 journal articles published between 2010 and 2021 (inclusive) were examined. Findings suggest that construction workers suffer poor mental health because of encountering numerous stressors at work, with complex interconnections among themselves. It is not plausible to assume a linear cause-and-effect relationship between stressors and the mental health of construction workers. Hence, a new model of work stress is proposed to provide a holistic picture of reality. The model postulates some primary or root stressors that cause significant psychological damage to the workforce. These are long workday/week, masculine culture, productivity-based pay system, short-term and contract-based jobs, inadequate management of cultural disparities among workers and unsafe worksites. Similarly, apprentices, females and young workers are more susceptible to mental stressors and psychological disorders. Workplace injuries and illnesses have a domino effect on the mental well-being of construction workers. Therefore, improving the physical safety on site can partly improve workers' psychological well-being. The study offers valuable practical insights for construction organisations and occupational health and safety authorities to guide the development of effective interventions to mitigate poor mental health in the construction workforce.

Keywords:
Cognitive map, Construction workers, Mental health, Systematic literature review, Work stressors.

1 Introduction

A significant proportion of construction workers suffer from work-related anxiety, stress, and depression (Flannery *et al*., 2021). Construction workers have higher than the national average suicide rates in many developed countries such as the United States, the United Kingdom, and Australia (Jacobsen *et al*., 2013; Burki, 2018; Chan *et al*., 2020; Chapman et al., 2020). Work-related poor mental health negatively affects workers in many dimensions. They experience personal suffering, absenteeism and presenteeism at work, deteriorated work ability, low productivity, reduced income, and decreased quality of life (Pincus and Pettit, 2001; Davies, 2013; Boschman *et al*., 2014; Unum, 2016; Pidd *et al*., 2017). These outcomes eventually affect organisations and the construction industry overall. The construction industry, therefore, would face significant potential losses of the capable workforce and productivity if the work-related mental health concerns among the workers are not addressed. Understanding the dynamics and complexities surrounding work-related poor mental health is a significant step towards developing effective interventions and preventive measures.

Many theories of work stress can be found in the occupational psychology domain, which can explain the causes of work stress (also known as stressors) and its consequences. Table 1 shows 15 prominent theories introduced over the last three decades between 1976 and 2009. Kamardeen (2020) asserted that there are significant variations in the perspectives considered by these theories, with each postulating a different source of work stress that leads to poor mental health. Moreover, the theories are generic and appear more suitable to explain the work stress of white-collar professionals. Liang *et al*. (2018) argued that the construction work environment is unique compared to other industries. It may be incorrect to relate the empirical research findings and theories from other occupations/industries to construction workers. Thus, there is a need to develop theories of work stress that represent the work settings and occupations in construction. Accordingly, many researchers have investigated work-related stress in the construction industry in the past decade. Nwaogu *et al*. (2020), based on their review of the existing studies, concluded that most research into stress, coping mechanisms, and mental health in the construction industry has focused on construction professionals, and limited studies have been undertaken on trades workers. Moreover, these studies investigate work stressors and effects in isolation, disregarding the dynamic and complex interconnections among work stressors in producing a mental health outcome for workers. To this end, the present study aims to model the complex relationships among work stressors facing construction trades workers in causing poor mental health.

Table 1. Work stress theories and premises (Source: modified from Kamardeen 2020)

Work Stress Theory	Premise of the Theory
Person-Environment Fit Theory	Work stress arises due to the misfit between the person and the environment; that is, because of a misfit between the abilities of the employee and the demands of the job or between the needs of the employee and the rewards from the job.
Demand-Control-Support Theory	Work stress is caused by the combined effect of work demand, control and support. A combination of high job demand and low job control, particularly decision-making freedom, and low support from superiors or co-workers would lead to “high-strain, isolated jobs”. On the contrary, high job demands combined with high levels of control and support would lead to “active jobs” that are not stressful as they allow individuals to regulate job demands.
Effort-Reward Imbalance Theory	Work stress is triggered when an imbalance is perceived by an employee between the efforts (job demand, obligations, time pressure, overtime, and performance expectations) he/she puts in and the rewards (pay, esteem, job security, career development) received.
Appraisal and Coping Theory	Individuals’ appraisal of situations and their coping ability is central to stress arousal rather than the external environment/event itself. Different individuals appraise the same environment/event differently, depending on their experience and psychological characteristics. Work stress occurs when a person appraises a situation to be harmful and doubts their ability to cope with it.
Vitamin Theory	The theory argues that job characteristics and affective well-being pose a curvilinear relationship. Job characteristics (e.g., job demands, job decision latitude, social support, utilisation of abilities, salary, safety, and work task significance) have an initial beneficial effect on an employee’s mental health and, beyond a certain required level, may produce either a constant effect on health (similar to vitamins C and E) or may be harmful to health (similar to vitamins A and D).
Organisational Health Framework	Employee well-being (morale, distress & job satisfaction) is affected by a dynamic system of interactions between multiple individual characteristics (personalities, coping processes, attitude & behaviours) and organisational characteristics (resources, structure, culture & organisational climate), which in turn, affect the organisation’s performance (company turnover, absence, medical expenses, customer satisfaction & compensation claims).

Work Stress Theory	Premise of the Theory
Cooper and Marshall's Theory	Work stress is the outcome of the interplay between work factors (intrinsic to the job, role in the organisation, relationships at work, career development, organisational structure & climate, etc.), personal life circumstances (family problems, life crises, financial difficulties, etc.) and individual characteristics (Type A personality, levels of anxiety, neuroticism, tolerance & resilience, etc.).
Demand Induced Strain Compensation Theory	Work stress results from a lack of job resources to address job demands. Adverse health effects of high job demands could be compensated for, by matching job resources (physical resources, social/emotional support from colleagues, breaks, availability of control, etc.) to the high demands. An unbalanced mix of specific job demands and resources activates psychological compensation processes of strains, while a well-balanced mix of specific job demands and job resources could stimulate employee growth and performance.
Cybernetics Theory	Individuals are the managers of stress, and they seek to maintain an equilibrium state and attempt to re-establish the equilibrium when an external force breaks it. The discrepancy between perceptions (the subjective representation of any situation, condition, or event) and desires (work goals and interests) is the cause of stress. Depending on the importance of the discrepancy, the stress may lead to an alteration of well-being and/or the employment of coping strategies.
Dynamic Equilibrium Theory	Stress arises when there is a state of disequilibrium that affects an individual's normal levels of psychological distress and well-being. Stress is suggested to come from a system of variables including personality, environmental characteristics, coping processes, positive and negative experiences as well as indices of psychological well-being.
Ethological Theory	Employees have their own "territory" (i.e., a space of familiarity resulting from routine actions) where they develop standardised behavioural sequences and knowledge needed for survival. Infraction or loss of one's territory leads to stress and, consequently, the activation of self-defence mechanisms (including identification of the problem and evaluation of coping strategies).
Individual Difference Factors Theory	Individuals respond uniquely to stressors depending on their genetic, dispositional and acquired differences. Genetic factors concern age, gender, and physique. Dispositional factors are self-esteem, coping style and negative affectivity. Examples of acquired factors include social class, education, job position and social support.
Multidimensional Theory of Burnout	High job demands (work overload & personal conflicts) and a lack of resources (social support, skills, autonomy, decision involvement & control) contribute to the development of occupational burnout (exhaustion, detachment from the job, frustration, anger and feelings of ineffectiveness and failure), which in turn, affect both the employee and his/her organisation (diminished organisational commitment, turnover, absenteeism & physical illness).
Job Demands – Resources Theory	Interactions between job demands and job resources affect the level of strain and motivation in employees. Job demands are physical, social or organisational components of a job that require sustained physical and/or mental effort. Job resources necessary to meet the job demand include pay, career opportunities, supervisor support, workplace culture, decision-making latitude, clearly defined role, task significance, autonomy and performance feedback. High job demand compensated by high job resources will lead to high motivation and average (manageable) strain on employees.
Demands, Resources and Individual Effects Theory	Work demands, individual differences and work resources have a main effect relationship on health outcomes and job satisfaction. Whilst work resources and individual differences moderate the relationship between work demands and health outcomes; perceived job stress is a mediator for work demands, resources, and health outcomes (along with job satisfaction).

2 Review Approach

The study adopted a systematic literature review (SLR) approach, using the PRISMA process to consolidate evidence that can enable the synthesis of a stressor connectivity model. The choice of this approach was determined by its reported benefits. Mallett *et al*. (2012) claimed that SLR is an unbiased method that allows researchers to assess and synthesise existing knowledge effectively. Clarke and Chalmers (2018) argued that SLRs produce high-quality summaries and discussions and propose new ideas and directions for future research, which benefit the broader community. Hence, 52 journal articles published between 2010 and October 2021, inclusive, were chosen and examined in the study. The SLR approach adopted in this study is explained in detail in the following paragraphs.

An initial search of relevant journal articles for this review was conducted using the Scopus database as it offers greater coverage of subjects/disciplines (Sadick and Kamardeen 2020). Figure 1 shows the search keywords and step-wise search results. A total of 219 articles were identified in the initial search. Next, 128 journal articles published in the final form in English in peer-reviewed academic journals between 2010 and 2021, inclusive, were included. This was to ensure that only recent studies were included in the review. As research on the construction industry evolves, it is crucial to analyse current literature that best represents the industry's present state. Moreover, only peer-reviewed academic journals were considered due to their rigorous review process before publication. Therefore, studies reported in conferences, books, reviews, editorial documents and trade journals were excluded.

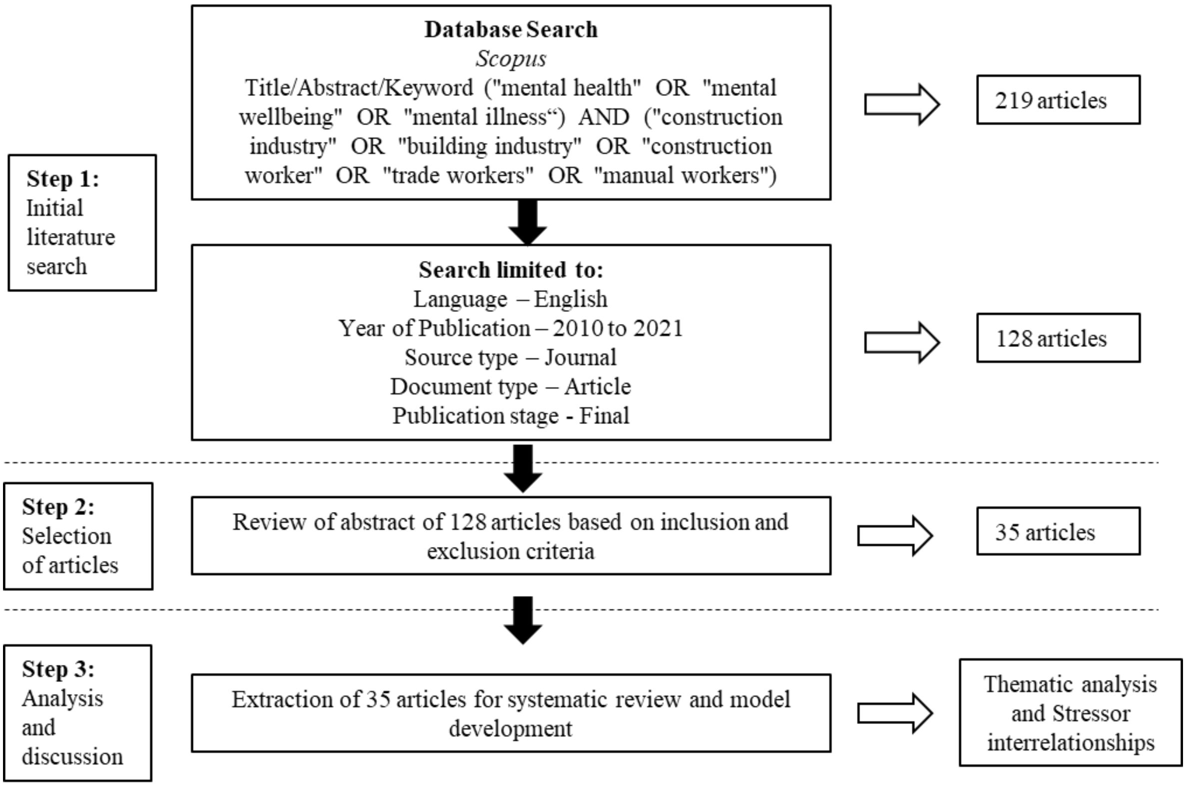

Figure 1. Research process flowchart

The abstracts of each of the 128 articles were examined to determine their relevance to the review. At this stage, only journal articles that discussed the mental health of manual and trade workers employed in the construction industry were considered. Therefore, the articles on the mental health of construction professionals were excluded. Similarly, articles examining the psychological challenges of construction management students were excluded. After carefully cross-examining the abstract of each article, the authors determined that 35 articles were relevant for the review and further analysis. Following that, the authors conducted a full-text review and assessment of these articles. The findings are discussed in subsequent sections.

3 Findings

The SLR revealed numerous job stressors for construction trades workers. After carefully evaluating the nature of these stressors and their interconnections, the authors synthesised them under five themes.

3.1 Harsh Work Conditions

This theme covers work demands and physical and social conditions in the workplace and their level of influence on the mental health of construction workers. Construction workers are required to carry out physically strenuous work in a dangerous, dirty, noisy, fast-paced and uncomfortable environment, which is constantly stressful and affects their mental health (Bodner *et al*., 2014; Turpin, 2021). Langdon and Sawang (2017) reported that long workdays and weeks are typical for construction workers. Working long days and weeks in physically strenuous, unsafe, and unfavourable site conditions harms their mental health (Lim *et al*., 2017). Moreover, it is challenging for construction workers to sustain a work-life balance and fulfil family/personal responsibilities with long workdays and weeks. This can weaken their personal and family relationships. These collectively impact their mental health (Lingard and Turner, 2017). The demand for working long days and weeks also hinders seeking support or treatment for psychological challenges (Chapman *et al*., 2020). Alroomi and Mohamed (2021) studied the stressors for offshore/ remote construction workers who lived in shared, crowded and uncomfortable dormitories with no privacy for an extended period. The workers also had limited communication and interactions with family members and friends. These combinedly led to sleep deprivation, fatigue, and isolation, eventually deteriorating their psychological health. Ross *et al*. (2021) report that construction workers sometimes experience workplace bullying, injustice, and social isolation on site, especially female workers and apprentices. Chapman *et al*. (2020) warn that perceived low control and poor workplace relationships are categorically detrimental to construction workers' mental health. In summary, excessive work demands and unfavourable physical and social conditions expose construction workers to physical and psychological distress and cause stress, anxiety and depression (Yuan *et al*., 2018).

3.2 Poor Work Culture

Most workers in the construction industry are employed on a short-term basis (Carmichael *et al*., 2016). The temporary work arrangements and macho culture prevalent in the industry discourages workers from discussing their mental health problems with other and seeking help or interventions as they fear losing their jobs due to job insecurity and mental health stigma (Carmichael *et al*., 2016; Eyllon *et al*., 2020). If workers try to share their mental health problems with their peers or supervisors, they feel ashamed due to traditionally held beliefs about masculinity in the construction industry (Milner *et al*., 2017). The masculine culture expects them to be tough and self-reliant, restricting their emotions and vulnerabilities (George and Loosemore 2019). Therefore, the affected workers pretend to act normal to avoid being seen as weak or incompetent and lose the respect of their fellow workers (Jacobsen *et al*., 2013; Kotera *et al*., 2019). Previous studies show that mental health stigma also results in sleep disorders among construction workers due to increased psychological distress (Eyllon *et al*., 2020). The poor sleep quality, in turn, aggravates the mental health of workers and leads to higher fatigue and depression (Kim *et al*., 2021). Finally, the presence of different cultures can sometimes cause various cultural stressors, such as conflicts, communication gaps, confusion, and different expectations (Liu *et al*., 2021). In addition, temporary employment often exposes workers to new cultures. As a result, vulnerable construction workers such as overseas workers and ethnic or culturally diverse workers experience more cultural stressors and psychological disorders due to isolation, low self-esteem, anxiety, depression and racial or cultural discrimination (Liu *et al*., 2021).

3.3 Physical Pain

The construction industry is identified as a high-risk or hazardous workplace due to a very high number of injuries and fatalities worldwide. Workers in the construction industry are exposed to various types of hazards, including musculoskeletal hazards. These hazards lead to high injury rates and chronic musculoskeletal diseases. Previous studies show that injuries and bodily pain cause poor mental health among construction workers (Dong *et al*., 2015). The physical pain affects workers' ability to perform the assigned tasks and their motivation level and attitude, directly or indirectly diminishing their mental health further (Dong *et al*., 2012; Turner and Lingard, 2020). Physical pain also causes anxiety, stress, sleep disorders and depression, further degrading workers' mental health (Turner and Lingard, 2020). Due to temporary employment and a culture of presenteeism, the workers do not take enough rest or actively manage their pain and return to work before full recovery (Turner and Lingard, 2020). Lingard and Turner (2017) argue that many construction workers accept physical pain as an inevitable and integral part of their work. They also fail to appreciate the impact of physical pain on their mental health, affecting their chances of receiving timely help or mental health interventions (Turner and Lingard, 2020).

3.4 Substance Use

Research shows construction workers are more vulnerable to alcohol and drug consumption and overuse than the general population in many countries (Hall, 2021; Turpin, 2021). They also have a higher representation in recreational marijuana and prescription opioid use (Ompad *et al*., 2019; Dong *et al*., 2020). Some of the risk factors that explain this trend are temporary employment, work pressure or high job demand, manual or physically demanding work and physical pain (Turpin, 2021). Job insecurity also exerts financial stress on workers and their families, causing mental health problems such as depression and anxiety (Dong *et al*., 2020). The long work hours and labour-intensive nature of construction work cause pain that is often treated with opioids as a pain reliever leading to addiction after a continuing or prolonged period of usage (Dong *et al*., 2020; Turpin, 2021). The male-dominated culture and risky work environment also promote alcohol and drug consumption (Hall, 2021). However, alcohol and substance use affect workers' physical and cognitive abilities leading to injuries and more physical pain, thus forming a vicious cycle, ultimately deteriorating their mental health.

3.5 Demographics

The worker demographics such as employment type, age, ethnic background and gender influence their exposure to various mental health stressors and resulting mental health disorders (Kim, 2013; Kamardeen and Sunindijo, 2017). Jiang *et al*. (2021) found that workers' characteristics, individual resilience and genetics affect their ability to cope with different mental health issues. Kamardeen and Sunindijo (2017) further add that individuals' traits and resilience levels influence their perception of work stress, coping methods and mental health symptoms. Similarly, Lim *et al*. (2017) found that younger and older construction workers experience different levels of stress concerning stressors, such as excessive job demands, poor occupational climates, and lack of job control. Middle-aged construction workers experience a higher prevalence of psychological distress resulting from the lack of social and emotional support systems around them (Chapman et al., 2020). Female workers also face higher mental health risk factors due to the male-dominated work culture in the construction industry, which often leads to discrimination, harassment, and bullying (Jiang *et al*., 2021). Dong *et al*. (2020)

found a higher intake of prescription opioids among women in the construction industry than men. Finally, previous studies show that construction apprentices experience increased psychological distress due to bullying and alcohol and drug-related harm (Pidd *et al*., 2017; Ross *et al*., 2021). They are also less inclined to seek help or participate in mental health intervention programs because they fear losing their apprenticeship (Ross *et al*., 2021). Finally, prior exposure or experiences with mental health issues in personal life or certain genetic conditions could also increase the risk of poor mental health and sleep disorders (Jiang *et al*., 2021).

4 Modelling Stressor Interconnectivity and Psychological Outcomes

The preceding sections identify various job stressors (both work stressors and demographic characteristics) affecting the mental health of construction workers. As evidenced in the findings, there are complex interrelationships among the stressors. Understanding the complexity of these relationships is vital to develop effective interventions to curtail the poor mental health issue. The cognitive map presented in Figure 2 models the stressor interrelationships, the direction and polarity of the influence among them, and how the dynamics produce mental well-being outcomes. These interrelationships and directions of influence were drawn from the findings of the SLR. The +/- signs on the arrows in the cognitive map represent the direction of influence between factors. For example, productivity-based pay in the construction industry increases chronic fatigue and injuries (denoted by +) and reduces mental well-being (denoted by -) among construction workers.

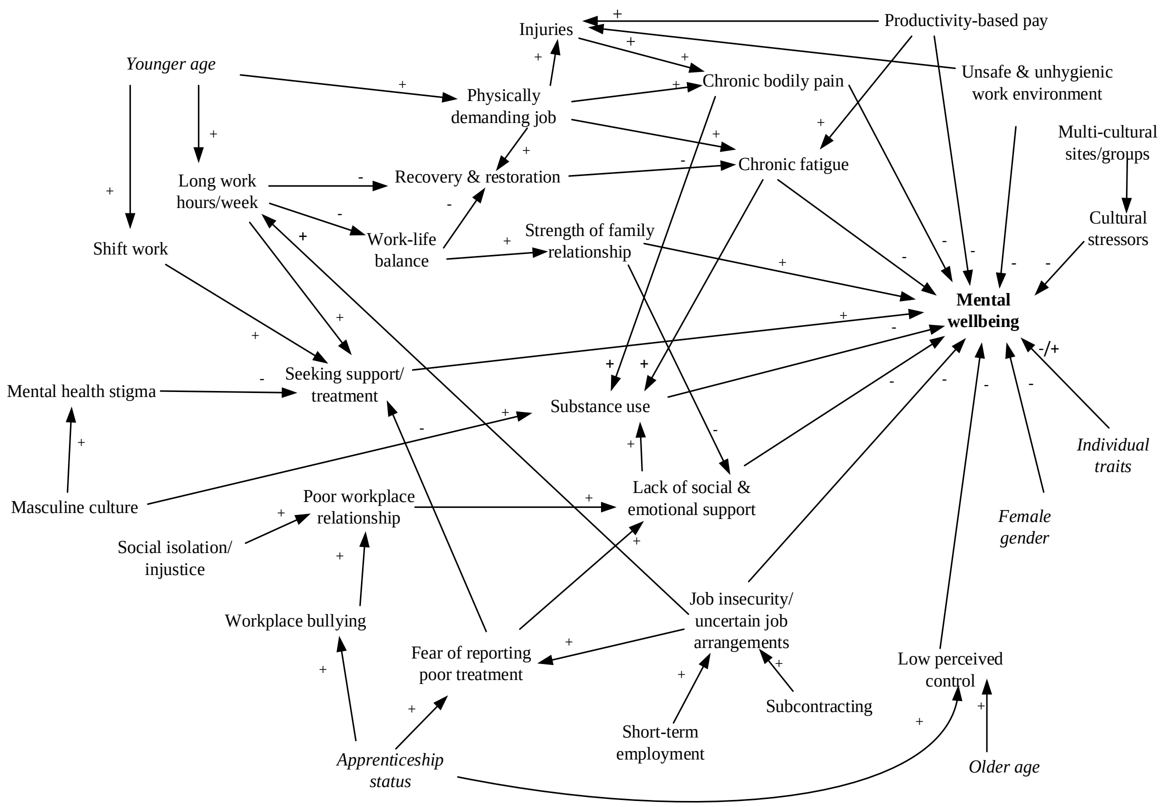

Figure 2. Stressor interrelationships

The model offers many insights and practical implications.

- It identifies some fundamental issues in the industry that cause significant psychological damage to the workforce, such as long workday/week, promotion of masculine culture, productivity-based pay system, short-term and contract-based job practices, and inadequate management of cultural disparities on sites and unsafe worksites.
- It further recognises that apprentices and female and young workers are more susceptible to mental stressors and psychological disorders. This explains why suicide rates are higher among young workers and apprentices in the construction industry of many countries.
- Mental well-being of construction workers may be maintained if organisations and the industry pay sufficient attention to improving the work-life balance and support sources/mechanisms for workers.
- Work-related injuries and illnesses have a domino effect on the mental well-being of workers. Therefore, improving the physical safety on site can partly improve workers' psychological well-being. On the other hand, disregard for safety will lead to productivity losses due to both direct physical and indirect psychological injuries.
- Unlike the piecemeal approaches adopted by the existing theories (shown in Table 1) to explain work-related mental health issues, the model provides a holistic picture of the reality around construction workers.

5 Conclusion and Further Research

Work stress and the mental well-being of construction workers is an underexplored topic. The limited research and literature available on this topic discuss different stressors sources. The present study consolidated the existing evidence and developed a holistic model to explain the complex relationships between work stressors and subsequent mental well-being outcomes. The model offers many implications. Primarily, it is a new, comprehensive theory for explaining work stress in the construction workforce. Secondarily, it enables construction organisations, OHS authorities and industry associations to identify critical stress factors, understand effective starting points for interventions and apply the findings to protect the most vulnerable worker groups.

The cognitive map in Figure 2 captures the most interconnections among the stressors. The cognitive map presents as if all the stressors are equal in terms of their degree of influence on each other. In reality, the influence varies across stressors. Developing a fuzzy cognitive map will allow theorising such variability. Hence, future research should develop a fuzzy cognitive map using primary data to explain the variability. Moreover, the strength of the influence of the stressors in producing a specific type of mental disorder and a particular level of severity of the disorder cannot be ascertained with the current cognitive map. Hence, future studies are suggested to investigate how workplace stressors and worker characteristics combinedly associated with the severity of psychological disorders among construction workers. Finally, the model presented in the paper was developed through a systematic review of existing literature. The plausibility of the model may be tested and refined in future research.

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Scientometric Analysis and Review of Safety in Design in AEC Industry

Weifang Shi[1,3], Alice Chang-Richards[1] and Brian H.W. Guo[2]

[1]Civil and Environment Engineering Department, University of Auckland, 20 Symonds Street, Auckland-1010 NEW ZEALAND
[2]Civil & Natural Resources Engineering, University of Canterbury, Christchurch-8140, NEW ZEALAND
[3]Civil & Architecture Department, Zhongyuan University of Technology,41 Zhongyuan Road, Zhengzhou-450007, P.R. CHINA

wshi306@aucklanduni.ac.nz; brian.guo@canterbury.ac.nz; yan.chang@auckland.ac.nz
* Corresponding author

Abstract:
Safety in design (SiD), is a new paradigm for managing workers safety in architecture, engineering, and construction (AEC) sector. However, there is a lack of a holistic mapping on the SiD research in a global range. To explore the advancement and sketch the panorama of SiD research, this research investigates SiD research through a scientometric review. A total of 199 bibliographic records from Web of Science, Scopus, and Engineering Village were retrieved and analysed.

Results show that the most distinguished countries where SiD research have been undertaken are the USA, UK, and China. Major studies fields concentrated on engineering and technology; however, studies on electrical, ergonomics, building information modelling, decision making, equipment, and education are emerging. In addition, the paper presents a framework genialised from several key themes, revealing the focal points and trends of SiD research over time. This review provides a comprehensive understanding of SiD research word wide, contributing to the existing knowledge in safe design and has laid a solid foundation for future research that look into the detailed design features for improving SiD implementation in the construction projects.

Keywords:
Architecture, Engineering, Construction (AEC) sector, Safety in design, Scientometric review.

1 Introduction

Compared to other sectors, the construction sector has not been pictured as a safe workplace for workers, with significant fatalities annually (Jaselskis et al., 1996; Martinez et al., 2020; Tam et al., 2004). Because of the complex nature of construction projects, long schedule, harsh working conditions with dangerous hazards involved, addressing construction safety has always been a challenging issue in the sector. Previously, the contractors have been responsible for the safety on site. Safety in design (SiD), however, has changed the roles and responsibility distribution among construction project participants, prescribing safety consideration in the design phase (Gambatese et al., 2005). Design suggestions and strategies have been collected, assisting designers in recognising the hazards and understanding SiD , such as "Design for Construction SafetyToolBox", a computer program composing the design suggestions for the best practice (Gambatese et al., 1997). To faciliate SiD, visualisation technology such as Building Information Modeling (BIM) has been leveraged to improve the productivity and safety of workers (Golabchi et al., 2018).

There are a number of studies in literature that are focused on reviewing and implementing SiD. For example, (Adaku et al., 2021) developed a theoretical framework aimed at advancing PtD in improving organisational capability. Reviews have been extended to understand SiD knowledge, skills, and experience needed that can significantly contribute to improve design practice and provide competency assessment for PtD implementation. Moreover, Hardison and Hallowell (2019) conducted a review with an analysis of aspects of feasibility, implementation, and designed instruments of SiD.

However, the knowledge of what, precisely, encapsulates broader and diverse research aspects in the SiD fields have not been reached. There has been currently little literature review generalising SiD and its applications in different types of construction projects and in different geographical areas. The evolution, trends, gaps and also future directions available to the entire research community also are yet to be uncovered.

To fill this research gap, the authors employ the scientometric review approach to the SiD body of knowledge. The findings are expected to provide researchers with a comprehensive understanding of the state quo of SiD by exploring the trends and prototypes of SiD, highlighting research themes, the areas for future studies. The findings will serve as a start point for new research in investigating the specific design features under the SiD approach.

2 Research method

Scientometric analysis is a quantitative study that contributes to a comprehensive understanding of a specific scientific field, and could be presented by bibliographic records based on previous publications (Vinkler, 2010). This scientometric review involves three stages, namely research question formation, bibliometric searching, scientometric analysis. Figure 1. shows an overview of the review process.

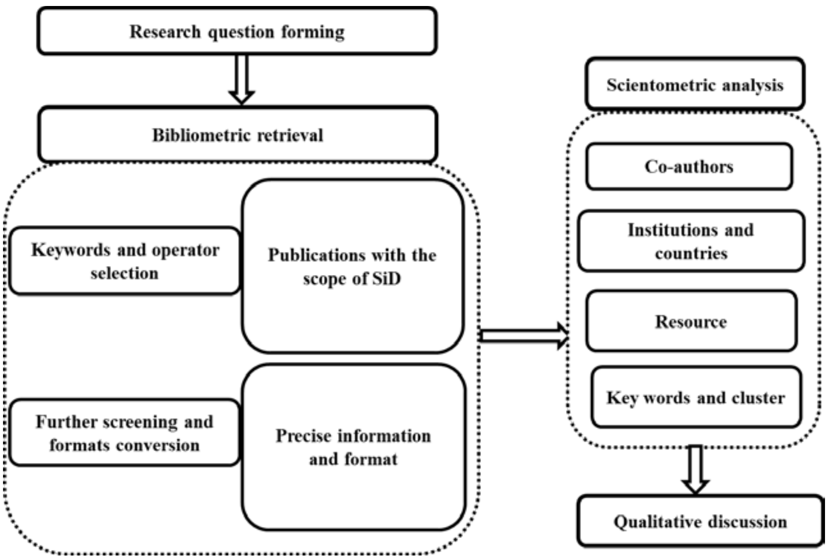

Figure 1. The procedures of the scientometric review

2.1 Formation of research questions

We have formulated the following questions in order to obtain a full picture of the SiD research. This has been done in accordance with previous scientometric reviews:

(1) Who are the key researchers, institutions and regions contributing to SiD research?
(2) What are the valuable sources including high cited journals and articles?
(3) Where are the advancements and trends in SiD research?
(4) What are potential areas for future research？

2.2 Bibliography searching

After determining the research questions, we accessed eligible resources. Articles from a certain time range, including books, journals, and conference proceedings, were considered to extract information. Three databases were used to search articles: Scopus, Web of Science, and Engineering Village. The searching strategies are indicated in Figure 2.

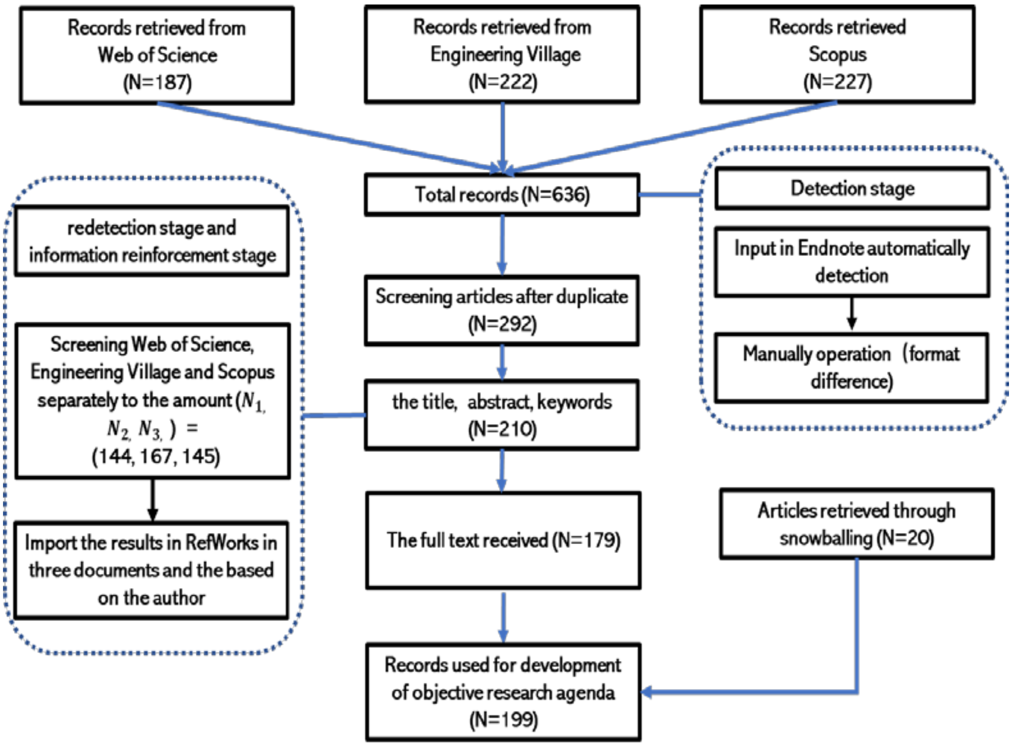

Figure 2. The search strategy and processing of the resource

3 Scientometric analysis results

This section describes results visualised in the science mapping, with network of the authors, institutions and countries, references, and key words.

3.1 Co-author network

A co-author network was generated through nodes and links. The node presents the author, and the link shows the cooperation in the form of publications. Figure 3 shows the author's information with the node indicating the amount of the publications and colour differentiating the groups cooperating on SiD research. The top contributor's information, institutions and countries/regions and contributions to the SiD field are listed in Table 1.

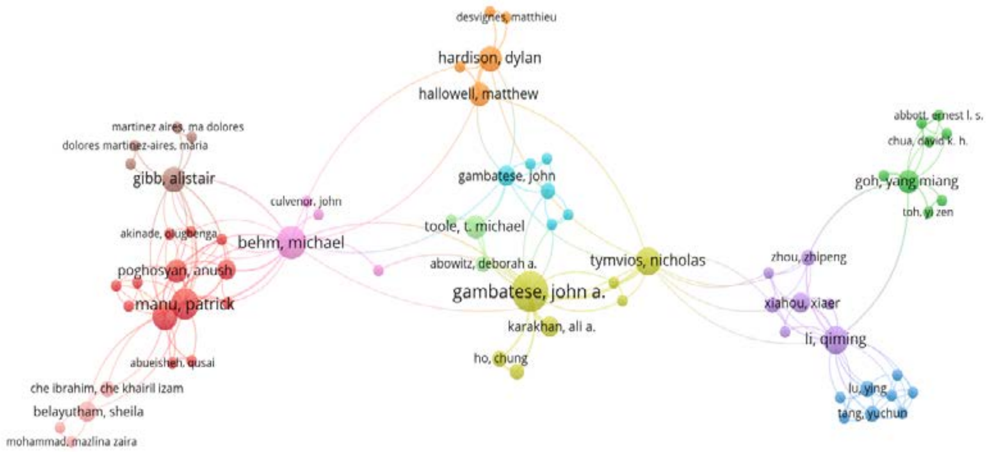

Figure 3. The authors information regarding the SiD reseach

Table 1. The top ten productive researchers on PtD

Author	University	Country/region	Number of papers
John A. Gambatese	Oregon State University	USA	14
Michael Behm	East Carolina University	USA	8
Patrick Manu	University of Wolverhampton	UK	7
Li Qiming	Southeast University	PR China	6
Abdul-Majeed Mahamadu	Univ. of the West of England	UK	6
Nicholas Tymvios	Bucknell University	USA	6
Sunwook Kim	Virginia Tech Blacksburg	USA	5
Maury A. Nussbaum	Virginia Tech Blacksburg	USA	5
Alistair Gibb	Loughborough University	UK	5
Hardison, Dylan	East Carolina University	USA	5

3.2 Network of institutions and countries

This section identifies the institutions and countries that contribute to SiD research.A network generated from the retrieved bibliography data was analyzed to find the contributions. Detailed information for countries is shown in Table 2.

3.3 Source analysis

3.3.1 Journals analysis

As summarized in Table 3, the top 10 journals including SiD studies were investigated according to statistical analysis in Vosviewer. Safety Science had 29 publications (14.5%), taking the top position among all the sources, followed by the Journal of Construction Engineering and Management (15 articles) and Automation in Construction (10 articles). Half of the numbers of the journals are in the USA.

3.3.2 Top cited articles analysis

According to (Small, 1973), the recurrence with which two reports are referred to is characterised as co-citation, another kind of archive coupling. Two papers' co-citation recurrence can be determined by contrasting how records are referred to in the Science Citation Index and tallying indistinguishable sections. The number of references referred to by distributions can be determined using record co-citation analysis (Zhao, 2017), thereby can be used for community's general knowledge and evaluation. The network constituted 621 nodes and 1943 links with modularity (0.8813) and meant silhouette (0.9278). A network's modularity refers to complexity breaking down into components or modules, and the metric serves as a benchmark for the overall clarity of a network decomposition. Its silhouette value [-1, 1] measures a clustering configuration's efficiency (Chen, 2016). The top10 documents that were selected for the recommendation to new researchers of SiD are listed in Table 4.

Table 2. Top institutions in the SiD research

Institution	country	documents	Citations	Link strength
University of Oregon	USA	17	560	8
East Carolina University	USA	12	547	12
Virginia Tech	USA	12	145	1
West England University	UK	7	31	9
University of Colorado	USA	7	79	5
Hanyang University	South Korea	6	396	0
National University of Singapore	Singapore	6	286	1
Southeast University	China	6	189	2
Bucknell University	USA	6	176	7
University of Manchester	UK	5	22	8
RMIT University	Australia	5	127	1

3.4 Keywords and cluster analysis

Keywords are extracted from the paper abstract and main content. This resulted in 360 nodes representing keywords, and 1,529 links presented in Figure 6. The keyword nodes are then placed on a timeline for those terms that are most prevalent. It was found that "Safety", "prevention", and "design" occurred with a maximum frequency in the keywords and clusters analysis. Management, ergonomics, and system have emerged as new trends. Virtual reality (VR) technology and construction processes were the heated topics, significantly influencing the advancement of BIM research.

According to the timeline, around 1998, the primary nodes (high frequency) were on VR, hazards recognition, design process, and methodology. After that, VR and the construction process became dominant. Electrical/electronics, equipment, and ergonomics had centrality around 2008. Around 2004, computer-aided simulation started to be applied in SiD research. Safety standards, innovation models, and ergonomics appeared in the research field around 2007. Building information modelling (BIM), learning, accident analysis, best practice, communication, attitude, game, and e-competence have increased since then.

Table 3. The top source journals in SiD

Source journal	Host country	Journal impact factor (2021)	Number of articles	Citations	Totally link
Safety Science	Netherland	6.392	29	1055	2264
Journal of Construction Engineering and Management	USA	5.292	15	472	1251
Automation in Construction	Netherland	10.517	10	697	1294
Journal of Safety Research	USA	4.262	4	225	352
Engineering Construction and Architectural management	USA	3.385	3	17	760
Journal of Professional Issues in Engineering Education and Practice	USA	1.667	3	94	433
Practice Periodical on Structural Design and Construction	USA	1.59	3	9	597
Architecture Engineering and Design Management	United Kingdom	2.57	3	15	399
Work a journal of prevention Assessment & Rehabilitation	Netherlands	1.803	3	22	392

The research diversified into new directions, such as organisational perspective, best practice and decision making. The latest keywords are artificial intelligence, expert system, and designer assistance, indicating that research will utilise more advanced technology and take full advantage of the experts' knowledge. It is interesting that BIM is a continuous focus of SiD research in the whole advancement process of SiD.

4 Discussion

4.1 Discussion according to the scientometric analysis

Through the *co-author analysis*, findings show that John A. Gambatese (Oregon State Univ. USA), Michael Behm (East Carolina University, US), and Patrick Manu (University of Wolverhampton, UK) are the most prolific researchers. The trajectory and focus from influential researchers the in the area worth focusing to better understand SiD.

Through the countries and institutions analysis, we found that researchers in the USA contribute most to the research domain, even Weinstein et al. (2005) commented on the USA's safe design implementation. However, the review found that the research on SiD has not been fully explored and the reasons for constraints of SiD research are unclear. The theory has been promoted through empirical studies, but the grounds and methods aimed at implementing SiD are yet to be solved. A future research direction potentially exists in exploring the path to global cooperation for advancing SiD implementation.

Through the sources analysis, we found that Safety Science, the Journal of construction engineering and management, and Automation in construction are high-ranked journals on SiD research. Significantly, these three journals were among the top sources where articles on SiD are cited.

Table 4. The top-cited articles in SiD research

Times Cited	Title	Authors and time	Journal
337	Building Information Modelling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules	Zhang et al. (2013)	Automation in Construction
165	Overview and analysis of safety management studies in the construction industry safety	Zhou et al. (2015)	Safety science
146	Design's role in construction accident causality and prevention: Perspectives from an expert panel	Gambatese et al. (2008)	Safety Science
138	BIM-based fall hazard identification and prevention in construction safety	Zhang, Sulankivi, et al. (2015)	Safety Science
121	Ontology-based semantic modelling of construction safety knowledge: Towards automated safety planning for job hazard analysis (JHA)	Zhang, Boukamp, et al. (2015)	Automation in Construction

The most popular research topics are automatic safety checking using BIM, exploring the knowledge, attitude, and practice in SiD, measuring designers' hazards recognising skills. These topics are the mainstreams enlightening future research and practice. SiD-related assessment elements have been added to LEED credits (Lee et al., 2020). An evaluation system that automates BIM-based risk rating estimation has been developed (Lee et al., 2020). Another representative research was to leverage VR in the design-for-safety-process (Hadikusumo, 2000).

4.2 Research themes, gaps and trends

The reviewed articles focused on a wide range of questions from design effectiveness, design linkage to morbidity and mortality, design metrics, information diffusion, and economic and business issues. In this review, we have used the categories of research, practice, education, and policy for SiD (Schulte et al., 2008) to analyse these studies. The research gaps and future research potentials were generated in the framework shown in Figure7. With the evidence from the scientometric record, a "survey" method is significantly used in previous studies. According to the science mapping, tacit knowledge on construction is essential for successful implementation of SiD (Hadikusumo & Rowlinson, 2004). The future direction recommends usage of objective data (Tixier et al., 2017) and empirical evidence (Tymvios et al., 2020) instead of personal experience. Hence evidence-based knowledge is essential for advancing SiD research. The sharing of technical knowledge advocated by Behm (2008) is still a gap to be addressed. There is a need for more efficient methods for assisting designers in understanding the SiD process.

There exist gaps in education and policy, requiring research in these areas. Gaps still exist in the approaches to better involve decision-makers, H&S professionals, project managers and clients in SiD. The project demands indicated the popularity of implementing SiD. Future research needs to be undertaken to look at the role the project owner/client and developers could play, design decision making, preliminary design stage, maintenance safety considerations, professional certification, and health & safety professional involvement.

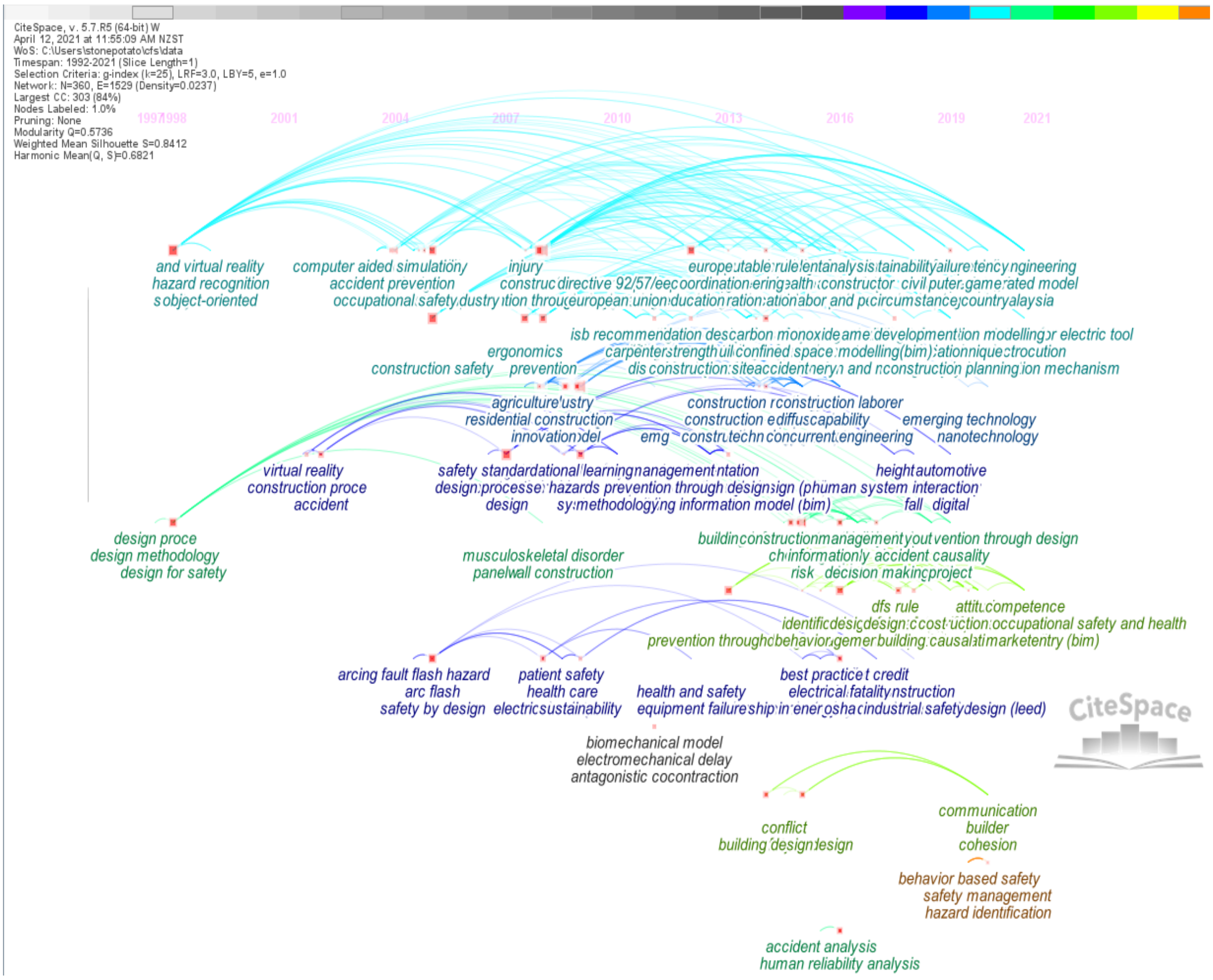

Figure 6. Keywords according to the timeline

Education, especially through experimental studies, is essential to enable the enhancement of awareness of SiD. Educating future designers and professionals using advanced technology is needed. However, for educational purposes, collecting and transferring experts' knowledge (such as experience and skills) still presents a challenge.

5. Conclusions and future directions

In the research area, four directions can be summarised from the scientometric review: (1) new techniques like prefabrication and industrialisation; (2) more cooperation between countries or institutions; (3) knowledge exploration and promotion; (4) business value. Four gaps can be identified as research directions: (1) the current market demand for safe construction; (2） the contractor's contribution; (3) safe design in the conceptual design stage; (4) methods for assisting designers to facilitate SiD. Meanwhile, as in a practice preference field, collecting design features are of great importance. Furthermore, the methods bringing the emerging technologies into the SiD knowledge transfer are in need, thereby finally promising safety knowledge sharing.

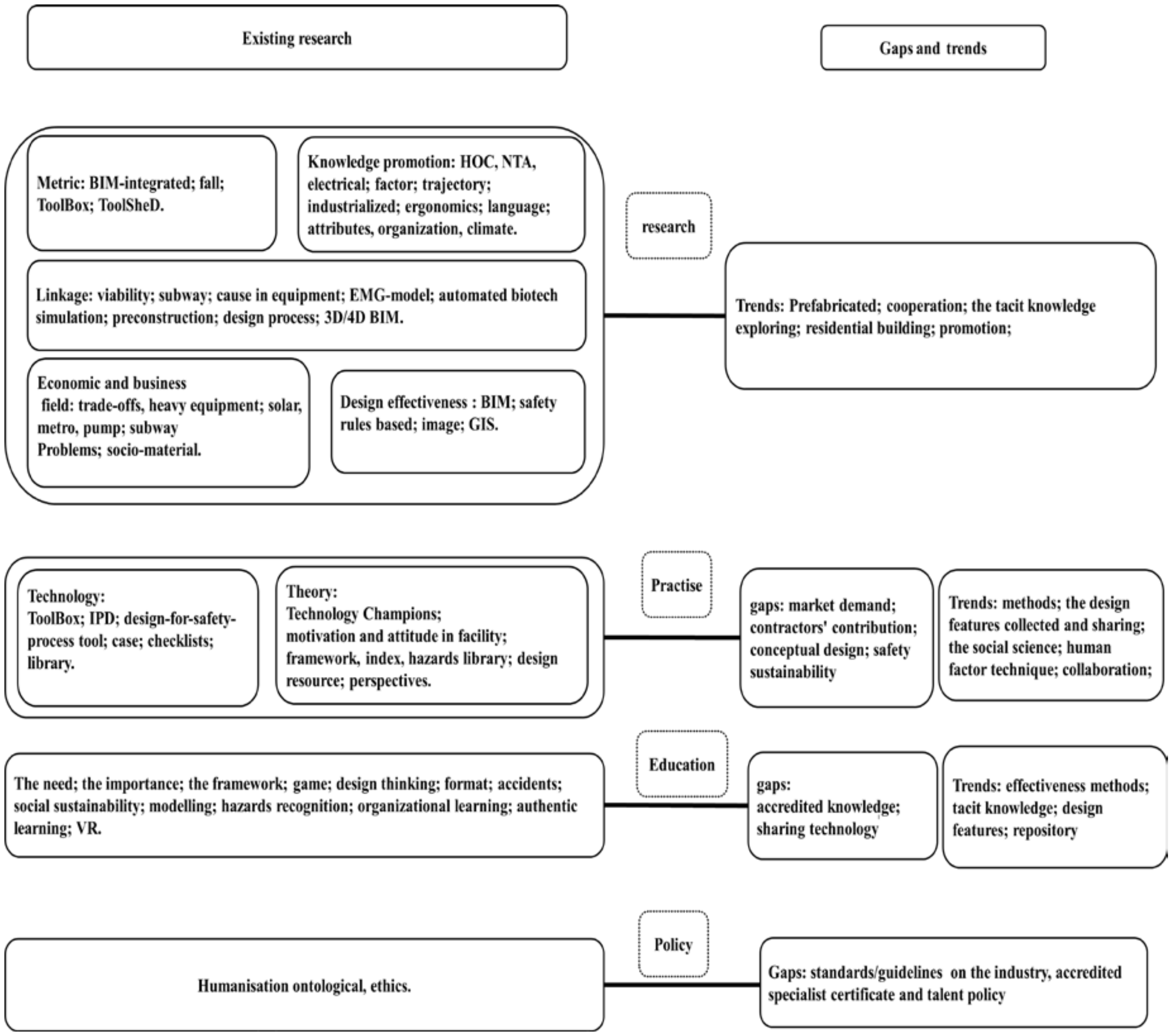

Figure 7. The framework of gaps and trends

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Recent National Construction Code Changes, Reduced Innovation, and Increased Contractual Risks

Christian van der Pump*[1], Eric Scheepbouwer[1]

[1] Department of Civil and Natural Resources, University of Canterbury, Private Bag 4800, Christchurch 8140, NEW ZEALAND

christian.vanderpump@pg.canterbury.ac.nz; eric.scheepbouwer@canterbury.ac.nz
* Corresponding author

Abstract:
A new clause recently added to the National Construction Code (A2.2(4)) has fundamentally changed the way performance-based design is developed. Previously, designers could formulate a design that was compliant as long as the applicable performance clauses of the National Construction Code were met. This freedom of design allowed designers to compete freely on innovation grounds as opposed to solely on price. However, on 1 July 2021, the new clause regulated this performance-based design process. Designers can no longer formulate a design that complies with the performance clauses. Now, designers must complete a performance-based design brief to be disclosed and approved by multiple parties, many of whom do not have an approval's role, contractual role, or suitable expertise. This process can represent a significant financial risk to developers since assumptions about how land may be built at the development approval stage may be inefficient if some parties do not agree to the performance-based design methodology for other than safety reasons. This new clause does not, by the authors' research, comply with the statutory Acts under which the National Construction Code is passed.

Keywords:
A2.2(4), Building Confidence Report, Combustible cladding, National Construction Code, Performance-based design brief.

1 Introduction

Due to numerous building failures in Australia, one of the most notable examples being the 2014 Lacrosse Tower cladding fire, Professor Peter Shergold and Ms. Bronwyn Weir were engaged by the Australian Federal Government to undertake an assessment of the compliance and enforcement systems for the building industry across Australia. This involved looking at reforms, considering strategies for improving compliance and enforcement practices, and making recommendations for best practice models for compliance and enforcement, to strengthen the implementation of the NCC. The result was the Building Confidence Report (BCR), published in February 2018 (Shergold and Weir, 2018).

As a result of this BCR, one of the main changes to the National Construction Code (NCC) was the introduction of Clause A2.2(4), which states the following:

Where a Performance Requirement is proposed to be satisfied by a Performance Solution, the following steps must be undertaken:

(a) Prepare a performance-based design brief in consultation with relevant stakeholders.
(b) Carry out analysis, using one or more of the following Assessment Methods: evidence of suitability, verification method, expert judgement, or comparison with the Deemed-to-Satisfy.

(c) Evaluate results from (b) against the acceptance criteria in the performance-based design brief.
(d) Prepare a final report that includes:
  i. All Performance Requirements and/or Deemed-to-Satisfy Provisions as applicable; and
  ii. Identification of all Assessment Methods used; and
  iii. Details of steps (a) to (c); and
  iv. Details of conditions or limitations, if any exist, regarding the Performance Solution.

Performance Requirement, Performance Solution, and Performance-based Design Brief are defined as:

Performance requirement means a requirement which states the level of performance which a performance solution or Deemed-to-Satisfy solution must meet.

Performance solution means a method of complying with the performance requirements other than by a Deemed-to-Satisfy solution.

Performance-based design brief (PBDB) means the process and the associated report that defines the scope of work for the performance-based analysis, the technical basis for analysis, and the criteria for acceptance of any relevant performance solution as agreed by stakeholders.

This new NCC clause was in response to BCR recommendations 8 and 14, namely:

Recommendation 8: *That, consistent with the International Fire Engineering Guidelines, each jurisdiction requires developers, architects, builders, engineers and building surveyors to engage with fire authorities as part of the design process.*

Recommendation 14: *That each jurisdiction sets out the information which must be included in performance solutions, specifying in occupancy certificates the circumstances in which performance solutions have been used and for what purpose.*

Recommendation 8 references the International Fire Engineering Guidelines (IFEG) which is a document produced by the Australian Building Codes Board (Australian Building Codes Board, 2005), with the most current version published in 2005. The IFEG methodology requires a “fire engineering brief” (FEB), described by the IFEG as “the scope of work for the fire engineering analysis and basis of analysis as agreed by stakeholders”. The word “stakeholders” is characterised in the IFEG as being the building consent authority, fire brigade, design fire engineer, peer review fire engineer, architect/designer, and building owner.

However, this paper will show that A2.2(4) of the NCC is of questionable legality and introduces significant contractual risks. Poignantly, it also does not respond to the likely causative factors that have contributed to the prevalence of combustible cladding across Australia (van der Pump and Scheepbouwer, 2022) despite recent cladding fires being the driver of the BCR. To illustrate the legality of A2.2(4) and the potential risks it introduces, the legal context will be detailed in Section 6 Findings and Discussion.

2 Literature Review

The literature reviewed covers legal areas the NCC is bound to by law, not just documents frequently cited within the construction industry, such as the IFEG, as the engineering literature is, by the author's investigation, devoid of any critique of the BCR's findings, whether it be positive or negative, and instead has accepted the outcome of the BCR (e.g., Cadena et al, 2022). The failure to review legislation for any type of (legal) deficiency in the face of significant building failures and conclude the issue is one of either design or workmanship is also reported (Buchanan et al, 2006).

The paper also addresses and references Australian case law, and in particular common law principles and doctrines that are accepted by Australia's state and territory supreme courts such as freedom of contract (Rares, 2013), negligence, and nuisance (Trindade, 2007) as well as the federal circuit and High Court of Australia (Australia's highest court).

It is against these legal references that A2.2(4), a key outcome of the BCR, is critiqued. The BCR recommendation to include A2.2(4), as well as the Regulation Impact Statement (Australian Building Codes Board, 2020) that was conducted by the ABCB, did not address any of the common law principles and doctrines that, as will be discussed, are relevant to A2.2(4)'s legality.

The importance of this research cannot be understated, as the building and construction market is a highly regulated market. And where any type of legal instrument (such as the NCC) that is below a statutory Act is found legally incorrect, the courts in Westminster countries such as the UK, Australia, and New Zealand have the power to rule such legal instruments 'null and void'. Such rulings clearly impact an entire industry.

3 Research Methodology

The methodology adopted in this paper firstly involves describing the structure of Australia's legal system and the different tiers of laws, where each tier has a legal hierarchy over the law beneath it. If the lower tier legal instrument is not legally consistent with the law above it, any of Australia's State and Territory Supreme Courts can find it 'null and void'.

Following an outline of Australia's legal system and its hierarchy, a description of how the courts can review for the legality of many laws, including anything in the NCC. This is based on Australia's most cited legal reference about the legality laws, Delegated Legislation by Prof. Dennis Pearce (AO) (Pearce and Argument, 2017). This type of analysis falls within the area of constitutional and administrative law, which the courts have authority to rule on via what is known as judicial review. Unlike in other sectors of the economy, it is uncommon for practitioners in the construction industry to exercise their constitutional right to challenge the decisions and actions of government departments via the courts to ensure that government officials obey the law and act within their prescribed powers (Australian Law Reform Commission, 2016). This includes A2.2(4).

A2.2(4) is analysed using the legal principles applicable to the NCC (that are arguable under judicial review), as the NCC is not (as it will be shown) supreme law. Therefore, the NCC – including any of its clauses – can be ruled invalid by any of the state and territory's supreme courts if found illegal.

Some of the more basic economic characteristics of A2.2(4) are also analysed, such as what is known as the ‘holdout’ problem, the contractual risks the holdout problem presents, as well as A2.2(4)’s potential to stifle innovation by way of its mandatory requirement to disclose innovative design methods to other parties, including rival companies.

4 Structure of Australia’s Legal System

Australia’s legal system is based on the United Kingdom’s Westminster system, whereby the Government is divided into three separate co-equal arms, namely:

Legislature: The Legislature consists of a lower house where statutory laws are voted on, and, if passed by the lower house, are then voted on by the upper house, where if passed, they become law. Statutory law (Acts) is the supreme law.

Executive: The Executive consists of Ministers and government departments. The Executive’s role is to recommend policy, propose and pass secondary legislation under statutory Acts – known as Delegated Legislation (DL) – and administer laws (whether they be Acts or DL). Typically, DL are regulations, codes, orders, rules, etc. DL cannot be passed into law unless authorised by an Act.

Judiciary: The Judiciary consists of the Courts and their judges, who interpret and apply the law and produce case law, whether it be the interpretation of statutory law, the common law, or both.

The three co-equal arms exist at both federal, state, and territory levels; however, Queensland, the Australian Capital Territory, and the Northern Territory do not have upper houses.

The national Government of Australia is the Australian Federal Government (AFG), but its role in determining the laws each state and territory must comply with is limited by the Australian Constitution. Under the Australian Constitution, the AFG has no authority to pass building Acts that each state and territory (‘jurisdictions’) must comply with. Nevertheless, to facilitate efficient commerce between all jurisdictions, there is an agreement between all jurisdictions that a national building code is produced and introduced as DL under each jurisdiction’s building Act. This DL is known as the NCC, produced by the Australian Building Codes Board (ABCB). The ABCB is funded by the jurisdictions.

The legal status of the NCC being DL is important (Katter *et al*., 2021), since each jurisdiction’s respective building Act adopts it. Therefore, what is written within the NCC must be legally consistent with the statutory law that enables it. This matter is discussed in more detail in the following section.

5 Executive Oversight and Judicial Review

A DL introduced under a parent Act, must be legally consistent with its parent Act. The DL cannot, for example, specify that ‘person A’ has legal authority over a particular matter (e.g., approving building plans) when the parent Act does not grant this power. Nor can it mandate a fee be collected by an Executive entity for something that is not permitted under the parent Act (analogous to an illegal tax). The reasoning behind the importance of DL having legal consistency is simple. The Legislature passes statutory Acts by majority vote, which is the essence of democracy, and therefore Acts are supreme law. DL is not passed by the Legislature but instead by the Executive who comprise of persons who have not been voted in democratically. Therefore DL, whilst important and necessary, is not passed into law by democratic vote. Therefore, if the DL is in any way 'inconsistent' with the parent Act, it is illegal.

A mechanism that can be applied to rule DL illegal is via judicial review under the Judiciary, as it is the Judiciary that has the power to oversee the decisions and actions of the Executive, which includes judicial oversight over the content of DL. Each jurisdiction's supreme court has the power to rule any DL illegal on several legal grounds. Each legal ground is a large subject, and it is well beyond the scope of this paper to describe. However, to analyse A2.2(4) a brief introduction to each of the legal principles and doctrines that determine the legality of any DL follows here (Pearce and Argument, 2017):

1. Simple *ultra vires*: The doctrine of *ultra vires* is one of "beyond the powers" (Latin); it is a broad-ranging doctrine that essentially all other judicial review principles fall under. Simple *ultra vires* has been defined by the Full Federal Court of Australia as:

   "*The general approach to such a challenge was described by Rich J in Footscray Corporation v Maize Products Pty Ltd (1943) 67 CLR 301 at 308; [1943] ALR 221 at 224 (Footscray Corporation) as follows:*

   "Authorities are of little use in determining the validity of a particular by-law. The appropriate steps are to construe the statute under which the by-law is made and then interpret it to ascertain whether it is within the ambit of the statute."

   Although those observations were directed to a local government by-law, we consider that they apply to any subordinate legislative instrument, including the determination."

   Examples of simple *ultra vires* include breaches of common law rights such as interference with the right to contract or illegal imposition of a tax (fee).

2. Inconsistency (analogous to Repugnancy): Inconsistency occurs when there is a power to make a regulation under an Act, but the form it takes contradicts the provisions of the parent Act or another law.

3. Improper Purpose: The DL making authority must have addressed the specified purpose, and not for some improper motive or bad faith.

4. Uncertainty: DL cannot be uncertain. To have valid DL (from an uncertainty perspective), it must have two properties – it must be certain, that is, it must contain adequate information as to duties to be met, and it must be reasonable.

5. Unreasonableness: DL cannot be unreasonable; that is, it must not be so oppressive or capricious that no reasonable mind can justify it.

6. Procedural *ultra vires*: Where the Act prescribes specific procedural steps to make in the development of DL and these steps are not followed, the DL is procedurally *ultra vires*.

It can be found that a DL (or any one of its subclauses) breaches more than one of the legal principles identified above.

6 Findings and Discussion

6.1 Analysis of A2.2(4)

The starting point to analyse the legality of A2.2(4) is to establish the characteristics of the statutory Acts that enable A2.2(4) into law (as DL). In all Acts other than the Australian Capital Territory's Building Act 2004, it is stated the purpose/objective of the Act is to create (to the effect of) safe built environments. It is left to DL by prescribing the NCC as the means to produce safe buildings by way of procedural and substantive laws, whether prescriptive or performance based. Moreover, no jurisdiction's statute specifies that any design must be completed in a manner that requires consultation with any parties, whether the private sector or the Executive. Specifically, on the Executive side, the roles are as follows under each Act:

Table 1. Roles of Fire Authorities and Local Authorities (e.g., councils) under each jurisdiction's building Act

Jurisdiction	Fire authority's approval role under jurisdiction's parent building Act	Local authority/council role under jurisdiction's parent building Act
QLD	None under Sustainable Planning Act 2016 or Building Act 1975. Commentary under Sustainable Planning Regulations 2017, only when a design is completed.	None. Private certification, at the end of a design.
NSW	None under the Environmental Planning and Assessment Act 1979.	None. Private certification, at the end of a design.
VIC	Approvals granted by the Building Act 1993 under s 261 (at the end of design).	None. Private certification, at the end of a design.
TAS	None. Commentary role only under the Building Act 2016 s 132 (at the end of the design).	Approval's role under s 138 – 147 of the Building Act 2016, at the end of the design.
SA	Approval's role under s 122 of the Development Act 2016 (at the end of the design).	None. Private certification, at the end of a design.
WA	None under Building Act 2011. Commentary role only under the Building Regulations 2012 (at the end of the design).	Approval's role under s 124 – 127 of the Building Act 2011, at the end of design.
ACT	Approval's role under Section 30A of the Building Act 2004 (at the end of the design).	None. Private certification, at the end of a design.
NT	Commentary role only under s 8 & Schedule 3 of the Building Act 1993 (at the end of design).	None. Private certification, at the end of a design.

Thus, it can be seen from the above table that the Executive has no role in any aspect of design under any building Act; design is preserved for the private sector. Also, on the matter of the role of the Executive, its role, whether it be a commentary role or approval's role, occurs at the end of the design period. No building Act grants the Executive an approval's role to determine how a building can be designed and to have what is effectively a 'veto role' in determining what process, scope of work, technical basis, and acceptance criteria are acceptable. The Chief Justice of the High Court of Australia (Australia's highest court) stated in Plaintiff M47/2012 v Director-General of Security [2012] HCA 46 that '*delegated legislation cannot be repugnant (inconsistent) to the Act which confers the power to make it*'. There is a clear argument that A2.2(4)'s requirement to involve the Executive in the design process, and to grant the Executive an effective veto role on the process, scope of work, etc., is inconsistent with each state and territory's respective building Act.

Where there is silence on a statutory matter, common law doctrines are the law such as the common law doctrine of freedom of contract. The Executive is not permitted to have any control over the private sector's activities. This doctrine is frequently cited by the courts, one example being in the New South Wales Court of Appeal in Biotechnology Australia Pty Ltd v Pace [1988]: "*It is an attribute of a free society, as we know it, that it is generally left to parties themselves to make bargains. It is therefore left to them sometimes to fail to make bargains or to fail to agree on particular terms. Well meaning, paternalistic interference by courts in the marketplace, unless authorised by statute or clear authority, transfers to the courts the economic decisions which our law, properly in my view, normally reserves to parties themselves*". One of the earliest judicial review cases in Australia to strike out a DL for violating freedom of contract was in 1917 where a by-law was passed regulating what could be traded, which was subsequently ruled invalid (*Attorney-General v Metropolitan Meat Industry Board* (1917) 18 SR (NSW) 9). A2.2(4) prohibits freedom of contract, because it mandates design be subject to stakeholder agreement. Thus, there is a clear argument that A2.2(4) is *ultra vires* ('beyond the power of') the common law right to freely contract, as it is not possible to produce a design that complies with the NCC's performance requirements without stakeholder approval.

6.2 Contractual Risks

The contractual risks associated with A2.2(4) are inherently obvious as developments across Australia go through two stages. The first stage is the development approval process, whereby approval is sought from local authorities as to how the land is to be used. In the case of buildings, by-law issues which must be complied with such as built area to land ratios, minimum floor areas for any residential units, recession planes for assessing compliance with shading requirements, number of car parking spaces, aesthetic qualities, noise limitations, are but a few of the myriad of by-law hurdles that developments must comply with. The development approval phase of a project does not assess compliance of the building with the building code and is largely focussed on the effect of the external building envelope on neighbouring property. Therefore, no consideration need be given to compliance with the NCC at this stage. However, the external form a building clearly has impact on how a building is designed internally. A building that is proposed to be built on the long narrow rectangular plot does not have the same floor plate flexibility as a building of equal floor area on a square plot. To elaborate, a residential development on a long narrow plot, to be financially feasible, would require a certain number of units to be built. Issues such as means of escape are not addressed at development phase, and so to make the development feasible, downstream reliance on a trivial fire PBD such as a minor increase in travel distance to avoid the DtS requirement of a stair is commonplace, as an additional stair would require an additional independent corridor to service the second stairwell to which may render a project unviable. This is because an additional corridor consumes ground floor space that reduces available floor area of each unit below that of the minimum thresholds under a by-law. Such 'increase in travel distance' solutions have commonplace in residential developments, especially given the NCC at DtS level is typically limited to 6 m before an additional stairwell is required (c.f. other jurisdictions such as New Zealand where a corridor length of up to 25 m is permitted until an additional stair is required under the same circumstances). Such problems to ground floor space may not occur for a square plot since the degree of ground floor corridor disruption is clearly less, especially where a long narrow rectangular plot can only access the street frontage via narrower width of the plot – a necessary condition for means of escape.

As development approvals and building designs are not mutually independent of each other from the prospective building owner's perspective but are legally independent. Any assumption made at the development approvals stage that cannot be rejected (e.g., an assumption that a commonplace fire PBD will be incorporated) can now fail under A2.2(4) simply because a stakeholder chooses not to agree (i.e., 'holds out'). Such 'holdout' problems are well-known in microeconomic literature and occur when permission of all involved parties must be obtained before an action can be made, with the negotiation process potentially dragging on indefinitely at the expense of a project's feasibility (in this case, the holdout problem can only be avoided if a DtS solution is adopted). Moreover, the holdout problem gives other parties (in this case 'stakeholders') monopoly power (Ogilvie and Carus, 2014), which encourages them to demand the maximum amount of benefits they can receive (e.g., excessive fire precautions, which can lower their exposure to liability in tort (Ehrlich and Becker, 1972)).

A2.2(4) gives rise to the holdout problem, since the building owner, unless they can get all stakeholders to agree to the analysis methodology to justify an extension of travel distance, the PBD will not proceed, regardless of whether the PBD meets the necessary substantive legal thresholds that the NCC prescribe for every performance criterion. Moreover, and as previously mentioned, no party, whether they be an entity of the Executive or the private sector, have a statutory right to effectively cause the holdout problem.

The consequences of the holdout problem are not trivial from the perspective of contractual liability, since to obtain finance for any development, one commonly needs to demonstrate to the financier (usually banks) that certain fiscally related criteria will be met e.g., a building being able to open within a specific timeframe, person(s) who have made a down payment on a residential unit at the development approval phase will receive what they paid for. Such fiscal arrangements occur under contract law, since these are agreements between members of the private sector. With the holdout problem now a characteristic of A2.2(4), breach of contract is a distinct possibility since specific performance may not be possible. And where specific performance is not possible, expectation damages become a legal entitlement for those whose contractual entitlements are breached. Such economic circumstances (e.g., breach of contract), described above, can only be avoided if DtS provisions are the chosen design pathway.

6.3 Reduced Innovation

Innovation, by definition, means doing something rival competitors have not, or are not, doing. The procedure to innovate obviously requires methodologies that have not in any way been repeated in the past (otherwise this would be emulation) with a result that is unique to that design. Innovation cannot occur with DtS solution, as DtS solutions are prescriptive. However, with a PBBC, innovation is obviously possible since a design's only requirement is that it meets or exceeds the relevant legal thresholds that are specified in a PBBC.

A2.2(4) creates the holdout problem, with the risk that any stakeholder may decide not to accept a methodology proposed by the designer for any reason. Any stakeholder may hold out until the cost of the PBD outweighs the cost of the DtS.

With these new procedural risks introduced into the NCC under A2.2(4), the best response to manage this risk is to avoid a PBD wherever possible. This then creates a cost to the developers of sites that were previously able to be developed to their maximum use no longer being able to do so.

Another factor associated with innovation is the right to protect intellectual property rights, often in the form of trade secrets. Trade secret law is not addressed in Australia in statutory law; however, a business's trade secrets can be protected via contract law. As A2.2(4) requires disclosure of the design procedure to all parties (stakeholders), there is no obligation for any stakeholder not under contract to not disclose any type of trade secret to a rival company. As trade secrets can therefore be disclosed to a rival company without the repercussions of breach of contract, any company wishing to see a return on its investment via trade secrets now has to compete with a rival company who can produce the same innovative solution but has not had to incur the cost of innovation. The net result is likely a move away from innovation.

6.4 Other Liability Risks

The purpose of a building code is not complicated. As described by Judge LC Rowe: "*a building code is concerned with the design and construction of buildings to meet specified objectives relating to such matters as the safety, durability, ventilation, sanitation of building to name a few*". The NCC is no different in this regard, where every performance clause in the NCC clearly states design requirements for buildings. Moreover, LC Rowe went on further to say that it is incorrect to suggest compliance with a building code depends to varying degrees on human agency or judgement. All NCC performance criteria reference design requirements for buildings and therefore set substantive legal thresholds that a design must meet. However, after its introduction, A2.2(4) of the NCC requires a PBDB, which, amongst other things, defines the criteria for acceptance of any relevant performance solution (as agreed by stakeholders). The NCC performance criteria does not state that design criteria are based on what stakeholders deem acceptable.

The liability risks here are that when forming a PBDB with stakeholders, even where parties agree to "the scope of work for the performance-based analysis, the technical basis for analysis, and the criteria for acceptance of any relevant performance solution as agreed by stakeholders", this design criterion may not result in a design that complies with the relevant performance clauses of the NCC. It is these performance clauses that must be adhered to.

6.5 Failure to Address Causative Factors

When some type of building failure occurs, as was the case with the Lacrosse Tower fire, it is the common law doctrines of negligence and nuisance that the courts consider, as there must be some type of actionable harm or damage before liability can be assigned. Australia's states and territories have largely adopted statutes that address these common laws (e.g., NSW's Civil Liability Act 2002), but they still closely resemble the common laws of negligence and nuisance.

The BCR report did not investigate any specific case of a building failure to determine causation, for example, defined under s 5D of the NSW Civil Liability Act 2002 as: *that the negligence was a necessary condition of the occurrence of the harm, and, that it is appropriate for the scope of the negligent person's liability to extend to the harm so caused*. It would not have been possible for the BCR's authors to establish causation, as this can only occur where the court sanctions the powers of discovery for one party to obtain the information held by the other party for a civil claim. And since causation is a key step in determining liability, there is no incentive for any party to disclose information that establishes causation, as this opens the door to civil claims. Thus, given the BCR did not have the legal authority to use the powers of discovery, it is difficult to see how A2.2(4) – an outcome of the BCR – in any way mitigates against future actions that may be a causative factor that results in harm. Moreover, the author, in a separate paper, has established that a causative factor that results in problems such as combustible cladding – the likely driver for the BCR – was the NCC itself, with deficiencies that did not adequately address the external vertical spread of fire.

7 Conclusion and Further Research

This paper has shown that National Construction Code clause A2.2(4), based on the IFEG, may be illegal. Not only does A2.2(4) lend itself to having characteristics of uncertainty and ultra vires, but it also allows the 'holdout problem' to operate, resulting in many prospective building owners preferring a DtS option over a PBD. Other issues, such as contractual risks and reduced innovation, are also likely to contribute to avoiding PBD. But perhaps the most concerning aspect of A2.2(4), is that it relies on a "stakeholder consensus" approach to determine what the acceptable design criteria must be, despite being legally defined by the performance criteria of the NCC, a matter that the Judiciary has already echoed its opinion on.

Concluding, as with any study on the legal soundness of delegated legislation, the issue under debate is hypothetical until tested in the courts, and as such theoretical implications are equally as debatable. On the practical front, should the courts be called on to review A2.2(4), in the opinion of the authors, A2.2(4) would be ruled invalid under judicial review. Moreover, an area for further research and publication, are the consequences of false or incorrect (negligent) design information supplied by a "stakeholder" who is not under contract. Under laws such as the Australian Competition and Consumer Act 2010, liability may not reside with the "stakeholder", but with the design consultant that adopts false or incorrect information.

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Ontology-based Representation of Implicit and Explicit Knowledge for Job Hazard Analysis: Focusing on Water Infrastructure Jobs

Sonali Pandithawatta[1]*, Raufdeen Rameezdeen[1], Seungjun Ahn[2], Christopher W.K. Chow[1] and Nima Gorjian[1,3]

[1]Sustainable Infrastructure and Resource Management, UniSA STEM, University of South Australia, 61-68 North Terrace Adelaide South Australia 5000, AUSTRALIA
[2]Department of Civil and Environmental Engineering, Hongik University, P506, 94 Wausanro, Mapo-gu, Seoul, 04066, REPUBLIC OF KOREA
[3]Sustainable Infrastructure, South Australian Water Corporation, 250 Victoria Square/Tarntanyangga Adelaide SA 5000, AUSTRALIA

thalpe_panditha_wattage_sonali.pandithawatta@mymail.unisa.edu.au; Rameez.Rameezdeen@unisa.edu.au; jun.ahn@hongik.ac.kr; Christopher.Chow@unisa.edu.au; Nima.GorjianJolfaei@sawater.com.au

* Corresponding author

Abstract:
Given that each construction infrastructure project is unique, it is necessary to perform a Job Hazard Analysis (JHA) for all high-risk activities in every construction project. Due to the dynamic nature of construction sites, JHA needs to be conducted before the job and then updated when new information is added. In most cases, JHA is performed manually, and it is challenging to reflect the changes in the construction plans or schedules in JHAs. Considering these challenges associated with JHA practices, previous researchers attempted to automate the JHA process by building ontology-based solutions. However, most of these studies have only considered the explicit knowledge of JHA and ignored the implicit knowledge for hazard identification and control, which is considered as one of the most important knowledge components in the process of JHA. Thus, this research attempts to represent the JHA knowledge based on both the explicit and implicit knowledge of JHA in a form of ontology, focusing on water infrastructure jobs. To achieve this goal, a document analysis on JHA documents and a qualitative Delphi method were adopted to identify the implicit and explicit concepts and relationships regarding the identification and control of various hazards from the practitioners. This paper provides the concepts related to JHA and the relationships among them that can be mapped onto an ontology for automating JHA processes.

Keywords:
Conceptualisation, Job Hazard Analysis, Ontology, Safety Management, Water Infrastructure

1 Introduction

The construction industry is considered as a high-risk industry which has one of the most risk-oriented working environments that accounts for about 20% of occupational fatalities in the world. The increased numbers of workplace injuries and fatalities create irrevocable damage to the industry and its stakeholders (Asadzadeh et al. 2020). Hazard identification, as the initial step in safety planning, is very critical since if hazards are not recognized during the early stages, they cannot be eliminated, reduced, or controlled and could cause injuries. Moreover, the process of hazard identification in the construction industry is subject to a larger number of variables and unknowns compared to other industries (Mihić 2020). Therefore, as the standard process used to identify construction hazards, Job Hazard Analysis (JHA) is a risk assessment exercise which is heavily influenced by the experiences, knowledge, and biases of safety personnel.

Automation is a new and trending research area of construction safety management. Considering the inherent limitations in the traditional JHA, many researchers have tried to automate hazard identification and analysis. Some of these studies directly contributed towards the automation of JHA (Chi, Lin & Hsieh 2014; Wang & Boukamp 2011; Zhang, Boukamp & Teizer 2015) while others created an indirect contribution (Ding et al. 2016; Goh & Chua 2009, 2010; Kim et al. 2016; Kim et al. 2013; Lu et al. 2015; Rahman et al. 2018; Xiong et al. 2019; Zhong & Li 2015). However, knowledge sources used in most of these studies is limited to the explicit knowledge and they failed to incorporate implicit knowledge which is a critical knowledge component for JHA. Because of this limitation, these studies failed to develop important relationships between the hazards, causes and risks which should be determined by a safety expert's experience. Considering these limitations of the past studies, the current research aims to acquire explicit and implicit knowledge of the safety experts and develop an ontology to develop an automated JHA process which can assist work planners during the safety planning phase of a project.

2 Literature Review

2.1 Causality of Construction Accidents

Many researchers tried to understand accidents in the industrial settings by introducing accident causation models. In general, the ultimate objective of these accident causation models is to provide tools to prevent industrial accidents (Abdelhamid & Everett 2000). The different models are based on different perception of the accident process. Some of the most influential accident causation models and methodologies are: single event concept, determinant variable concept, domino theory, fault tree analytical methodology, management oversight and risk tree, Petersen's multiple causation model, Reason's 'Swiss Cheese' model, and system model of construction accident causation (Department of Energy 1992; Heinrich 1936; Mitropoulos, Abdelhamid & Howell 2005; Petersen 1971; Reason 1990). All these accident causation models attempt to identify the factors and process contribute towards an accident. For example, the system model of construction accident causation considers a system view of accidents and identify the production factors and conditions that create hazardous situations. Thus, these accident causation models can be really useful during the JHA process as the process try to recognize contributing factors, causes, and sub causes of possible accidents.

2.2 Job Hazard Analysis

A safety management system is an important mechanism to assist accident prevention and reduction by employing appropriate and consistent safety management programs including planning, education, training, and inspection (Bunn et al. 2001; Labour Department 2002; Moorkamp et al. 2014; Yoon, JS et al. 2013). JHA has been identified as one of the most important elements of a safety management system (Crutchfield & Roughton 2019). JHA is an efficient, proactive method for identifying, evaluating and controlling safety risks before the work takes place (OSHA 2002). In the Australian industry context, completing a JHA is required for any high-risk construction and maintenance work activities and is regulated by WHS authorities (Safe Work Australia 2019).

JHA is usually performed by a JHA team, which usually comprises a JHA manager, a safety representative, the leader of the work team and the people undertaking the work (Rausand

2011). JHA is a risk assessment method for analysing hazardous operations and concerns all risks relevant to a specific work task. JHA can help minimise WHS risks especially when the type of task or the work environment is new (ISO 2009). Generally, the JHA is performed through six main steps (Albrechtsen, Solberg & Svensli 2019): step 1 - Decomposing the job into functions, tasks, and steps, step 2 - Identifying potential hazardous events and conditions that can occur during the execution of each sub-task identified in previous step, step 3 - Assessing the potential consequences of the identified hazards, step 4 - Assessing the expected probability of occurrence of the identified hazards, step 5 - Assessing the risk of each sub-task based on the assessed probability and consequence with the use of risk matrix, step 6 - Identifying risk reduction measures that improve safety of the sub-tasks that have an intolerable risk.

As a systematic method for loss prevention, JHA has several advantages (Glenn 2011). When the JHA process is identified as a main element of the safety management system, it provides a methodology to bring reality to discussions about the quality of work being performed by employees. Since tasks are properly assessed, the control of hazards and associated risk is better defined and communicated. This will result in improvements in procedures, methods, protocols, quality of materials, equipment, tools, standard of training of employees and the identification of environmental problems and issues (Crutchfield & Roughton 2019). If the results of the JHA is properly applied, it delivers so many advantages by increasing the efficiency through proper control of hazards. A study conducted by Zheng, Shuai and Shan (2017) proves that a systematic JHA has the capacity to reduce the number of recordable injuries considerably. Crutchfield and Roughton (2019) and Yoon, IK et al. (2011) identify JHA as a simple instrument that helps to highlight the hazards of risky operations. Both managers and non-managerial level workers gain insight into task-specific risks by performing a JHA. The JHA gathers the team who are responsible to complete the work activity, and the process. Therefore, a JHA is not only making plans for safety, but also functioning as a planning tool for the productivity and quality of the task to be completed (Albrechtsen, Solberg & Svensli 2019).

2.3 Risk Assessment of Hazards

Mitigating risks as early as possible in the project life cycle is one of the main principles in any construction project. Despite undertaking risk management in the early stages of the project, residual risks will always be there which needs to be prudently handled during the construction phase. JHA process provide effective results in situations where the safety is not guaranteed by adherence to standard procedures or plans or by established barriers. Therefore, JHA is considered as one of the successful methods which has the ability to deal with this residual risk (Kjellen & Albrechtsen 2017). Evaluating the relative risk level of sub-tasks is considered as one of the most important steps in the JHA process (OSHA 2002). Risk is usually defined as the severity of an event combined with the probability or likelihood of that event occurring. The two measures, probability of occurrence and consequences place the risk in a standard scale from most negligible to the most severe to determine the priority order of treatment (Rozenfeld et al. 2010). Statistical analysis of historical accident data, which could provide the numerical probabilities and severity levels for accidents, would be a straightforward way to assess the risks. However, Albrechtsen, Solberg and Svensli (2019) has identified that the risk of hazards is often evaluated without expressing the values for probability of occurrence and consequences. The reason behind this is the extremely small likelihood of occurrence of most potential accidents, and the high rate of incident under-reporting. Thus, very large sample sizes would be required to achieve statistical significance of the distributions obtained. Fortunately, although evaluation of risk level of hazards is critical to improve safety management, precise assessment is not certainly necessary (Jannadi & Almishari 2003). As per Rozenfeld, Sacks and

Rosenfeld (2009) an estimated predicted risk level will be sufficient for the safety manager to take decisions.

3 Research Methodology

Ontology is a formal information model that explains and describes knowledge of a specific domain that can be communicated and shared by people and computer applications (Batresa et al. 2014). Thus, ontology development required sufficient understanding of the targeted knowledge domain. Knowledge can be acquired through the acquisition of explicit knowledge (knowledge that is easier to access and verbalize) and implicit knowledge (knowledge an individual acquired through experience, in an incidental manner, without awareness of what has been learnt) (Ettlinger, Margulis & Wong 2011; Hélie, Proulx & Lefebvre 2011). The development process of JHA ontology was supported by both explicit and implicit knowledge to increase the reasoning capability of the JHA ontology.

Water facility infrastructure projects consist of high-risk construction activities which involve dynamic interaction between workers, heavy plants and equipment, materials, and complex surrounding environment. Given the execution complexity and high potential risk involved in the infrastructure projects, the number of safety research conducted is significantly low (Altawil 2017). Considering these aspects, the research was conducted focusing on water infrastructure industry and the methodology was designed to acquire both explicit and implicit safety knowledge relevant to water facility construction.

The research was conducted in two stages. In the first stage, a thorough document analysis was conducted to identify the hazardous activities, hazards and control measures. The second stage comprised of three rounds of expert interviews to identify the relationships in the targeted domain. Research tools used during the development of JHA ontology is demonstrated using a flowchart as shown in Figure-1.

3.1 Document Analysis

A total of 115 JHA documents from 10 different contractors were analysed to identify hazards that are commonly found in the water infrastructure industry. These JHA documents represented the common construction activities such as excavation, concreting, welding, compaction, plumbing, drilling, lifting construction elements etc. The analysis also included 12 Australian codes of practices that are relevant to the construction work. The codes represented excavation work, hazardous manual tasks, welding work, abrasive blasting etc. From the document analysis a list of construction hazards was created and categorised based on the factors/causes of hazards identified from the literature. Moreover, a comparative analysis of multiple JHA documents produced for the same activity revealed some dissimilarities in the hazard's risk level and associated control measures. Thus, it was identified that there are some factors which are not depicted in the JHA documents influencing the risk level of hazards. Based on this information, a semi-structured interview guideline was prepared to identify relationships between causes, hazards, and risks.

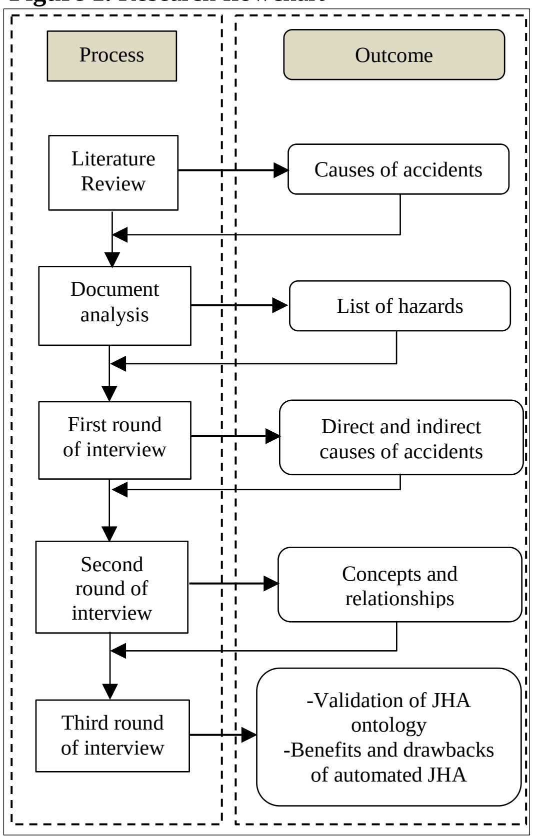
3.2 Delphi Study

Delphi methodology is known to be an effective technique for collecting and synthesising informed opinion on a specific topic and the information collected from the experts remain anonymous preventing participants from dominating others in the process (Whitehead & Day 2015). The purpose of adopting Delphi in this research is to identify the concepts and the relationships in the construction safety domain to develop an ontology. 18 construction professionals from 5 different companies were selected using purposive sampling technique based on their involvement in the JHA process of water facility construction activities. Participants' experience ranged from 5 – 34 years, with an average of 20 years. Table 1 shows the composition of interviewees who participated in this research study. SUP denotes the experts with a direct involvement in the JHA process and SAFE denotes the experts with an indirect involvement. During the first round the hazards and their causes identified from the document analysis were presented to the experts and asked to consider two broad questions – "How these causes could lead to an accident" and "What are the factors influence the risk level of hazards at the stage of JHA". Additionally, the experts were asked to identify any causes that were not recognised from the literature review. Content analysis of the collected qualitative data has resulted a list of direct and indirect causes of hazards and these direct and indirect causes were further categorised based on the nature of the origin and relationships exist between them. At the start of the second round, the categories resulted from the previous round were presented to the interviewees to obtain their consensus. The second round was mainly focused on risk analysis process of hazards done at the stage of JHA. Interviewees were asked to consider two broad questions – "How the risk level of hazards is determined during JHA" and "How control measures are selected to mitigate the hazards" – as a stimulus for generating relationships for the ontology. Moreover, during this round, the interviewees were informed about the automated system for JHA and asked them to identify the factors that can be successfully incorporated into the system based on their predicting capability. The content analysis of the qualitative data collected from this round resulted in a set of relationships between direct causes, indirect causes, hazards, risk, and control measures. This has resulted in a list of concepts and relationships that are needed build the JHA ontology. The third round was mainly focused on validating the findings of the two rounds and finding out the benefits and drawback of automated JHA process.

Table 1. Composition of interviewees

Interviewee ID	Designation	Experience
SUP1	Supervisor	28
SUP2	Supervisor	24
SUP3	Supervisor	32
SAFE1	Safety consultant	27
SUP4	Supervisor	15
SUP5	Supervisor	5
SUP6	Supervisor	18
SUP7	Site safety advisor	12
SAFE2	Senior safety advisor	21
SAFE3	Safety manager	27
SAFE4	Health and safety consultant	14
SUP8	HSEQ advisor	7
SAFE5	Safety manager	23
SAFE6	HSEQ administrator	12
SAFE7	HSEQ manager	34
SUP9	Supervisor	14
SAFE8	Safety consultant	30
SUP10	Field operation implementation manager	22

Figure 1. Research flowchart



4 Findings and Discussion

4.1 Risk Analysis for hazards

Risk assessment of hazards is the most important step that has to be done once hazards are identified. During the JHA process, risk analysis is performed at two stages. Initial risk is assessed with the existing conditions and the residual risk is assessed considering the impact of implementing mitigating strategies. According to the interviewees, a hazard by itself do not provide enough information to decide the suitable control measures. Hazard has to be expressed with its associated risk level to decide what control measures need to be undertaken. Therefore, risk analysis plays a vital part in the JHA process.

4.1.1 Initial risk analysis

The initial risk of a hazard varies with numerous factors. Document analysis revealed that risk level of a hazard depends on the nature of job step and the conditions presented during the execution of job step. According to the interview data all the interviewees who were directly and indirectly participate in the JHA process undertakes qualitative risk assessment due to the lack of statistical data presented in the field. Moreover, the interviewees highlighted the difficulty of relying on previous accident data to predict the risk level of hazards.

> "Even though the probability of a particular accident is 0.001%, no one can say that the same accident will not be repeatedly occurred within a small period of time". *(SAFE4)*

Historical analysis of safety data can be resulted in number of valuable features, which can be very useful for performing risk assessment and formulating risk mitigating strategies (Casal & Darbra 2013)). Numerous researchers have used multiple methodologies to determine accident probabilities using historical data (Bilir & Gürcanli 2018; Jannadi & Almishari 2003; Jocelyn, Chinniah & Ouali 2016; Lee & Halpin 2003; Nowobilski & Hoła 2022). However, some interviewees argued about the possibility of assigning a probability value for a particular hazard. These values could be precise for a system or for a plant. But applying these figures in the construction industry which has a dynamic environment may not be successful to assess the risk of hazards as in other industries.

> "It is impossible to give a numerical value as the probability of a particular hazard. Probability of hazards depends on various external conditions that present during the execution of an activity. Predetermined probability values do not represent those conditions. Thus, using quantitative method for risk assessment during JHA process wouldn't give much valuable input for decision making". *(SUP3)*

Determining severity of hazards is less problematic compared to determining probability or likelihood (Leveson 2015). Hazards that arise during a job vary based on the executing method and material or component associated with that particular job. When material or component and the executing method of the job step is known it is easier to determine the severity of hazards. Therefore, if it is possible to define a job step using the execution method and material or component associated, a severity value can be easily assigned to the hazards. As mentioned by interviewees if all the external conditions that presents at the working environment keep unchanged and workers are competent, the risk level of hazards won't change for a job step if it is executed using the same method and material or component. This revealed a relationship between the severity and the nature of the activity.

4.1.2 Residual risk analysis

Risk is expected to be remained even after implementing risk mitigating strategies. Thus, complete elimination of risk from the workplace is hard to achieve. Since risk can be mitigated by either controlling severity or probability, control measures can be broadly divided into two main categories. When it comes to the phase where JHA process is undertaken the control measures that are aimed to control the severity have already been implemented. Because the execution method and material are finalised at the early stages of risk management process. Therefore, at the moment of performing JHA, it's all about dealing with probability of hazards.

> "Out of the five hierarchies of controls, elimination and substitution are implemented at the early stages of risk management process. Elimination and substitution of hazards is achieved by changing the executing method or materials. When it comes to the JHA stage, it may not be cost effective to implement those control measures." *(SAFE5)*

Lower four rungs of the hierarchy of control: isolation, engineering controls, administrative controls, and Personal Protective Equipment (PPE) are used to control the probability of hazards. Isolation, engineering controls and PPE reduce exposure to hazard and thereby control the probability. Administrative controls help to regulate the behaviour of worker to reduce the probability of occurrence of hazards. During the assessment of residual risk, impact of each of these control measures in terms of controlling the probability, has to be taken into the consideration. Interviewees also flagged the importance being knowing the emergence of new hazards as a result of implementing risk mitigating practices. Sometimes hazards that were not originally identified during the hazard identification stage can become aggravating condition due to the execution of risk control measures.

4.1.3 Concepts and their relationships in the JHA ontology

Through the analysis of data collected from the first and second rounds of the expert interviews, concepts and the relationships for the JHA ontology were determined. In order to enable automatic reasoning over the represented JHA knowledge, concepts and relationships were categorised into distinct types and this created the foundation for the semantics of the JHA ontology. Using these data semantic rules were developed to enable the automatic risk evaluation of hazards over the external factors. Thus, each and every concept and the relationship in the JHA ontology support two inference mechanisms; "type inference" and "rule-based inference". Table 2 shows the list of relationships and the main concepts of the JHA ontology. All together these concepts and the relationships represent the main elements of the schema of JHA ontology which will later become the blueprint of the Knowledge Graph for JHA process.

Table 2. Relationships and concepts of the JHA ontology

No	Relationships	Associated concepts	Denotation
1	1A. primary_hazards_relationship	job_step, primary_hazards	These relationships exist between causes of hazards and hazards
	1B. workplace_hazards_relationship	workplace, workplace_hazards	
	1C. weather_hazards_relationship	weather, weather_hazards	
	1D. proximity_hazards_relationship	proximity, proximity_hazards	
	1E. atmospheric_hazards_relationship	atmosphere, atmospheric_hazards	
2	2A. primary_hazards_cm	primary_hazards, cm_ph	These relationships exist between hazards and their control measures
	2B. workplace_hazards_cm	workplace_hazards, cm_wph	
	2C. weather_hazards_cm	weather_hazards, cm_weh	

	2D. proximity_hazards_cm	proximity_hazards, cm_proh	
	2E. atmospheric_hazards_ cm	atmospheric_hazards, cm_ath	
3	3A. high_risk_relationship_wp	primary_hazards, workplace	High risk relationships exist between primary hazards and risk increasing external conditions to demonstrate the increased risk situations
	3B. high_risk_relationship_we	primary_hazards, weather	
	3C. high_risk_relationship_pro	primary_hazards, proximity	
	3D. high_risk_relationship_atm	primary_hazards, atmosphere	

4.2 Benefits of automated JHA

Each construction project is unique, due to the continuously changing nature of work activities, labour force and work environments. Therefore, JHA need to be conducted not just at the commencement of an activity but every time when a risk influencing external factor changes. Moreover, safety personnel identify JHA as a challenging task due to its labour intensive, complex and time-consuming nature. This makes it hard to quickly respond to the changes in the construction plans while maintaining the appropriate safety standards. Thus, a computer-based system could assist the safety personnel to execute the JHA process in a timely and accurate manner. Risk of construction hazards depends on numerous factors. Therefore, person who conduct JHA must consider many variables for each hazard in order to assess its risk. This makes the process more complex and time consuming. Consequently, there is a great chance for analysts to obliterate some important variables. Moreover, inaccurate risk analysis could lead to implement unnecessary control measures which could become a cost to the builder. Further, assessment of risk highly depends on the knowledge of the personals who perform it. Consequently, the process could be biased and inaccurate. A computer-based system would allow the analysts to largely incorporate historical data into the JHA process and to reduce the bias during risk analysis. Construction sector progressively becoming sustainable and because of that, organisations try to minimise the paperwork. With the recurrent nature of JHA process the involvement of paperwork is considerably high. Thus, a computer based JHA process could assist the creation and storing ability of JHA documents and reduce the paper waste largely. Interviewees also said that a computer-based system would attract the analysts and they may be more interested to engage in a computerised JHA process rather than in a paper-based system.

4.3 Drawbacks of automated JHA

Even though a computer based JHA process is developed with the hopes to increase its efficiency, it has some drawbacks as well. Traditional JHA process encourage worker participation and it is vital for the quality of JHA process. By incorporating the workers in the JHA process, they get a chance to share their valuable knowledge and promote greater ownership of the decisions taken. Further, it also enhances safety communication between workers and managers. Computer-based JHA process do not encourage worker participation in the process as traditional process and reduces situational awareness of workers. As construction can happen at anywhere in the world, there can be situations where the analysts have no access to the internet. This could limit the development of JHA documents and sharing it with workers. Since the risk analysis of the JHA process depend on numerous variables and the relationships are complicated, it is impossible to automate the entire JHA process. Thus, the analysts still have to put some effort to the process. Work health and safety standards change regularly. Thus, the computer-based system may need to update quite frequently in order to incorporate these new changes. Computer-based applications could force its users to rely too much on technology. Since JHA process is responsible for the safety of workers during the entire activity, possible inaccuracies could be ended as to injuries or accidents.

5 Conclusion and Further Research

Traditional JHA process has its own limitations due to lack of computer integration in the process. With the dynamic nature of construction industry, manual execution of each and every step make it harder to conduct necessary updates in the process. Considering this inherent drawback in the process, this research aimed to develop an automated method to execute the JHA process. An ontology-based method was adopted to achieve the aim of research. The developed JHA ontology covers comprehensive domain knowledge by incorporating codes of practice documents and previous JHA documents. Moreover, the integration of implicit knowledge of safety personnel, resulted in emergence of new concepts and relationships which facilitated the risk evaluation of hazards. During subsequent stages of the research, a Knowledge Graph will be developed on top of this JHA ontology and will be validated through case studies. As limitations, the proposed JHA ontology can only perform risk evaluation to the hazards that arise through the execution of the activity. No risk evaluation could be performed for hazards that arise from external conditions. Moreover, no residual risk evaluation is performed for the hazards after the implementation of suggested control measures. However, the system will still provide all the necessary information for analysts to determine the residual risk level of hazards.

6 Acknowledgement

Authors would like to thank South Australian Water Corporation and Mr. John Persinos for the support given during this study.

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Conceptual Framework for Suicide Prevention Process in Construction

Aparna Samaraweera[1*], TADK Jayasanka[2], Vidana Gamage Shanika[3], Rameez Rameezdeen[1] and Sonali Alankarage[1]

[1]UniSA STEM, University of South Australia, Mawson Lakes, SA 5095, AUSTRALIA
[2]Department of Building and Real Estate, The Hong Kong Polytechnic University, Hung Hom, Kowloon, HONG KONG
[3]Department of Building Economics, University of Moratuwa, Moratuwa, SRI LANKA

Aparna.Samaraweera@unisa.edu.au; kasunjayasanka22@gmail.com; vgshanika9@gmail.com; Rameez.Rameezdeen@unisa.edu.au; sonali_madhuwanthi.hewa_alankarage@mymail.unisa.edu.au
* Corresponding author

Abstract:
Suicide claims a substantial health and social issue for Australian construction industry. Being a male dominant industry, construction workers are known to be at a greater risk for suicide than other occupational groups. Recently, this issue has received high attention of the Australian government due to the reason that majority of the suicide victims being younger and working age generation. However, still the research related to construction suicide does not cater for the actual necessities in suicide prevention of the sector. Thus, this research aims to develop a conceptual framework for suicide prevention process in construction. This aim was approached through a systematic literature review. 57 research papers were considered for the systematic literature review and data were analysed through a content analysis. Systematic literature review revealed five major themes of: 'Suicide Risk', 'Suicide Behaviour', 'Suicide Prevention', 'Suicide Intervention', and 'Suicide Postvention'. A conceptual framework was developed by mapping these five themes. According to the framework, 'suicidal behaviour' will be particularly elevated in those, who are at suicide risk. Elevated suicide desire, respectively, causes suicidal ideation, suicide attempts, and ultimately suicide death. To mitigate suicide behaviour, the framework establishes suicide prevention strategies, which include Suicide Prevention, Suicide Intervention and Suicide Postvention. This research outcome would be important for the future researchers, policymakers and other funding organisations to develop research agendas related to suicide prevention in the construction sector.

Keywords:
Construction Industry, Mental Health, Suicide Behaviour, Suicide Prevention, Suicide

1 Introduction

Suicide rates among construction workers are estimated to be higher in the overall working male population in many geographical contexts around the world, particularly Australia, the United States (US), and the United Kingdom (UK) as developed countries (LaMontagne and Shann, 2020). National-level coronial statistics and census population data in Australia from 2001 until 2016 reports that workers in the construction industry have the highest suicide risk in both time and space clusters (San Too and Spittal, 2020). Consequently, Suicides in the construction industry have drawn national and international attention from the media, politicians, governments, and non-profit organizations (Tijani et al., 2021). In 2020, The Chartered Institute of Building (CIOB), which is the most prominent and the largest professional body for construction management declared that investigating the mental health and suicides among the workers in the construction industry should be a major priority. (Rees-Evans, 2020).

In light of elevated suicide rates of the world, researchers have been investigating suicide rates within different occupations (Windsor-Shellard and Gunnell, 2019) and job-related factors that influence suicide, to identify the link between suicide and occupation (Nishimura et al., 2004). Centres for Disease Control and Prevention (CDC), United States (US) has analysed suicide data from 32 states in 2016 by industry and occupation. This analysis reveals that construction industry having the second highest suicide rates among five major industry groups, and construction workers as an occupation group having the highest suicide rates among six major occupational groups when compared to rates in the entire study population (Peterson et al., 2020). Confirming mortality data from death registrations in England and Wales, the suicides of construction workers and machine operatives were reported as the greatest number of suicides among all other occupations in 2001-2005 (Meltzer et al., 2008) and again in 2011-2015 (Windsor-Shellard and Gunnell, 2019). There is not much difference in Australian context. The risk of suicide among Australian construction workers is six times higher than the risk of work accidents. Young construction workers are more than twice as likely to commit suicide as other young Australian men (MATES in Construction, 2022). For every person who dies by suicide, it is estimated at least 20 more attempt suicide (Wellbeing SA, 2021). In Australia, it is unknown the full prevalence of non-fatal suicidal and self-harming behaviors in the workplace. According to surveys, many people fail to seek medical care for self-harm injuries (AIHW, 2022). Thus, in recent few years, well-being of construction workers has received special attention of national authorities.

As construction workers are representing the majority of the suicides in the country, different non-government organisations such as MATES in Construction and Beyond Blue have initiated construction industry specific projects to enhance the well-being of construction workers (MATES in Construction, 2022, Beyond Blue, 2022). Tyler (2019) has underlined the need for more research in this area by conducting the first in-depth meta-analytical review of suicidal ideation and mental health conditions in the construction industry. Since research related to suicides in construction are at an infantry stage, few popular studies in the extant literature provide a theoretical or conceptual framework for the researchers to assist in studying the prevention of suicides in construction.

Many of the recent research is more focused on studying only the suicide ideation, and importantly the factors related to work and non-work that influence suicides in construction industry (see Ross et al., 2022; Tijani et al., 2021). In addition, Lingard and Turner (2017) elaborate on causal determinants of construction workers' health-related behaviour, health and wellbeing. Introducing the first ever Australian building and construction industry blueprint for better mental health and suicide prevention for 2018–2022, Beyond Blue (2018) publishes an intervention model including five aspects of suicide intervention such as (1) Promote positive impact of work on mental health; (2) Minimise harmful work impacts; (3) Provide the literacy on mental health and suicide prevention; (4) Enable treatment and, early intervention and (5) Provide return-to-work and continuous ongoing support. This model is more of a list of specific suicide prevention strategies to be adopted than a model to inform about all strategies available. However, to develop sound coping mechanisms construction industry wide, there needs to be a sound model that links the suicide ideation factors with the possible strategies. Therefore, the aim of this study is to develop a conceptual framework for suicide prevention process in construction. The methodology adopted in this study is described in the subsequent section.

2 Research Methodology

The aim of this study was approached through a systematic literature review. According to Li et al. (2014), systematic literature searching is transparent and minimizes the potential bias in identifying relevant publications for the study. Furthermore, such an effort demonstrates a mapping of how research is carried out in a specific area, clarifying the concepts and in the literature, identifying key issues related to a concept, analysing, and identifying knowledge gaps, and examining how research is carried out in a specific field as a precursor to a review (Chan et al., 2004). Hence a systematic record selection was carried out by following the checklist of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) since it directs researchers to implement best-practice for conducting a systematic review (Pahlevan et al., 2019)

The Scopus database was selected as the search engine and searched up to February 2022. The Scopus search engine has a comprehensive and up-to-date database of publications that includes over 23,452 peer-reviewed journals, 852 book series, and over 9.8 million conference papers from over 120,000 global events (Elsevier, 2020). The publications in this database are highly influential in directing future research fields. Moreover, the search was carried out on Web of Science (WoS) and Google scholar databases too. Journal publications in English language were only considered and no time duration was allotted for the search results. Authors have focused on main two aspects in keyword selection: “Suicide” (type A) together with “Construction industry” (type B) as detailed in Table 1.

Table 1. Keyword Selection.

Item no	Type A	Type B
1	Suicide	Construction industry
	suicidality	Construction sector
	suicide behaviour	Building industry
	suicide ideation	Building sector
	Suicide prevention	Construction work (worker)
	Suicide intervention	Building workers
	Suicide attempt	Building construction
	Suicide cost	Built environment

Hence, the search was carried out by using the following search string:

TITLE-ABS-KEY (("Suicid*") AND ("Construction industry" OR " Construction sector" OR "Building industry" OR "Building sector" OR " Construction work*" OR "Building work*" OR "Building construction" OR "Built environment")) AND (LIMIT-TO (LANGUAGE , "English"))

The search engines automatically search for the plural spelling of the same keyword. (Scopus and WoS). For google scholar, ‘Suicide’ ‘Construction industry’ search string is used. Search results from Scopus, WoS and google scholar were exported into Endnote software and then uploaded into Covidence software. After the Covidence software automatically removed 85 duplications, two authors independently completed an initial screening of titles and abstracts for eligibility. However, no inconsistencies or arguments were reported. Consequently, 92 irrelevant records were eliminated. Remaining 103 records were extracted for full text screening according to the eligibility criteria. 7 records were eliminated due to the unavailability of full text during that screening. The following eligibility criteria (exclusion criteria) were formulated to attain final records:

- Past review papers since they did not provide original primary findings.
- Past records that derived patterns of suicide by occupation
- Past records that only focus on suicide cost of construction industry
- Past records that only focus on calculating suicide rate in construction industry
- past records of research on mental health and well-being in the construction industry but not forcing suicide.

Ultimately, 57 studies were identified as eligible records for the systematic review. Next, a Microsoft Excel spreadsheet was prepared for extracting key details such as author, title, aim, findings, and limitations, to carry out the content analysis.

3 A Critical Analysis of Past Research in Suicides in Construction

Several reviews related to suicide in construction have been published through the years to identify the current state of art of the topic. Content analysis of the systematic review of literature revealed that all research could be categorised under five major themes of: 'Suicide Risk', 'Suicide Behaviour', 'Suicide Prevention', 'Suicide Intervention', and 'Suicide Postvention' as described below:

3.1 Suicide Risk and Suicide Behaviour

Many researchers focus on mental health in construction industry highlighting the increasing rates of suicide (see Chan et al., 2020; Tyler, 2019) to alarm the threat. Tyler, (2019) has conducted a meta-analysis to summarise the existing understandings of the prevalence and rates of suicidal ideation in the construction industry. Suicidal ideation is accompanied by suicide risk factors (Ge et al., 2017). Suicidal ideation is one of the most significant antecedents of suicidal risk, and it has been utilized in numerous studies to determine the presence of a suicidal behaviour (Ross et al., 2022).

There are researchers, who have attempted to discover the factors that increase the risk of suicides in the construction industry (see Kamardeen and Loosemore, 2016) that translate suicide ideation into suicidal behaviour (Ge et al., 2017). High levels of work pressure, the culture of drug addiction, isolation work, or work at remote locations, are prominent drivers for reporting high suicide rates in the construction sector. There are several explanations and research that highlight high suicide risk factors in the construction industry (see Milner et al., 2014). Bowles et al. (2019) have specifically focused on the Australian construction industry. Mental health issues, transient working conditions, job insecurity, workplace injury or illness, financial or legal troubles, maintaining relationships with children, interpersonal relationship difficulties, alcohol use, marital breakdown and associated issues, and substance issues are more general and industry-specific suicide risk factors among construction workers (Gullestrup et al., 2011; Milner, 2016; Tijani et al., 2021). Suicidal behaviour is defined as an action through which an individual hurt himself (self-aggression), despite the degree of lethal intention and recognition of the genuine reason for this action or continuum of behaviours (Milner et al., 2020). It starts from suicidal ideation, which serves as a warning sign of vulnerability and can progress to a suicide attempt or suicide. Hence, suicidal behaviour includes suicidal ideation, suicide attempt and suicide (Tijani et al., 2021; Ge et al., 2017).

Many researchers have calculated the economic cost of suicide and suicide behavior in the period of 2001-2012 by using Australian National Coronial Information System (NCIS) data (see Doran et al., 2015a). Kinchin and Doran (2017) discovered that the economic and financial advantage of reducing suicide behaviour far outweighs the expense of the strategy. Most of the studies including Doran, et al (2015a) have calculated economic cost of suicide by considering economic agents viz employers, workers, government; and categorizing it into six conceptual cost groups viz production disturbance costs, medical costs; human capital costs, transfer costs; administrative costs; and other costs. According to Gullestrup et al., (2011), every dollar invested in a workplace suicide prevention program such as MATES in Construction (MIC) in Australia yields a benefit greater than $1.50 of its cost, resulting in a positive economic investment. Numerous studies highlight the significant financial returns and social benefits from investing in workplace suicide prevention programs such as MIC (Kinchin and Doran, 2017). Hence, from suicide risk to the levels of suicidal behaviour following suicide ideation, suicide attempts, and suicide, suicide prevention strategies have been given the world's foremost attention.

3.2 Suicide Prevention

Suicides are preventable thus, much can be done to prevent suicides at individual, community and national levels. Suicide has a high human and economic cost, so measures to prevent it are critical (Turner et al., 2017). Suicide prevention strategies are established and implemented all over the world, which necessitate the use of up-to-date, high-quality evidence. In 2006, World Health Organization released the development of guidelines for workplace suicide prevention (Zalsman et al., 2016). The Australian Federal Government has responded with a variety of programs and activities in the face of terrible rate of suicide in construction industry (Kinchin and Doran, 2017; Tyler, 2019). "Mates in construction (MIC): impact of a multimodal, community-based program for suicide prevention" is one of the significant contributions of Australian researchers in this topic (Gullestrup et al., 2011). MIC can be identified as the workplace and industry-based program, which receive significant commitment from building site management for addressing this suicide issues. It includes suicide first aid, suicide intervention, training workers; training of gatekeepers (volunteer connectors); postvention support in the occurrence of suicide and providing suicide prevention hotline services (LaMontagne and Shann, 2020; Milner, 2016; Gullestrup et al., 2011). Education and training programs and life-care skills programs are provided by IncoLink from 2006 aimed at apprentices and young workers in the construction industry who are identified as the highest risk group (Broadbent and Papadopoulos, 2014). A policy addressing mental health and suicide has been issued by the Australian Institute of Building (AIB) as a national professional body. Other than support MIC, it raises the awareness amongst its members about this issue and the community at large (Turner et al., 2017, Tijani et al., 2021). The Blueprint in USA is supported by employers, industry associations, unions, and government bodies for suicide in construction (Turner et al., 2017) by introducing strategies under three streams such as 1) upstream: prevent problems from happening in the first place 2) midstream: identify problems early and connect people to help, 3) downstream: safe and compassionate responses to mental health crises (McIntosh et al., 2016). The Construction Financial Management Association (CFMA) is a professional organisation in US that is established by Construction Industry Alliance for Suicide Prevention (CIASP) and it educates, raises awareness, and provides training to its members about mental health issues (Beyer, 2020). Educate and inform the workforce, support an organisation in creating the right programme, visibly support the framework throughout the organisation with relevant and accessible communication materials and help build an evidence base (research) are major prevention strategies of Mates in Mind, UK which is led by Health in Construction Leadership Group (HCLG) (Jones et al., 2019). Restricting the means, reporting media responsibly, treatment and therapy, training, access to services, raising awareness, crisis intervention, stigma reduction, postvention, oversight and coordination and surveillance are commonly identified national and international suicide prevention strategies (Zalsman et al., 2016, Turner et al., 2017, Campbell and Gunning, 2020, Beyer, 2020).

3.3 Suicide Intervention

The much more appropriate type and amalgamation of effective and efficient evidence-based interventions for reducing suicidal attempts can be proposed based on related risk (Das, 2019), resources availability and situation analysis (Organization, 2012). Suicide Intervention can be defined as stepping in to assist an individual's proceeding system, which start from suicide ideation to suicide attempt (Klonsky and May, 2015). If suicidal ideation is disclosed, a safety plan should be created even if the danger appears low or non-imminent (Large et al., 2016). As intervention, it is always better to inform first responders or emergency services responders if a client is injured or at imminent risk of injury from suicidal behaviour (Juhnke et al., 2010). It is critical to educate clients, their families, and any other important stakeholders about probable variations in suicide mood and function, as well as what to expect in terms of relapse and how to react quickly before a psychiatric crisis occurs. Three forms of suicide intervention exist, including: 1) universal interventions, which are directed at the general public and cover the population as a whole; 2) Selected interventions target groups with a high risk of harm and can be used based on sociodemographic traits, geographic location, or the incidence of mental and drug use disorders. 3) interventions aiming to persons who are already recognised to be suicidally vulnerable or who have made suicide attempts are the target audience for the specified interventions (Gutman, 2005). A typical comprehensive suicide prevention framework employs a combination of these three types of interventions: universal, selective and indicated interventions (Organization, 2012). The studies emphasized suitable workplace health upgrading strategies and interventions viz encouraging quality relationships among colleagues, encouraging building teamwork, communication, job security etc. These interventions have the potential to improve protective factors against suicide attempts and mental illness in the construction workplace (Boschman et al., 2013).

3.4 Suicide Postvention

There is also a postvention component for suicide and industrial deaths (LaMontagne and Shann, 2020). Postvention refers to processes to lessen the consequences of the suicide attempt (Cox et al., 2012). Postvention refers to a set of pre-planned, proactive actions that are done following a suicide attempt but before suicide happens (Robinson et al., 2013). The basic goals of suicide postvention are to provide services for people affected by suicide, to facilitate coping skills, to prevent probable suicide contagion or imitative behaviours, and to identify members' ongoing needs (Lynn, 2008). That is, given that the suicide death of a person may raise the chance of suicidal behaviour in other populations in that person's life, preventing subsequent suicides is an important component of suicide postvention (Leschied et al., 2018). Postvention provides continuous assistance and care to workers who have tried suicide, as well as bereavement support in the event of an industrial worker's suicide (Gullestrup et al., 2011).

Suicide postvention includes monitoring of employees' mental health after inpatient or outpatient treatment and after suicide attempt, maintaining counselling and other service responses that are specifically tailored to the needs of the individual and reducing the impact of peer stigma reactions in the workplace (Research and Prevention, 2006). It is essential to complete a social assessment following a suicide attempt to determine which aspects of the treatment plan need to be changed. Further, following suicide attempts, rebuilding of trusting, therapeutic alliance, communicating with all involved healthcare providers and implementing a concerted postvention strategy to heighten awareness and ensure quick responses to avoid a cluster of suicides should be carried out as critical postvention activities (Ramsay and Newman, 2005). It is at most important the understand that each person will grieve in unique ways depending on their past and relationship with the person who has died, when formulating postvention strategies (Deranieri et al., 2002).

4 Conceptual Framework for Suicide Prevention Process

The major five concepts of 'Suicide Risk', 'Suicide Behaviour', 'Suicide Prevention', 'Suicide Intervention', and 'Suicide Postvention' were mapped into a conceptual framework for suicide prevention as depicted in Figure 1.

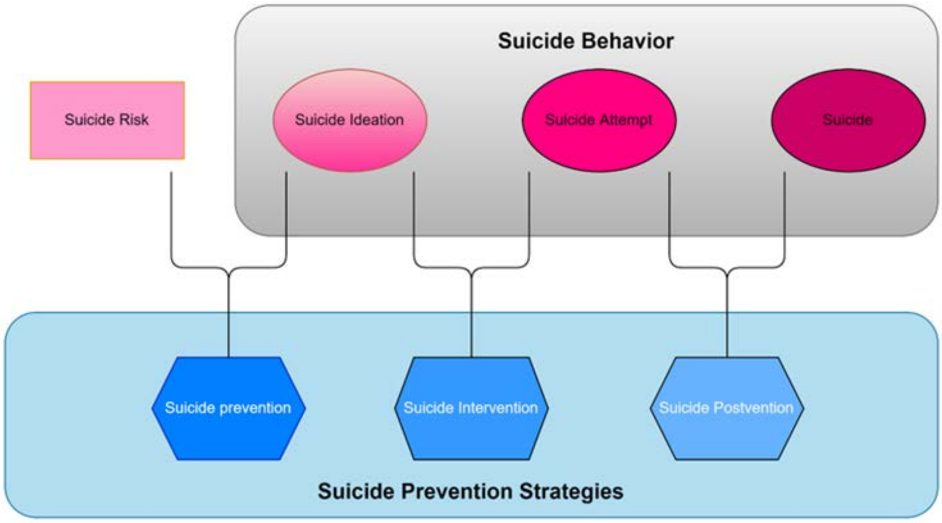

Figure 1. Conceptual Framework for Suicide Prevention.

Contemporary literature on the roots of suicide and the potential of suicide prevention indicates the possibility of reducing suicidal behaviour through prevention, intervention, and postvention as demonstrated in Figure 1 and as described subsequently. The interpersonal theory of suicide, which is the most prominent theory on suicide, explains why people commit suicide and how to spot people and who are at risk of doing so (Van Orden et al., 2010). Thwarted belongingness and perceived burdensomeness, which are birthed from suicide risk produce the desire for suicide (Joiner Jr et al., 2009). The desire for suicide is the most critical variable, which has a positive relationship with suicide behaviour (Bedrosian and Beck, 1979). Elevated suicide desire, respectively, causes suicidal ideation, suicide attempts, and ultimately suicide death (Jiang et al., 2021). Suicide-related outcome variables such as suicidal ideation, suicide attempts, and suicide deaths must be considered in broader prevention strategy (Zalsman et al., 2016; 2016; Ross et al., 2022). To mitigate suicide behaviour, the framework in Figure 1 establishes suicide prevention strategies which include Suicide Prevention, Suicide Intervention and Suicide Postvention. Suicide Prevention denotes the proper understanding of the risk factors for suicide ideation and the defensive steps made before the event occurs. Hence, prevention strategies may implement to mitigate suicide ideation resulting from suicide risk factors. Moreover, Suicide Intervention can be detailed as stepping into assisting an individual's proceeding system which starts from suicide ideation to suicide attempt (Klonsky and May, 2015). Suicide Postvention, according to Robinson et al. (2013), is a set of proactive, planned steps that are carried out following a suicide attempt but before the actual suicide. Thus, the suicide prevention strategies lead the Suicide Prevention Process, while minimizing suicide behaviour as denoted in the conceptual framework for suicide prevention in Figure 1.

5 Conclusion and Further Research

The aim of this study was to develop a conceptual framework for the suicide prevention process in construction. While it presents a comprehensive landscape of suicide in construction, it addresses the most important aspects: suicide prevention and goes beyond all other narrow views of past reviews, such as suicide rate, suicide risk, suicide cost, etc. The systematic literature review revealed five major themes of: 'Suicide Risk', 'Suicide Behaviour', 'Suicide Prevention', 'Suicide Intervention', and 'Suicide Postvention'. A conceptual framework was developed by mapping the five themes with an interpretation of "suicidal behaviour following 'suicide ideation', 'suicide attempts', and then 'suicide' would be particularly elevated in those, who are at 'suicide risk' for which, suicide prevention, intervention, and postvention strategies must be implemented". More importantly, this research identifies that three types of suicide prevention strategies could be identified from the extent literature named: 'suicide prevention', 'suicide intervention' and 'suicide postvention'. It is evident that majority of the support and directions for suicide prevention worldwide prone towards reactive measures involving suicide interventions and suicide postventions. However, it is evident that a new research agenda along with proactive solutions should be arisen by focusing more on suicide prevention strategies than suicide interventions and postventions.

Even though some governmental and non-governmental organizations in many countries around the world have implemented suicide prevention initiatives, many of them are unaware of the stage of the suicide behaviour at which those initiatives can be applied. As a result, the many of the efforts seems not giving the expected results and suicide behaviours are arising, and workplace well-being is being disrupted. The suggested framework in this study has revealed a significant finding that suicide prevention campaigns should be implemented to break the chain between suicide risk and suicidal ideation. Further, this framework provides a guide for suicide preventions, interventions and suicide postvention to policymakers, construction stakeholders, and other Non-Government Organisations to prevent suicides and ultimately its impact. The knowledge created from this research is essential for future researchers into suicides in construction to conceptualise the major themes in the area. Researchers and organizations worldwide have conducted thousands of surveys by sampling construction workers for years. Future studies can employ the proposed framework to mine these big data to derive useful information for suicide prevention.

The overall framework is an original work for construction literature since it was developed from past empirical findings of the "Suicide in the construction industry" in major. However, suicides are similarly prevalent among farmers, ambulance and fire services workers, veterinarians, entertainers, artists, miners, and transport industry workers (Case et al., 2020). Therefore, the proposed conceptual framework could be adapted by researchers and policymakers in those industries too, to expand their suicide prevention research, but with careful justifications and further studies.

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Re-Thinking Spatial Design in Homes to Include Means and Access Restriction with Material Impacts as Passive Suicide Prevention Methods: A Systematic Review of Design for Australian Homes

Michael Booth[1*], Pushpitha Kalutara[2] and Neda Abbasi[3]

[1]School of Engineering and Technology, CQUniversity, Brisbane, Queensland, 4000, AUSTRALIA
[2]School of Engineering and Technology, CQUniversity, North Rockhampton, Queensland, 4700, AUSTRALIA
[3]School of Engineering and Technology, CQUniversity, Sydney, New South Wales, 2000, AUSTRALIA

m.booth@cqu.edu.au; p.kalutara@cqu.edu.au; n.abbasi@cqu.edu.au
* Corresponding author

Abstract:
This systematic review analyses research discovering commercial design applications that could be adopted for suicide prevention in homes. Furthermore, the study equips a larger systematic literature review capturing social, spatial and biophilic design methods to improve wellness in homes using environmental design psychology. Safety and human wellness frame this spatial design research examining access and means restriction to improve home safety and prevent suicides. Suicide is a growing phenomenology deserving attention considering environmental impacts. There is a substantial evidence base to evaluate suicide prevention methods used in high-risk environments of health and healing environments, workplaces, and incarceration facilities. This review discovers design methods using spatial arrangement and material choices to improve human wellness in homes. Biochemical reactions as toxicology impact show stress impacts from this research for design use considering material choices and applications to *improve mental health in homes. Spatial design suicide prevention can guide various prevention measures, such as, adopting access and means restriction and environmental design methods for wellness, considering impacts during lock-down periods (e.g., during COVID-19). Environmental design psychology research supplies evidence for improved spatial arrangements in homes, with evidence showing design applications can restore and improve mental health. This systematic review shows evidence for planning methods to prevent suicides considering both access and means restriction with considerable biochemical impacts from design. Design methods discovered by this systematic review will be considered for future studies and used within economic modelling to demonstrate design guidelines to improve wellbeing and support existing suicide prevention methods, for Australian homes.*

Keywords:
Environmental psychology, Home design, Spatial design, Suicide prevention, Value management.

1. Introduction

This paper explores the question of suicide prevention using building design, by reviewing existing research using a systematic review process. The issue of home suicides provides significant impact to community function, where this systematic review is conducted to discover building design methods in homes for suicide prevention. A significant gap in knowledge is shown to exist in this review considering home design psychology research for suicide prevention. Suicide prevention considering mental health for home design planning provides phenomenal benefits, with 1 in 5 Australians experiencing mental health at some point in their lives (statistics, 2022). Environmental experience has potential to improve mental health (Abdelaal and Soebarto, 2019) and quell negative feelings that lead to, or contribute to ideation or intentional self-harm (Connellan *et al*., 2013).

Environmental neuroscience research shows biochemical impacts from building materials (Berman *et al*., 2019) that cause physical health impact to mental health as stress or depression. The rationale for this home design research is to determine causes for biochemical reactions or suicide triggers resulting from home designs, such as confusion, stress, sickness, or depression. Design solutions promote better mental health in homes to support community interventions, health treatment and physical suicide prevention methods. Considering mental health and psychological impacts as adverse biochemical reactions, can prevent impacts and promote health in homes using design (Julie, 2019, Torgal *et al*., 2012). Strategies of injury and suicide prevention design are reviewed for commercial health and healing spaces, (Abdelaal and Soebarto, 2019, Chrysikou, 2019, Connellan *et al*., 2013), incarceration facilities, workspaces (Hähn *et al*., 2020) and learning spaces (Peters and D'Penna, 2020).

Researching mental health benefits shows environmental psychology design improves productivity and wellbeing with improved health and recovery rates (Abdelaal and Soebarto, 2019, Gaminiesfahani *et al*., 2020). Mental health management using design for suicide prevention is explored in recent health and healing design research (Abdelaal and Soebarto, 2019, Chrysikou, 2019, Connellan *et al*., 2013, Postolache and Merrick, 2011) and demonstrates effectiveness for use in homes. Improving mental health in homes is important for designers to consider for our society, considering statistics in 2020-21 during COVID-19 which, out of 19.6 million Australians aged 16-85 years: Over two in five (43.7% or 8.6 million people) had experienced a mental disorder at some time in their life. (statistics, 2022) Further to this it was reported: 21.4% or 4.2 million people had a 12-month mental disorder and experienced a mental disorder at some time in their life and had sufficient symptoms of that disorder in the twelve months prior to the survey. (statistics, 2022)

Mental health affects approximately 43.7% of Australian society, where natural biophilic designs provide restorative effects from positive cognitive interpretation of natural forms and shapes (Oana *et al*., 2020). Complimentary stress reduction theory (SRT) and attention restoration theory (ART) shows benefits for wellbeing in homes using biophilic, social and spatial design (Abdelaal and Soebarto, 2019, Berg and Joye, 2012, Blaschke *et al*., 2020, Connellan *et al*., 2013, Kaplan and Kaplan, 2008, McGregor *et al*., 2017, Raby, 2018, Rentfrow and Jokela, 2016, Rowe *et al*., 2020). Environmental design psychology considering SRT and ART shows positive impacts where designers can micro-manage adverse design impacts in planning that cause biochemical stress impacts such as cortisol release (Luke, 2021). Health impacts by ‘routines of stress’ can alter brain patterns with continued release of chemicals such as cortisol, related to design impacts by odour, air quality, heat stress, mould, or allergies from material toxicology (Torgal *et al*., 2012). By considering environmental neurocognition and biochemical impacts (Bailey *et al*., 2021, Berman *et al*., 2019) design applications can support mental health, such as; anti-viral lighting in high density residential space (Seme *et al*., 2021). Value management can be useful for considering the cost/benefit variables (Kelly *et al*., 2014) in the design stages for constructions. For this research design we consider suicide prevention methods and demonstrate preliminary value estimates of methods based on research findings.

2. Research methodology

Six sub-questions supply a systematic review framework for this suicide prevention method research, using spatial design considering material impacts. Sub-questions show the need for this systematic review with resounding societal benefits, listed in short below.

- Investigate the effect of intervention using building design for suicide prevention.
- Investigate the frequency and rate of mental health conditions to the population of Australia including the models of suicide, and statistics in homes.
- Establish supportive design guidelines for health improvements considering mental health impacts for home designs.
- Aetiology examining impact theory for physical and contributory causal factors related to phenomena of suicide, in homes.
- Determine suitable design solutions for addressing biochemical impact risks for future cost/benefit economic analysis.
- Identify adverse design impacts for future value management cost/benefit analysis as a supportive quantification analysis for suicide prevention guidelines.

The research design is a systematic review, which is part of a larger systematic literature review into suicide prevention in home designs. This building design review finds evidence to advance methods to improve health (Jiang *et al*., 2021, Manzar *et al*., 2021, Pollock, 2019, Raby, 2018, Thodelius, 2018, Wang *et al*., 2020) and prevent suicide. Environmental psychology, environmental neuroscience and biochemical environmental impact are reviewed for impact evidence, with Prisma systematic review diagram adopted, (Page *et al*., 2021) as shown below.

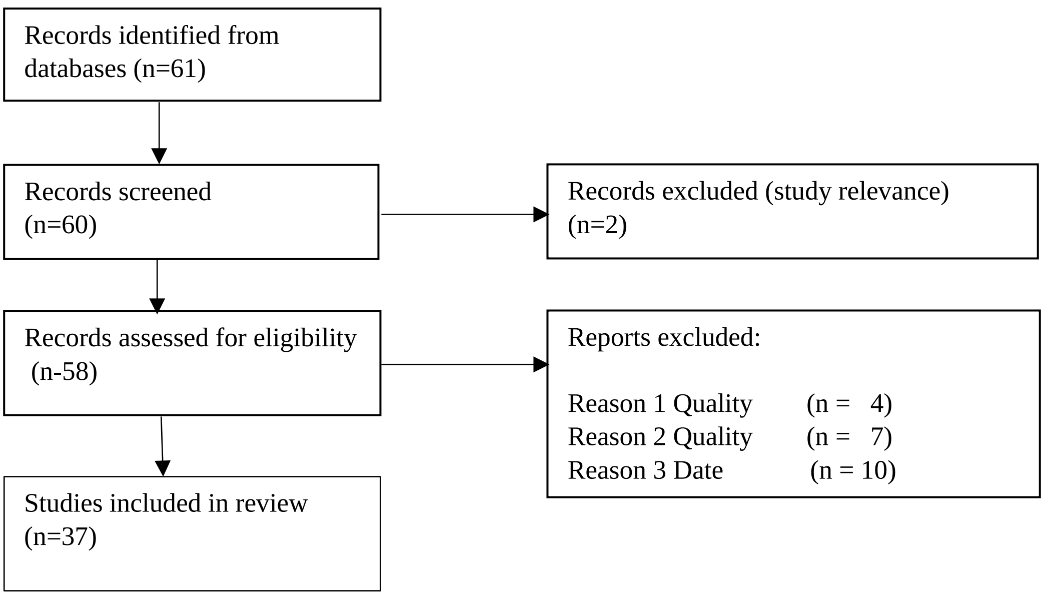

Figure 1. Prisma systematic review screening diagram.
Source: Page et al. (2021)

Exclusion search criteria was by relevance, date and topic significance for suicide prevention and mental health benefits. Inclusion of articles was conducted using search terms;

environmental psychology, suicide prevention, mental health design, access and means restriction, biochemical impacts, toxicology, biophilia, SRT and ART. This systematic review explored 61 articles, searching academic databases including PubMed, ProQuest, EBSCOhost, Science direct, Emerald, Wiley, and PubMed, for peer reviewed research in health and design methods. 37 articles were included for this systematic review study, with 21 articles removed by exclusion criteria related to quality, relevance, date and or relevance as key industry findings where research on topic is sparse. Key findings show methods using design addressing suicide and identifies considerable design benefits to improve wellbeing, and ameliorate feelings of hopelessness, suicide ideation and/or biochemical impacts from stress (Luke, 2021). Future research will stem from topics identified from this research and combine theory findings to collate empirical evidence-based design guidelines (EBDG).

3. Results and discussion

This systematic review examines existing design evidence suitable for health improvement and suicide prevention including wellbeing design methods for homes. Mental health is a considerable part of environmental neuroscience as design psychology for neurotransmitter reactions from design that can cause biochemical reactions such as stress, fear, or confusion. Stress reaction cause cortisol release, whereas toxicology causes more physical impacts such as allergies, and asthma as caused by pollutants or poor air quality (Torgal *et al*., 2012). Along with physical reactions to design, adverse environmental design psychology impact can cause or contribute to adverse mental health reactions such as fear, confusion, helplessness, anxiety.

Relative models of theory for suicide prevention by design were included in the review by Wasserman (2022). Sociological theory (societal and community influences on suicidality), hopelessness theory (central role in suicide as a fatalistic expectation of an individual), psychache theory (intense psychological pain; pain can overpower any protective mechanism), escape theory suicide (failure, disappointment; used to escape problems), interpersonal-psychological theory of suicide (feeling disconnected from society and burdensomeness) with a relevant model considering environmental impacts for suicide by Stress diathesis model (Wasserman, 2022). The stress diathesis model describes suicidal behaviour as influenced by individual biological/psychological predisposition, as well the surrounding environment (Wasserman, 2022). Mental health design is included in health and healing settings for suicide prevention, which can be used in homes, considerable for ameliorating feelings related to the stress diathesis model, hopelessness theory and interpersonal-psychological theory. Design to improve metal health in homes will supply recovery and restoration environments to boost recovery from sociological theory, psychache theory, hopelessness theory, interpersonal theory, and stress diathesis model, as suicide prevention. Improving mental health in homes for suicide prevention shows benefits across literature to include biophilia, spatial and social aspects (Abdelaal and Soebarto, 2019, Oana *et al*., 2020). Environmental design information from healthcare spaces (Connellan *et al*., 2013) can reduce stress and ameliorating depression or suicidal ideation effects. Means and access restriction is further reviewed (Connellan *et al*., 2013, Pollock, 2019, Raby, 2018, Thodelius, 2018, Jiang *et al*., 2021) as a useful physical strategy to prevent suicide events considering mental health, biochemical and adverse physical reactions to built environments.

This systematic review research has been designed collating physical restriction, physical and mental health design impacts, for home designs considering risk areas, as a way to support existing prevention. Subsequent sections will further guide through a detailed description given to those critical aspects of home design and suicide prevention.

3.1 Spatial design: Access restriction and wayfinding

'*A persistent challenge for built environment design approaches to similar designs for means restriction applies to statistics that 75% of suicide deaths occur at home, (Pollock, 2019)*'.

Barriers for suicide by jumping is an important suicide prevention strategy, where access to lethal means is included in suicide prevention literature regarding firearms, poisons and medications (Wasserman, 2022) where barriers for tall buildings with casual or video surveillance is shown to be useful (Raby, 2018, Wang *et al*., 2020). Means and access restriction is suitable to compliment mental health design and suicide prevention design in homes with tall spaces, considering barriers, and reduced capacity persons. Prevention of hangings is shown as more suitable for controlled environments and institutions considering forced confinement with access by design considerable for psychiatric hospitals and prisons (Wasserman, 2022). Safety is a structural objective of building design legislation such as the National Construction Code (NCC) and in this review we further analyse impact of designs post construction considering safety, psychology, and health impacts. Badly designed wayfinding causes confusion if complex and not user friendly that can cause life loss, in emergency events. Wayfinding is important for design to reduce mental health impacts where mental health research by Mackett (2021) shows factors related to confusion, helplessness, and anxiety, as threatening or uncomfortable experiences. Negative wayfinding design feelings can lead to future psychological sequalae for avoiding those systems (Mackett, 2021). Means and access restriction is reviewed (Pollock, 2019, Thodelius, 2018, Connellan *et a*l., 2013, Raby, 2018, Jiang *et al*., 2021) as a useful physical strategy preventing injuries and suicide events, with barriers, guards or fencing as effective access restriction, supported by educational signage for support services in high risk areas, (Wang et al., 2020). Spatial design research showed benefits for spatial design to prevent injuries or jumping. Further health benefits stem from spatial design planning to safety and refuge along with privacy diagrams, with biophilia showing benefits for cognitive restoration (Berg and Joye, 2012, Peters and D'Penna, 2020), spaces to escape, rest and restore mental cognition.

3.2 Biochemical impacts: Physical and mental health

Biochemical impacts to human health and wellbeing can include adverse reactions to a built environment, often resulting from incompatible material choices, poor assembly, or design methods. Air quality, sick building syndrome or odour are considerable causes for both physical and mental health impact from prolonged exposure. A common example of material impacts in adverse biochemical reactions in homes often arises in situations by water penetration, or wet seal failure providing chemical material decomposition factors.

A review of microbial aerosols shows 'exposure to microbial aerosols is still common in many different environments and is often the cause of many adverse health effects' (Górny, 2020). Toxic reactions from buildings are researched by Torgal (2012) on 'toxicity of buildings' showing a variety of health-related material impacts for users. Bio-material reactions result from: wood preservatives, nanoparticles (insulation, cement, paint), volatile organic compounds (VOC) including chemical carcinogens, and endocrine disruptors (Torgal *et al*., 2012). Toxicity in buildings leads to health concerns from users over building material impacts, causing poor health from dangerous gases, particles, or fibres emitted at room temperature. Materials can decompose over time and use, such as carpet, linoleum, paint or plastic products becoming airborne, with older paint products containing lead, and other materials containing radionuclides that can lead to ionizing radiation exposure (Torgal *et al*., 2012). Common VOC air pollutants occur in indoor spaces such as; formaldehyde, benzene, xylene, acetaldehyde, naphthalene, limonene, and hexanal that can cause health effects such as; eye and respiratory irritations, headaches and mental fatigue (Torgal *et al*., 2012).

Environment impacts such as heat stress, climate and geographical design location can be considerable for design impacts on wellbeing. Results of a study by Florido (2021) investigating heatwaves and relative humidity with suicide (fatal intentional self-harm) showed humidity more significant related to suicide than heatwaves, with youth and women more significantly affected (Florido Ngu *et al.*, 2021). Findings show design for heat stress humidity can address patterns of poor mental health related to suicide. Daylight impacts on wellbeing, (Connellan et al., 2013) circadian rhythms and melatonin (chemical) release, impacting function over time. Literature reviewed showed 'that windows and skylights confer benefits to home occupants through physiological and psychological mechanisms' (Connellan *et al*., 2013). Benefits are experienced by access to a view and increased daylight exposure (Knoop et al., 2020, Wirz-Justice, 2018), that can easily be included as a base measure for design suitability. Disease spread considering impact of COVID-19 to mental health impacts can be mitigated, adopting health design. Lights and fittings can be used at entries and exit of public spaces for high density home environments such as lifts, foyers and exits. Copper handles 'enable a reduction of the bacterial load on surfaces, in liquids and air' (Seme *et al*., 2021). Automatic disinfection in publicly accessible surfaces, such as handrails and material choices such as copper or brass doorknobs can help to reduce disease spread, improve safety, and improve mental health. Copper/brass doorknobs can be installed to reduce disease and viral transmissions, with a review by Govind *et al*. (2021) showing the following results:

1. Copper surface: COVID-19 virus active – 4hrs (plastic/stainless steel – 3 days).
2. Disease spread minimized.
3. Copper preferred for doorknobs, push plates, handles, stair railings, restroom faucets, and other applications. Public surfaces prone to disease-causing microbes.
4. Copper has antimicrobial properties (Govind *et al*., 2021).

'Exposure of copper to COVID-19 is reported to inactivate viral genomes and showed irreversible impact on virus morphology, including envelope disintegration and surface spike dispersal'. (Govind *et al*., 2021) Design using biomaterials to reduce disease spread in home is a promising design method to mitigate COVID-19, improving health in homes. Lighting benefits for wellbeing can be considered for design now including anti-bacterial lighting (Seme *et al*., 2021) at entrances and public spaces. Research by Rentfrow and Jokela (2016) on geographical psychology showed: Ecological influence contributes to geographical variation in psychological phenomena. Considerable evidence indicates features of natural and built environments, such as climate, terrain, green space, and urban crowding, can affect individuals psychological processes. (Rentfrow and Jokela, 2016) Further results showed living near green spaces fosters well-being, reduces stress, and in geographical areas with high pathogen prevalence, personality traits were cautious and risk-averse behaviour is more common

(Rentfrow and Jokela, 2016). Architectural health design is covered in the systematic literature review conducted by Connellan (2013), for suicide prevention design planning methods considering stress, and shows design evidence for:

- Biophilic design
  - Gardens and art
- Social design
  - Casual observation and connectedness
- Spatial design aspects
  - Security, access restriction and natural lighting (circadian rhythms, chronobiology)

Design evidence on mental health impacts for improving interior design in health and healing environments, includes a mental health focus on user experience, including post occupancy evaluations (Connellan *et al*., 2013). Biochemical and psychological stress responses to environmental design impacts such as allergies, is a natural stress response to defend our human environment from harmful events or impact. Complete home environment analysis provides limitations for this research by complexity, although relevant for inclusion in economic modelling cost/benefit analysis, in a larger future systematic literature review.

3.3 Environmental design psychology: Mental health

Environmental psychology research demonstrates robust evidence for designs to improve mental health and prevent feelings associated with suicide. Literature shows benefits of stress reduction, using design theory of Stress reduction theory (SRT) to improve health and healing in environments (Connellan *et al*., 2013), to improve mental health in homes. Environmental design psychology considered for health spaces and aged care designs (Marston *et al.*, 2021) can be used in home design to improve functionality. Environmental psychology theory of Attention restoration theory (ART) can further provide benefit of rejuvenation, healing, stress reduction (Connellan et al., 2013) and increase cognitive function (Oana *et al*., 2020, Nilsson, 2006). Literature shows benefits of improved mental health in homes during lock-down periods, where poor mental health effect is correlating to increased injury events (Thodelius, 2018).

3.4 Value management

Construction economics as value management (VM) design planning of building projects provide opportunity to improve benefits as presented in project life cycle and life cycle cost planning measurements. VM considers planning decisions for specified performance outcomes, such as legislative compliance and risk management. Value relates to design outcomes that is improved during planning and data analysis. Value can be considered for design changes, such as more detailed design drawings, change of plant, assembly, or construction methods; to improve both cost and value outcomes such as efficiency, material durability, or aesthetics (Kelly *et al*., 2014). VM provides opportunity for issues analysis, risk management, functional design analysis, material compatibility, ethics, legal requirements, or community consideration, to suit design goals. Suicide prevention analysis can include VM cost/benefit measures for risk management in high density residential projects (Wang *et al*., 2020). VM planning can include preventative access measures and wellbeing considerations for community impact, and risk management. Risks for suicide and adverse mental health impact by design has management and prevention potential by including design for social, spatial and biophilia, for evaluation against cost/benefit measures. Therefore, design guidelines can be developed during the larger systematic review that can provide design guidelines for VM analysis, with preliminary review findings listed below.

Table 1. Design method preliminary cost/benefit VM design table.

Design method	Cost ($) 1 to 5	Suicide Prevention	Wellbeing benefit (mental health)	Physical Prevention
Biophilia	2 Low	Yes	Yes	No
Spatial design	3 Medium	Yes	Yes	Yes
Access and means restriction	2 Low	Yes	Yes	Yes
Social design	1 Low	Yes	Yes	No
Environmental psychology	2 Low	Yes	Yes	No
Legislation SP EBDG	4 High	Yes	Yes	No
Materials - Biochemical impacts	2 Low	Yes	Yes	No
Suicide prevention (SP) Evidence based design guidelines (EBDG)	1 Low	Yes	Yes	No

4. Systematic review findings

The literature reviewed shows design evidence to complement existing suicide prevention methods with findings summarised in subsequent paragraphs. Physical design methods are considered using spatial design to include means and access restriction in VM planning. Means and access restriction strategies are suitable for suicide prevention in high density residential and urban planning settings, such as roof tops and car parks. Suicide prevention considering lethal access as means and access restriction to jumping sites is useful for design planning consideration, supplying low-cost planning solutions. Wayfinding spatial design solutions bolster environmental impact improving health in dense housing spaces as a low-cost VM planning solution. VM planning design for suicide prevention can include biomaterials lifecycle cost analysis and toxicology to improve mental health in homes. Biomaterial design choices for suicide prevention provide future research for considering cost/benefit economic modelling. Suicide prevention methods can consider both physical and mental health design to improve homes and combat depression resulting from environment impacts. By considering both material design choices and lethal means access for suicide prevention in planning we can improve life cycle costs, quality of design and quality of life for users. Improving mental health design for homes to improve psychological wellbeing using environmental design psychology is the future of home design and spatial analysis. This is further demonstrated that these planning aspects can benefit 44% of society, with health design solutions presented in this systematic review, on the complex issue of home suicides.

5. Conclusion

This systematic review displays the significant knowledge gap in suicide prevention using building design, where there are no design guidelines for preventing suicide in homes using building design. Further design methodology can be used to complement existing evidence based environmental design guideline discovery, for use as suicide prevention in homes. This review shows supportive evidence to use spatial, social and biophilic design to improve mental health in built environments, with preliminary cost/benefit considerations. This review displayed further information gaps regarding mental health design for homes, considering disease control and toxicology along with environmental psychology and biochemical impact variables, for mental health. This review shows benefits for future cost/benefit home design economic modelling and VM planning uses. This suicide prevention research can help the greater community, proving low-cost design planning suicide prevention methods for homes.

6. Acknowledgments

Special thanks to community support: Lifeline, Mind frame and suicide prevention services. If anyone is affected by this information on suicide, call Lifeline 13 11 14.

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Theme:

Education in Built Environment

A Transdisciplinary Learning Approach to Teaching Construction Entrepreneurship

Seng Hansen[1*] and Susy F. Rostiyanti[1]

[1]Department of Construction Engineering & Management, Universitas Agung Podomoro
Grogol, West Jakarta 11470, INDONESIA

seng.hansen@podomorouniversity.ac.id; susy.rostiyanti@podomorouniversity.ac.id
* Corresponding author

Abstract:
Construction Entrepreneurship is a unique subject taught in the Construction Engineering and Management program at the Podomoro University in Indonesia. As a new course, it is necessary to develop an effective and efficient teaching syllabus. This paper describes construction entrepreneurship teaching through a transdisciplinary learning approach as an effective way to develop its syllabus. The transdisciplinary learning approach was chosen to provide insights of real-world problems to students through collaborative learning with industry speakers. Six construction entrepreneurs were invited to share their experiences in starting a construction business, followed by two reflective discussion forums to explore lessons learned from the sharing sessions. At the end of the term, online surveys were distributed to seek feedback from the enrolled students regarding the design, methods, and benefits of learning construction entrepreneurship. In addition, the survey was also intended for construction students who have never taken this subject to gain their perspectives on the relevance and interest of this subject. Overall, the approach to teaching construction entrepreneurship to enrolled students was found to be effective. The statistics also show the high level of student interest from other construction-related programs to take this subject.

Keywords:
construction entrepreneurship, entrepreneurs, teaching, transdisciplinary learning

1 Introduction

The construction industry plays a crucial role in increasing socio-economic growth, especially in developing countries such as Indonesia (Ditjen PPI, 2021). Likewise, innovation and entrepreneurship are critical factors for economic development (Cavallo *et al.*, 2019). This is reinforced in Vatavu *et al.*’s (2022) study of G8 countries (consisting of France, Germany, Italy, Japan, United Kingdom, United States, Canada, and Russia) which confirmed that entrepreneurship has a significant positive correlation on the country's economic growth. Similarly, Sebastian and Alina (2014) reveal the important role of entrepreneurship in countering unemployment and increasing living standards.

On the other hand, along with expectations for the university's contribution in solving socio-economic issues such as the unemployment problem (Taha *et al.*, 2017) and improvement of standards of life (Ndofirepi, 2020), many academic institutions promote entrepreneurship learning (Nsanzumuhire and Groot, 2020). Entrepreneurship has become a popular program at many universities. This leads universities to focus their attention on helping students to develop entrepreneurial skills and knowledge (Ndofirepi, 2020).

According to Ayalp (2019), the construction industry is a sector with many opportunities for entrepreneurship knowledge to be developed and disseminated. However, Construction Entrepreneurship (CE) has received little attention in construction management research

(Sebastian and Alina 2014). The available studies were mostly focused on characteristics of a construction entrepreneur as well as its barriers and motives (Jaafar *et al.*, 2014; Setiawan and Erdogan, 2018, Ayalp, 2019; Emmanuel *et al.,* 2020). Several studies have focused on entrepreneurial potentials of specific construction professionals such as contractors (Jaafar *et al.,* 2014), architects (Ayalp, 2019), and quantity surveyors (Sampath *et al.,* 2020). There is only one study related to the exploration of entrepreneurship necessity in the construction program in Malaysia (Jaafar and Aziz, 2008). Thus, there is a research gap regarding how entrepreneurship should be taught to construction students.

This research focuses on evaluating the implementation of the CE syllabus as observed in a study program. This is important considering the idea of which single course is designed specifically to develop a particular comprehensive entrepreneurship competence recommended by Mindt and Rieckmann (2017) to achieve a specific learning outcome. In addition, this study also tries to explore the potential interest of students to take CE as a unique subject taught in the construction-related disciplines.

2 Literature Review

2.1 Construction Entrepreneurs

The term entrepreneurship is vague and used differently by many researchers (Jaafar *et al.*, 2010). For instance, Drucker (2014) defines it as "imagination, flexibility, creativity, willingness to think conceptually, readiness to take risks, ability to mobilise agents of production, and the capacity to see an opportunity". Others describe it is a process carried out by someone when starting up a company (Brandstatter, 2011) and a strategic process of developing an existing company (Yalcin and Kapu, 2008). Setiawan and Erdogan (2018) provide a more accurate definition as "a process of an individual creating and/or running a business as well as the process within the company of attempting to gain new business and/or to manage the existing business with the aim to achieve business success that involves several specific characteristics, such as seeking opportunity, risk taking, creativity, and innovation."

Along with the development of the construction industry and technology, construction professionals are required to develop their competencies as entrepreneurs who will provide innovation in the construction business (Chandramohan *et al*., 2020; Hansen, 2021). Even though it is very much needed, the number of construction entrepreneurs is still relatively small (Sampath et al., 2020). This is reflected in the percentage of business by sector where the Indonesian construction sector is only 4.09% (Utoyo *et al*., 2021) even though this sector contributes significantly to GDP by 10.48% in the 4th Quarter of 2021 (Rahmasari and Yuniastuti, 2022). In addition, the construction sector is also the least innovated business with only 11.74% of companies innovating (Utoyo *et al*., 2021). This is caused by several factors inhibiting innovation, including reluctance for construction innovation (60.81%), difficulty in funding innovation (16.46%), lack of experts (24.54%), lack of knowledge to innovate (13.69%), and lack of supporting government regulations (9.50%). All of these certainly have an impact on the growth and performance of the Indonesian construction industry.

One of the reasons for the lack of entrepreneurs in the construction sector is the lack of provision of entrepreneurial spirit and skills to construction students. Bazan *et al.* (2020) highlight the need for university degree programs to evaluate the impact of various factors related to the entrepreneurial potentials of students. In the field of construction, Jaafar and Abdul Aziz (2008) argue that in order to obtain quality construction entrepreneurs, entrepreneurship education should be emphasized in the industry. The provision of entrepreneurship education to construction students is not only in the form of theories and materials related to the business process, but mainly on the required characteristics of entrepreneurs in starting up a construction business.

2.2 Construction Entrepreneurship Education

Traditionally, construction education is designed to prepare students to be ready to work in the construction industry (Bhattacharjee *et al.*, 2013). This is reflected in Astuti and Martdianty's work (2012) which found that more graduates were more interested in becoming job seekers rather than becoming job creators. However, looking at technological developments and industry demands, expectations of new graduates are changing (Bhattacharjee et al., 2013) and there is a growing opportunity for construction students to become entrepreneurs in the industry (Sampath *et al*., 2020). Similarly, Silva (2014) shows the potential role of entrepreneurship for construction students and professionals in various areas of construction work such as claim management, estimation, transportation and energy.

On the other hand, construction students have the opportunity to become entrepreneurs because they are equipped with competencies related to managing a construction business such as project management, risk management, value engineering, cost analysis, financial management, etc. (Chandramohan *et al*., 2020). However, the reluctance to become an entrepreneur and the stability of job demand are the main barriers in increasing the number of construction entrepreneurs (Shah *et al.*, 2020). According to Shah *et al.* (2020), entrepreneurial intention is the most important predictor that determines the entrepreneurial behaviour needed by entrepreneurs. For this reason, construction students need to be given an introduction and understanding regarding entrepreneurial thinking and spirits to foster intention and interest toward entrepreneurship.

As a subject, CE is needed to bridge the needs of the construction industry for innovation and performance improvements. In fact, the construction industry is amongst the least digitalized sector in the world (Hansen *et al*., 2022). Its annual productivity growth is stagnating around 1% over the past 20 years (Barbosa et al., 2017). In addition, this sector also faces various issues such as sustainability, globalization, security, and susceptibility (Hansen *et al*., 2022). Construction entrepreneurs see this not as an obstacle but as a business opportunity. Therefore, CE education is essential to train construction students and professionals on strategies to improve the performance of the construction industry and respond to these challenges.

However, the assessment of construction students' entrepreneurial orientation shows a lack of alignment of entrepreneurship studies with construction practices. There are not many educational institutions that provide CE as a teaching subject in their programs. If any, this subject is only equipped with general entrepreneurship principles and construction practices. Consequently, there is a need to develop a CE syllabus that is designed systematically according to the industry needs. This paper highlights the importance of developing a syllabus that is able to absorb more entrepreneurial knowledge and practices that are relevant to the construction disciplines. Here, CE is defined as the combination of entrepreneurial thinking and spirit that applies to construction industry. Through learning this subject, it can facilitate the emergence of fresh construction entrepreneurs in the industry (Sampath *et al*., 2020).

2.3 Transdisciplinary Learning

The terms multidisciplinary learning, interdisciplinary learning, and transdisciplinary learning are often used interchangeably even though they have fundamental differences (Park and Son, 2010). Multidisciplinary learning refers to a combination of various disciplines as independent and separate components of learning (Garner, 1995). It focuses on developing learning within the traditional discipline (Finch *et al.*, 2021). Interdisciplinary learning provides not only perspectives of different disciplines (multidisciplinary) but also sets up collaborative tasks that the diverse perspectives are discussed and integrated (Feng, 2012). Thus, it creates learner-driven learning in immersive learning contexts (Park and Son, 2010). On the other hand, transdisciplinary learning encourages critical reflection on and liberation of disciplinary boundaries toward learning goals (Finch *et al*., 2021). Here, the academic learning is amplified through collaborative learning with partners from other sectors (Mindt and Rieckmann, 2017) such as the construction professionals and entrepreneurs. Thus, students are expected to gain insights into real-world problems and apply their knowledge in a real-life context (Mindt and Rieckmann, 2017).

The fundamental difference between these three lies in the mode and purpose as described by Park and Son (2010). The multidisciplinary learning provides learning on various topics from various disciplines, interdisciplinary learning highlights the combination of diverse disciplines to solve a problem, while transdisciplinary learning facilitates collaborative learning through a shared conceptual framework. Hence, transdisciplinary learning is a further step of interdisciplinary learning (Park and Son, 2010).

In terms of levels of interactivity, the multidisciplinary learning mainly focuses on the interactivity between students and content, the interdisciplinary learning is learner collaboration driven, whereas the transdisciplinary learning is based on learner participation and new knowledge creation. The identity of students becomes different from being a knowledge consumer in multidisciplinary learning, developing into a knowledge collaborator in interdisciplinary learning, and evolving into a knowledge producer in transdisciplinary learning. Likewise, the teacher's role has changed from a knowledge facilitator in multidisciplinary learning, to a learning designer in interdisciplinary learning, and finally to an interactive learning designer in transdisciplinary learning (Park and Son, 2010).

3 Research Methodology

This study aims to investigate the CE teaching in a Construction Engineering and Management (CEM) study program. It obtained a research ethics approval from Podomoro University, LPPM Project Number: LPPM/RE/002/22. A mixed method approach was adopted to provide a more complete picture of the teaching model. According to O’Cathain *et al*. (2007), this approach can be used to engage with the variety of questions relevant to the complexity of the research phenomenon. Previous studies have employed the similar approach (Astuti & Martdianty, 2012; Emmanuel *et al*., 2020; Hansen *et al*., 2022). The data collection process in this study includes interviews and questionnaire surveys. A case study was observed from a CEM program of Podomoro University located in Jakarta, Indonesia. Interviews were used as a technique to collect qualitative data from students who were involved in two reflective discussion forums and construction business plan presentations. Two reflective discussion forums were conducted on March 15, 2022 and May 10, 2022 to explore opinions and lessons learned from students on six sharing sessions by actual construction entrepreneurs.

Construction business case presentations were conducted to assess students' skills in developing a construction business idea. At the beginning of the semester students have been grouped into three groups to create a business plan in the construction industry. The development of this business plan was carried out for 11 weeks and they were able to learn from the experiences of actual construction entrepreneurs in sharing sessions to obtain ideas and/or innovations in the construction sector. Then on week 15 (May 17, 2022) each group was given a duration of 5-10 minutes to present their construction business pitches. Interviews were conducted to reflect the effectiveness of the method and delivery of this subject.

Next, questionnaire surveys were developed to explore students' perceptions regarding construction entrepreneurship teaching. There are two types of questionnaires served for two different purposes. The first type was a self-evaluative survey addressed at 37 students who had taken the construction entrepreneurship subject. It consists of three parts, namely Part A1 related to the design of construction entrepreneurship teaching (with five questions), Part A2 related to the learning methods (with seven questions), and Part A3 related to the benefits of taking the subject (with five questions). Meanwhile, the second type questionnaire (Part B) received 67 responses from students who had never taken this subject (both from Podomoro University and other universities) and only focused on the relevance and interest in taking the subject (with five questions). The surveys were distributed to students at the end of semester (May 12 to June 7, 2022) and received 104 valid responses.

All questions use a 4-point Likert Scale with 1 representing 'strongly disagree', 2 representing 'disagree', 3 representing 'agree', and 4 representing 'strongly agree'. The data were analyzed using descriptive statistics involving means and standard deviations (SD). While the means represent the averages of all responses per question, the SDs represent the extent of deviation for that question. Similar evaluative self-assessment survey has been applied to previous studies (Karim et al., 2019; Hansen et al., 2022). To determine the internal consistency of the data, a Cronbach's alpha coefficient of reliability must be calculated when using a Likert scale in a questionnaire (Nunnally and Bernstein, 2007). The value of Cronbach's alpha coefficient is between 0 and 1. George and Mallery (2003) suggests that a value of 0.7 is acceptable, 0.8 indicates good internal consistency, while close to 1 is superb. The results of reliability statistics in this study ranged from 0.998-0.999 which shows a very high internal consistency of each dataset.

4 Findings and Discussion

4.1 Transdisciplinary Teaching Model for Construction Entrepreneurship

A discipline is defined as a distinct study area with its own subject matter and content (Davies and Devlin, 2007). This paper suggests a transdisciplinary teaching model for CE subject as a unit to be taught at the CEM program. At Podomoro University, this subject (code CEM3414) was introduced in 2020/2021 and is a unique subject taught in the sixth semester with a weight of two semester credits (one credit equals to 170 minutes of learning per week). The learning outcomes are to: (1) internalize the spirit of entrepreneurship, (2) gain knowledge about entrepreneurship in general and the construction entrepreneurship in particular, (3) recognize various aspects of construction entrepreneurship development, and (4) demonstrate quality independent and group performance related to construction entrepreneurship topics.

In developing the syllabus, a transdisciplinary learning approach was adopted by fulfilling the six elements of transdisciplinary learning as shown in Table 1. ‘Learning methods’ refers to the dominant learning method to achieve the fulfilment of TL elements. 'How to' refers to the relevant implementation details of the learning method. While 'Outcome' refers to the expected results from the application of the learning method.

Table 1. Transdisciplinary learning approach matrix
(Source: Authors' work, 2022)

Elements	Learning Methods	How to	Outcome
Collaborative learning	• Sharing sessions	Encourage the actual entrepreneurs to share their ups and downs in starting their construction business	Effective teamwork and networking
	• Group assignment	Promote students working together in developing a construction business plan	
Critical reflection	• Reflective discussion forums	Explore lessons learned from the experience of actual entrepreneurs	Critical thinking
	• Group assignment	Develop a construction business plan by considering lessons learned from the experiences of actual entrepreneurs	
Real-life context	• Problem-based learning	Present actual data and case studies related to the construction business in Indonesia and the world	Authentic and relevant learning
	• Sharing sessions	Share the actual experiences of construction entrepreneurs both successes and failures	
	• Group assignment	Focus on business plans that can answer the challenges of actual problems in the Indonesian construction industry	
Learner participation	• Sharing sessions	Encourage students to lead the sharing sessions	Student-led learning
	• Group assignment	Ensure that each member has done their tasks and that everyone understands the business process well	
Knowledge producer	• Reflective discussion forums	Discussions are directed at the discovery of innovative ideas to answer actual problems in the construction industry	New knowledge creation
	• Group assignment	Develop a construction business plan that is innovative and applicable	
Interactive learning designer	• Problem-based learning	Encourage students to solve open-ended problems together in the class	Flexible and engaging learning
	• Sharing sessions	Invite actual entrepreneurs to share their experiences in starting a construction business	
	• Group assignment	Ensure all students participate in the group assignment by sharing tasks and responsibilities	
	• Examination	Provide interactive examinations that explore students' critical understanding on the subject	

Taking into account the transdisciplinary learning approach above, Table 2 presents the CE syllabus that has been implemented in the CEM Program of Podomoro University. This syllabus emphasizes more on the aspect of 'thinking and acting like an entrepreneur' in the context of the construction industry. Hence, the portion of collaborative learning and critical reflection receives great attention. Meanwhile, the problem-based learning method was performed on specific topics as a foundation for students' understanding of CE knowledge and practice including: the definition and characteristics of CE, construction technology, construction start-up business and case studies, critical success and failure factors of construction business, Construction Small-Medium Enterprises (CSMEs) and family business.

Table 2. Recommended construction entrepreneurship syllabus
(Source: Authors' work, 2022)

Week	Topic	Dominant Learning Method
1	Introduction to construction entrepreneurship	Problem-based learning method
2	Characteristics of construction industry, construction entrepreneurship and technology	Problem-based learning method
3	Construction start-up business: how to and case studies	Problem-based learning method
4	Construction business experience: architecture consultant	Sharing session
5	Construction business experience: contractor	Sharing session
6	Construction business experience: real estate developer	Sharing session
7	Lessons learned from three sharing sessions	Reflective discussion forum
8	Mid-term exam	Examination
9	Critical factors influencing the success and failure of construction business	Problem-based learning method
10	Construction Small-Medium Enterprises (CSMEs) and family business	Problem-based learning method
11	Construction business experience: subcontractor	Sharing session
12	Construction business experience: supplier	Sharing session
13	Construction business experience: green construction	Sharing session
14	Lessons learned from three sharing sessions	Reflective discussion forum
15	Construction business case presentation	Group assignment
16	Final exam	Examination

4.2 Response to the Design of Construction Entrepreneurship Subject

After the above syllabus was implemented, the students' perceptions were collected to evaluate the effectiveness of the transdisciplinary learning approach in CE teaching. The first part of the survey explores students' opinions regarding the design of CE subject. Table 3 presents statistical results on five questions covering the importance of CE subject (Q1), the increased understanding of CE after taking the subject (Q2), the usefulness of CE subject (Q3), the relevancy of CE subject (Q4), and the structure of CE curriculum design (Q5). The analysis shows that in general students have a positive response related to learning design with a mean of above 3 out of a possible value 4. There is only one point (Q2) where students think they are close to agreeing that their understanding of CE has increased after taking the subject (with a value of 2.95).

Table 3. Students' perceptions on the design of Construction Entrepreneurship subject
(Source: Authors' work, 2022)

No	**Questions**	**Mean**	**SD**
Part A1	**Related to the design of Construction Entrepreneurship subject**		
Q1	Construction Entrepreneurship subject is important for me	3.24	0.8
Q2	My understanding of Construction Entrepreneurship increased after taking the subject	2.95	0.74
Q3	Construction Entrepreneurship subject is useful for me	3.19	0.78
Q4	Studying Construction Entrepreneurship subject is relevant to my major	3.16	0.83
Q5	The curriculum design of Construction Entrepreneurship subject has been well structured	3.03	0.73

A well-designed entrepreneurship education curriculum can significantly improve students' entrepreneurial competencies and interests (Trivedi, 2016). For this reason, entrepreneurship education must be designed with an experiential approach, training, work-related learning, and action-learning (Smith, 2010). By focusing on the construction industry, this subject is designed to prepare construction students to have the understanding and attitude of entrepreneurs in the construction industry. It adopts a transdisciplinary approach emphasizing on the critical thinking and collaborative learning between students and industry partners. Looking at the statistical results above, in general it can be concluded that the CE subject teaching has been properly designed.

4.3 Response to the Learning Method

The second part of the Part A survey explores students' opinions regarding the learning methods applied to the CE subject. Table 4 presents statistical results for seven questions. The analysis shows that in general students agree that the interactive learning method applied is useful and interesting to follow. This is indicated by all mean values above 3.

Table 4. Students' perceptions on the interactive learning methods
(Source: Authors' work, 2022)

No	Questions	Mean	SD
Part A2	**Related to the interactive learning methods**		
Q6	The subject has provided interactive learning methods (including problem-based learning, group assignments, sharing sessions from entrepreneurs, discussion forums, and exams)	3.03	0.91
Q7	The problem-based learning method (by presenting actual data, presentations, and question-answer on construction entrepreneurship problems, etc.) is useful and interesting to follow	3.16	0.83
Q8	The group assignment (by creating construction business plans) is useful and interesting to follow	3	0.94
Q9	The sharing sessions from six actual construction entrepreneurs (different backgrounds) are useful and interesting to follow	3.11	0.89
Q10	The discussion forums (related to lessons learned from six sharing sessions) are useful and interesting to follow	3.03	1
Q11	The exams (in terms of questions, scope, and relevance) are useful and interesting to take	3.11	0.7
Q12	Overall, the Construction Entrepreneurship subject is useful and interesting to follow	3.22	0.87

Entrepreneurship teaching must be complemented by practical case studies, business simulations, sharing sessions from entrepreneurs, project team works, and development of a business plan (Henry and Treanor, 2010). Some of these methods were adopted in the CE syllabus by inviting six construction entrepreneurs in sharing sessions, providing problem-based learning accompanied by case study examples, conducting two reflective discussion forums led by student groups, assigning students to make a detailed construction business plan, and carry out examinations that focus on students' critical thinking in providing ideas related to CE. In the observed semester, students succeeded in making a construction business plan with the following topics: Group 1 presents development strategies for 3D printing construction company, Group 2 aims to provide drone services for on-site monitoring, and Group 3 explores the potential of BIM online training for construction workers.

4.4 Response to the Benefits

The third part of the survey investigates students' perceptions on the benefits from taking the CE subject. It consists of five questions and the results of the analysis are presented in Table 5. Based on the statistics, it can be seen that in general students have a response that is close to agree (with the smallest value is 2.89) that taking this subject is useful in terms of increasing confidence and taking initiatives, opens networking opportunities, trains critical and innovative thinking, and the desire to become an entrepreneur after graduating from college. Students also responded agreeing that this subject provides an adequate understanding regarding how to prepare a construction business plan properly.

Table 5. Students' perceptions on the benefits from taking the subject
(Source: Authors' work, 2022)

No	Questions	Mean	SD
Part A3	**Related to the benefits from taking the subject**		
Q13	The subject has increased my confidence to actively ask questions, and take initiatives during the learning process	2.97	0.73
Q14	The subject opens networking opportunities with business actors in the construction sector	2.92	0.89
Q15	The subject trains my critical thinking and innovation within the construction sector	2.97	0.76
Q16	The subject provides an introduction on how to properly prepare a business plan in the construction sector	3	0.75
Q17	I want to be an entrepreneur after graduating from college	2.89	0.81

The statistical results above show that there is a room for improvement, especially for students who will take this subject in the future. Observations show that perceptions related to these benefits can be further improved if lecturers convey the expected benefits of this subject to students. Other future CE activities that can be developed include construction business case competition and construction innovation week to encourage the spirit of entrepreneurship among construction students.

4.5 Response to the Interest and Relevancy

The second type questionnaire (Part B) targets students who have never taken the CE subject. It consists of five questions that explore aspects of the level of importance, interest, usefulness, relevance, and expected curriculum design. As shown in Table 6, these five aspects received a positive response from students (with a maximum value of 3.4 out of 4).

Table 6. Non-participating students' perceptions
(Source: Authors' work, 2022)

No	Questions	Mean	SD
Part B	**Related to the interest and relevancy of Construction Entrepreneurship for non-participating students**		
Q1	Construction Entrepreneurship subject is important for me	3.3	0.67
Q2	Construction Entrepreneurship subject is interesting to me	3	0.76
Q3	Taking Construction Entrepreneurship subject will be useful for me	3.28	0.65
Q4	Taking Construction Entrepreneurship subject is relevant to my major	3.25	0.72
Q5	The curriculum design of Construction Entrepreneurship subject must be properly prepared through interactive learning methods (problem-based learning, group assignments, sharing sessions, discussion forums, and exams)	3.4	0.7

The statistics above show the potential for CE subject to be taught and become an elective subject for other similar study programs. In Indonesia, the CE subject can only be found in the CEM Program of Podomoro University. Other related programs in Podomoro University such as Architecture and Urban Planning can make CE subject as their elective subject. Likewise, other universities that have Civil Engineering and other construction-related study programs can also adopt this syllabus to develop the CE subject on their respective campuses. Alternatively, it is recommended to promote CE subject by inviting other construction-related study programs from other campuses to participate in this unique subject.

4.6 Research Implications

Considering the specific nature and challenges of the construction business, efforts are needed to increase the innovation and competitiveness of construction players in Indonesia which will ultimately improve the performance of the construction industry. Efforts to deal with this issue can include increasing experiences (Fu *et al.*, 2002), building corporate entrepreneurship (Setiawan and Erdogan, 2018), and establishing effective networks (Keung and Shen, 2017). Ayalp (2019) argues that entrepreneurship is a critical factor in maximizing the performance of the construction industry. However, there are not many studies that focus on CE teaching for construction students. This study succeeded in answering this challenge by providing a CE syllabus and evaluating its implementation to a CEM program.

Learning outcomes are usually defined and/or measured based on a level of dispositions or sub-competencies, not of whole competencies (Mindt and Rieckmann, 2017). Likewise, this study does not intend to apply the principle of entrepreneurship as an achievement for all subjects in the CEM program, but focuses only on the CE subject. This subject aims to open students' insight regarding their potential to become entrepreneurs in the construction industry, explore real-world problems and lessons learned from actual construction entrepreneurs, and try to come up with construction business ideas and innovations that are able to answer construction business challenges and problems.

The provision of CE as a teaching subject for undergraduates is one of the most effective methods of promoting entrepreneurship (Sampath *et al.*, 2020). Statistics from the opinions of students who have taken this subject at Podomoro University show a positive response to the syllabus design, the interactive learning methods, and the benefits received by students. In addition, statistics also show the high potential for CE subjects to be taught in other construction-related study programs such as Civil Engineering and Architecture.

The results of this study can be used as a reference in the development of entrepreneurship education in construction-related study programs. The university and government collaboration is the key tool facilitating entrepreneurship development (Taha *et al.*, 2017). Emmanuel *et al.* (2020) also suggested the active role of the government in providing more initiatives to support and equip the construction graduates with relevant entrepreneurial skills in collaboration with educational institutions. Thus, this study encourages the active role of the government to adopt the CE teaching that has been implemented by the CEM program of Podomoro University.

5 Conclusion and Further Research

This paper has described the effectiveness and success of implementing transdisciplinary learning on CE subjects in a CEM program. The results of the case study reported suggest that the application of transdisciplinary learning is very applicable and useful for students taking the CE subject. The CE syllabus designed has met the learning outcomes and the statistics show student agreement regarding the syllabus design, interactive learning methods, and the benefits of taking this subject. In addition, the statistics also show the interest of students from other construction-related programs to take the CE subject.

This study contributes by promoting CE as a teaching subject in the construction-related disciplines. The findings can serve as a reference model for the development of the CE module in other universities, both in Indonesia and on a global scale. This study provides more insights to construction lecturers on how entrepreneurship should be incorporated into the construction-related disciplines. The limitation of this research lies in the survey design which is cross sectional (administered at just one point in time) rather than longitudinal survey which might provide further light on the effectiveness of CE teaching. Therefore, subsequent subject delivery needs to be analysed to evaluate its effectiveness and potential for future development. Further studies can also focus on the harmonization of the laws to support entrepreneurship education in the construction industry. This is important given the lack of studies on the role of government in regulating construction entrepreneurship and its education.

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Construction Engineering and Management: A Review of Australia-based Research

Tayyab Ahmad[1*], Husnain Arshad Qazi[2] and Ajibade Ayodeji Aibinu[3]

[1]Department of Civil and Architectural Engineering, Qatar University, QATAR
[2]Department of Building and Real Estate, Polytechnic University Hong Kong, HONG KONG
[3]Faculty of Architecture, Building and Planning, The University of Melbourne, Parkville, Victoria, 3010, AUSTRALIA

tayyab@qu.edu.qa

* Corresponding author

Abstract:
Construction Engineering and Management (CEM) is an important discipline of the built environment providing a scientific and management-oriented perspective for construction projects. CEM research is highly context specific as it is governed by social needs, environmental challenges, and industrial issues. Australia is home to several universities engaged in CEM-related research and training. To understand the research trends in CEM discipline across Australian institutes, this study conducts a review of highly representative 3,748 CEM-related publications from Australian universities. This study helps see the research topics considered by CEM academics in Australia, the temporal changes in research topics, and the research collaboration among Australian institutes. The review has shown that CEM academics in Australia have high degree of collaboration with China and UK-based academics. In terms of publication volume, Curtin University, University of New South Wales (UNSW), Royal Melbourne Institute of Technology (RMIT) University, Queensland University of Technology (QUT), and Deakin University have performed extraordinarily. Some of the highly considered research topics by Australian CEM academics include performance assessment, energy, project design, BIM, project management objectives (i.e., safety, time, cost, quality), social aspects of construction, construction materials, sustainability, and project stakeholders. While this study provides a detailed understanding of the past CEM research trends in Australia, it also provides recommendations for future research development in Australia. The findings of this review will be able to generate a discussion regarding the improvement of CEM research across Australian institutes.

Keywords
Australia, Collaboration, Construction Engineering and Management, Research trends, Review

1 Introduction

Construction Engineering and Management (CEM) is an internationally recognized research field which enjoy support from a strong and growing community of researchers, scholars and practitioners (Betts and Lansley, 1993). In the last few decades, Construction Engineering and Management has developed into an independent discipline addressing the challenges and needs of increasingly construction complex projects. Part science and part art, this discipline has its roots across civil engineering as well as social sciences and economics. There are numerous specialist university degree courses being offered to instil the knowledge of CEM among built environment professionals. Conducting location-specific reviews of a knowledge area such a CEM can help understand how the institutional efforts across a region help shape the body of knowledge. A review of CEM research conducted in Australia can therefore help map the efforts of Australian institutes towards the development of knowledge in this area.

1.1 Study context

Construction is the third-largest industry in Australia in terms of the number of people it employs and its share in national GDP (Gross Domestic Product). In 2019, over 1.15 million people were employed in the construction sector constituting almost 9% of all the jobs in Australia. The Australian Construction industry generates over $360 billion in revenue, producing around 9% of Australia's Gross Domestic Product. The value of the construction activity in Australia in the 2019 financial year stood at AUD 212.85 billion of which the total value of private-sector construction work done across Australia amounted to approximately AUD 109.7 billion (Intelligence, 2022). The growing construction industry in Australia has a need for construction engineering and management research associated with it.

CEM research activity in Australian institutes is also of critical importance since Australia hosts large number of international students most noticeably from Asia (i.e., China, India, Nepal, Malaysia, South Korea, Thailand, and Indonesia). Many of the international graduates from Australian universities upon returning to their home countries take leadership and management roles in relevant organizations including construction-related businesses. The CEM-related research conducted in Australian institutes, therefore, has not only a direct effect on the local construction sector but also an indirect effect on the Global Construction sector. Owing to the cross-border impact-ability of research the CEM research from Australian institutes can impact industry practices worldwide. Understanding the development of CEM research in Australia is critical to see how this research domain has developed, and can therefore ease policy-making in this area. The aim of this study is to investigate how CEM research in Australia has progressed through the years. Accordingly, the objectives of this study are to investigate how CEM research in Australia has developed temporally, how collaborations in this area materialized, and which topics are typically explored in this research domain.

2 Methodology

Review studies are invaluable tools for both the decision-makers and for research community. Reviews are used by the researchers to identify, rationalise, and improve hypotheses; recognise and prevent pitfalls of previous studies; assess the degree of agreement regarding the state-of-the art in the field; and identify challenges and potential prospects (Chen and Song, 2019). Scientometric reviews are focussed on knowledge production, the spatiality of knowledge production, and knowledge relationships between the network of global actors. This paper is based on a scientometric review of literature on the topic of 'Construction Engineering and Management'. To analyse the CEM publication volume from Australian institutes, the key parameter used in this study is the number of publications which is a widely accepted measure for such assessment (Toutkoushian *et al.*, 2003). Also, number of citations is used as a measure of the prominence of research topics, journals, and institutes.

2.1 Review approach

For scientometric review, 'science mapping' approach is used in this study which was conducted in two consecutive stages. The first stage was about creating networks through analysis of the keywords co-occurrence; direct citation analysis of outlets; and co-authorship analysis. In the second stage, network analysis generated maps to present useful measures of the network. These measures presented the intellectual, conceptual, and social evolution of the research in the subject area, highlighting trends, patterns, outliers, and seasonality (Cobo *et al.*, 2011).

For refining the bibliographic data, OpenRefine, an open-source desktop application for data clean-up and transformation (Verborgh and De Wilde, 2013), was employed. For Scientometric analysis, VOSviewer tool was selected which offers the basic functionality needed for visualizing Scientometric networks (Eck & Waltman, 2014; Van Eck and Waltman, 2010). To conduct word cloud analysis, NVIVO, a qualitative data analysis computer software package (Wiltshier, 2011), was used.

2.2 Selection of studies for review

A search strategy can be transparent and repeatable if the sampling methodology is well defined (Whittemore & Knafl, 2005). Accordingly, a rigorous approach of searching and selecting relevant publications is implemented in this review. Scopus was used as citation database for this review owing to its relatively wider coverage, rapid indexing process, and its access to recent publications, in comparison to other databases (Meho and Rogers, 2008). Web of Science (WoS) was not used as the citation database since previous review studies in the discipline of Construction Engineering and Management have found that the majority of studies in this discipline are concurrently indexed in both Scopus and Web of Science (WoS). Also, for journal articles, Scopus has a much higher indexing of publications compared to Web of Science (WoS) (Det Udomsap and Hallinger, 2020).

To identify relevant publications on the subject matter, keywords associated with the concept of CEM were used. Keywords were selected using both, the induction and deduction-based approach. A preliminary literature review of over 100 publications was conducted, to develop a list of keywords using inductive reasoning. The selected keywords included ‘construction’, ‘building’, ‘infrastructure’, ‘material’, ‘project’, and ‘management’. The search was limited to journal articles, relevant subject areas, and Australian institutes. The search conducted using these criteria resulted in 113,532 articles. To ensure that the search only included CEM-related publications and not the studies from other disciplines, the filtration criteria of authors was applied. Authors with expertise in CEM discipline were selected. For this purpose, authors (n=158) with at least 6 studies containing the above-mentioned keywords were selected. Consequently, the search engine only produced the CEM publications affiliated to Australia and authored by 158 academics. As a result of the subsequent filtration, 3748 relevant publications were identified and the scientometric review presented in this paper is based on those publications only. These publications only represent journal research articles and do not include books, conference proceedings, and review articles. It is therefore important to indicate that CEM research in Australia is ‘not’ limited to 3748 publications. However, the selected publications are ‘most representative’ of the CEM research trends set by Australia-based academics.

3 Review findings

The scientometric review provides a detailed account of research trends in the subject area on a temporal scale, analysis related to keywords co-occurrence, co-authorship of documents, and direct citation analysis.

3.1 Temporal research trends in subject area

The first published study in the database regarding Australia-based CEM research was published in “Architectural Science Review” in 1983. Figure 1 illustrates the variations in the overall publications in the dataset from 1983 to 2022. While generating the word cloud charts from the titles of shortlisted publications, the terms such as ‘Construction’ and ‘Projects’ are eliminated to produce much focussed and meaningful infographics. As shown in Figure 1, the findings indicate a developing interest in the subject matter from 1983 onwards. This appears to be reassuring, demonstrating that the CEM field of research is not only active but thriving four decades later. Nonetheless, the issue of 'research aging' must be considered. The expression refers to the time span following publication during which a research study retains sufficient influence to be cited in subsequent studies. There is evidence that studies lose relevance after around ten years (Wang, 2013). Considering this, the history in this field spanning four decades has been analysed through word clouds and keyword maps (see Figure 1). Somewhat discontinuity in research focus is observed between recent studies and those of the earlier 80s and 90s. It can be observed that the studies during the first two decades had more focus towards project scheduling, procurement, cost, quality, conflicts, and structural aspects. From third decade (*i.e.*, 2001) onwards risk, BIM, safety, public infrastructure, sustainable practices, as well as performance, management, and development of projects have started to receive increasing attention.

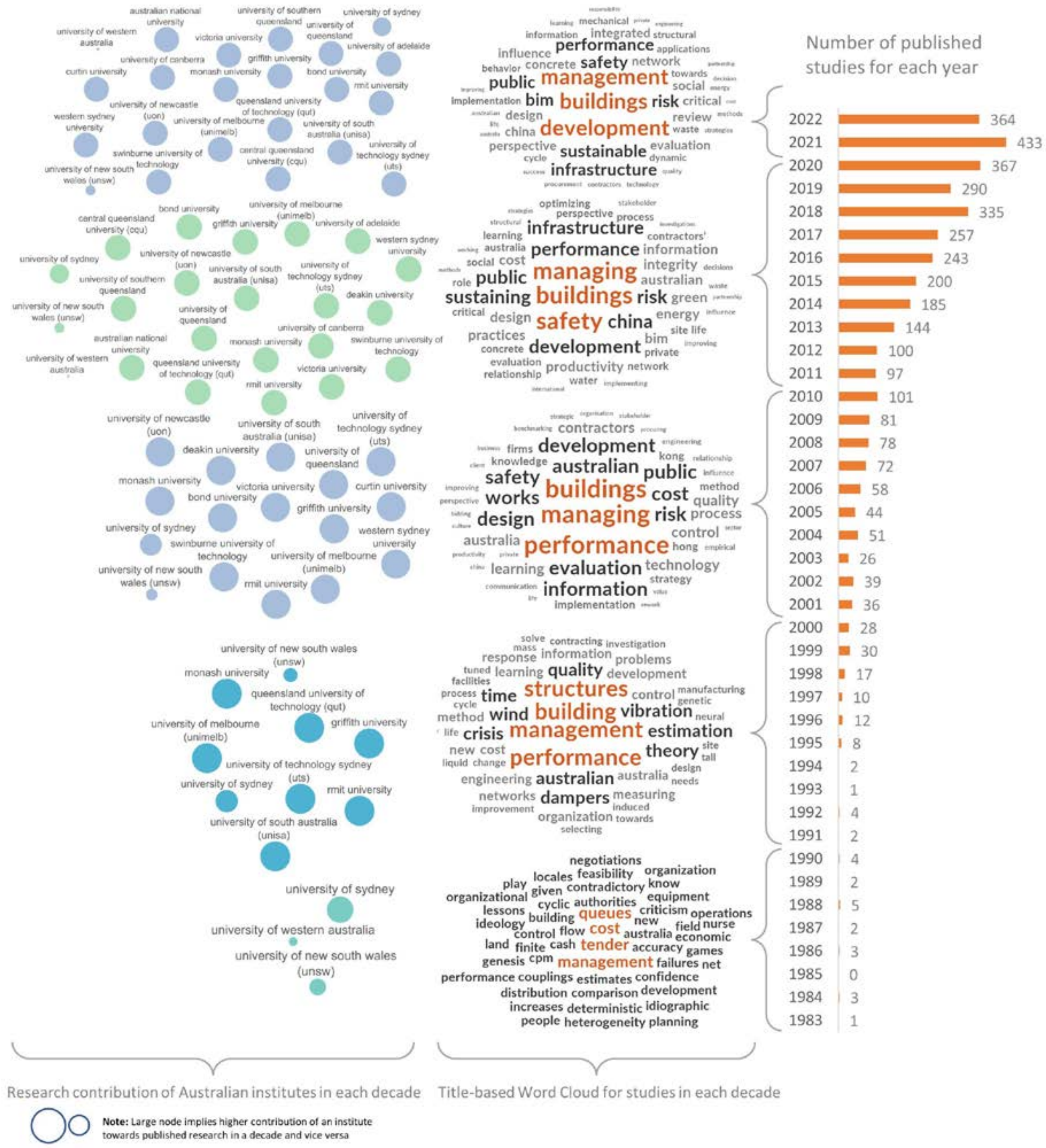

Figure 1: Temporal variations in the number of Australia-based CEM studies

The universities which have consistently contributed high number of studies in the subject area for multiple decades include Curtin university (n=468; 12.5%), University of New South Wales (UNSW) (n=468; 12.5%), Royal Melbourne Institute of Technology (RMIT) university (n=467; 12.5%), Queensland University of Technology (QUT) (n=465; 12.4%), Deakin university (n=427; 11%), and Western Sydney university (n=399; 10.6%) (see Figure 1). These institutes also performed well in terms of the total number of published studies from 1983 to 2022. From these institutes with high publication volume in CEM area, only UNSW is a member of the Group of Eight (Go8) which is a coalition of highly research concentrated and top-ranking Australian universities (Karami and Vafaei, 2012). While University of Sydney had high CEM publication volume in the first decade, only nominal number of studies on the subject matter were produced by this institute in the subsequent decades.

3.2 Detailed word cloud analysis

For the selected studies, a word cloud of their abstracts and a word cloud of their titles is developed using NVIVO as shown in Figure 2. In these infographics, the most frequently used words indicated the focus of studies i.e., performance assessment, management, energy, project design, BIM, project management objectives (i.e., safety, time, cost, quality), social aspects of construction, construction materials (i.e., concrete), waste, sustainability, project stakeholders (i.e., contractors, workers). The word clouds also indicated the prevalent data collection approaches such as ‘surveys’. Additionally, they indicated the contexts of the selected studies such as Australian and Chinese projects, building and public infrastructure projects. They also show how the aspects of CEM have been studied, for instance via Critical Success Factors, Risks, Barriers.

Figure 2: Title-based and Abstract-based word clouds for CEM studies

3.3 Analysis of keyword co-occurrence

Keywords reflect the core content of published studies and demonstrate the scope of research conducted in a field (Su and Lee, 2010). A network of connected keywords presents an accurate map of scientific knowledge generation in terms of the topics addressed, their patterns, relationships, and intellectual organization (Eck and Waltman, 2014). Resultantly, a network of keyword co-occurrence was developed using VOSviewer. The weight attributed to a link between two keywords is determined by the number of publications that contain both the keywords (Eck and Waltman, 2014). VOSviewer developed this network based on the closeness and strength of existing links.

Nodes in the network were sized using their Total link strength values, with larger nodes indicating higher values and vice versa (see Figure 3). Total link strength is a standard weight attribute indicating the total strength of the links of an item with other items (Van Eck and Waltman, 2011). The use of Total link strength value in sizing the nodes ensured that the size of keyword nodes in the network reflected their influence on each other. The ranking of the main research areas, and their relatedness as indicated in the map (see Figure 3), reveal many interesting findings, reflecting problems and gaps in Australia-based CEM research. Regarding the key focus of CEM research in Australia, the Keyword co-occurrence analysis (see Figure 3) supports the findings of word cloud analysis.

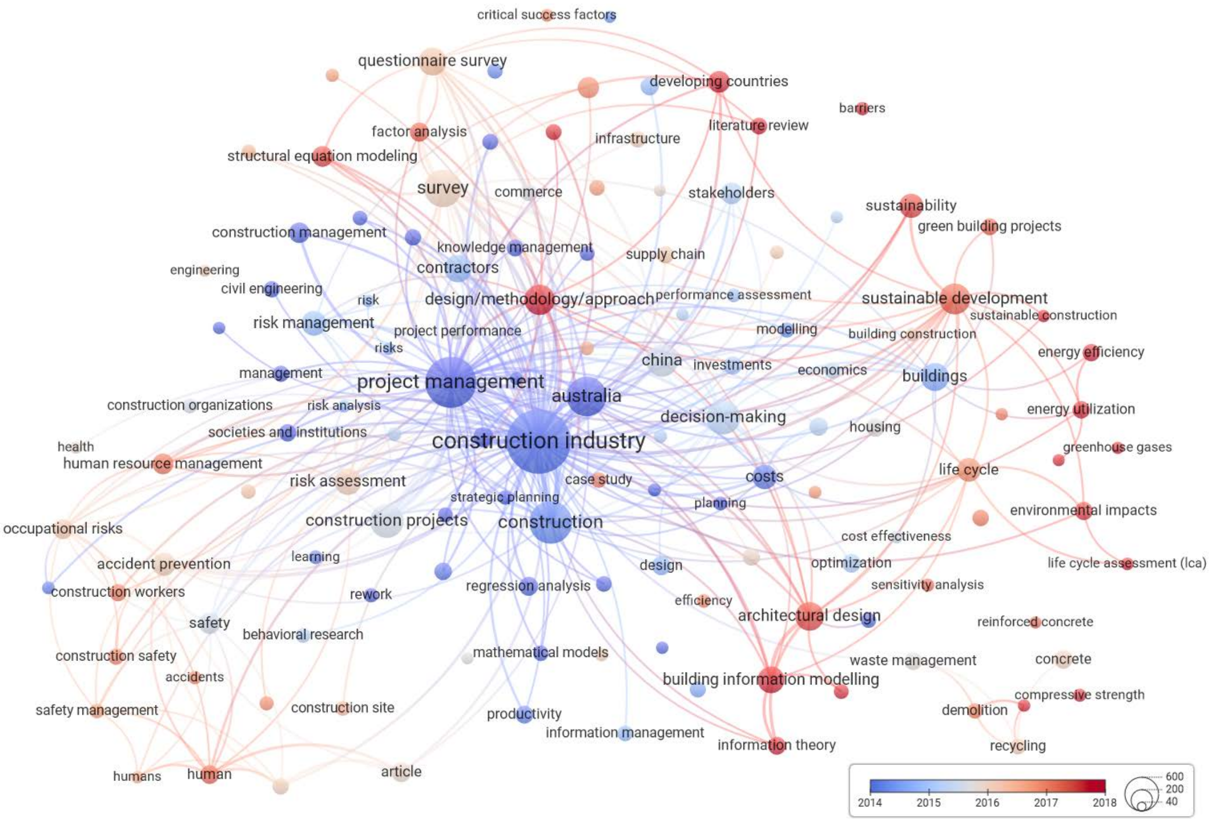

Figure 3: Top keywords from CEM studies and their relatedness (Note: Scale indicates Average Publication Year)

The colour of the nodes shown in the keyword map (see Figure 3) represents the Average Publication Year (APY) of the studies in which certain keywords/themes appeared. Based on this, it can be assumed that sustainability, green buildings, life cycle assessment, BIM, energy efficiency, architectural design, and structural equation modelling, social network, and construction waste are relatively recent research topics in Australia.

3.4 Direct citation analysis

Direct citation analysis of outlets provides insight into an outlet's prominence in any field of study, with recent studies indicating an increased interest in employing direct citation analysis to create bibliometric networks (Eck and Waltman, 2014). For this review study, a network for direct citation analysis of 64 most popular outlets is developed and visualized (see Figure 4). The colour of the nodes shown in Figure 4 represents the Average Publication Year (APY) of the studies published in different journals. The size of the nodes (reflecting journals in which CEM studies are published) is based on the criteria of number of documents (i.e., number of selected CEM studies published in those journals). Citation count of the source (journals) indicates the use of a journal in informing similar research. A high citation count for an outlet shows that it serves as a directory to other outlets involved in research.

Journals publishing most of the Australia-based CEM studies are ‘Engineering, Construction and Architectural Management’, ‘Journal of Construction Engineering and Management’, and ‘Construction Management and Economics’. The CEM studies with highest number of citations are published in ‘International Journal of Project Management’, ‘Journal of Construction Engineering and Management’, ‘Automation in Construction’, ‘Construction Management and Economics’, and ‘Journal of Cleaner Production’. Some journals have published high number of CEM studies but have scored relatively low in terms of citations such as ‘Engineering, Construction and Architectural Management’ and ‘International Journal of Construction Management’. On the contrary, some other journals have published relatively less number of CEM studies but have scored high in terms of citations such as ‘International Journal of Project Management’ and ‘Automation in Construction’.

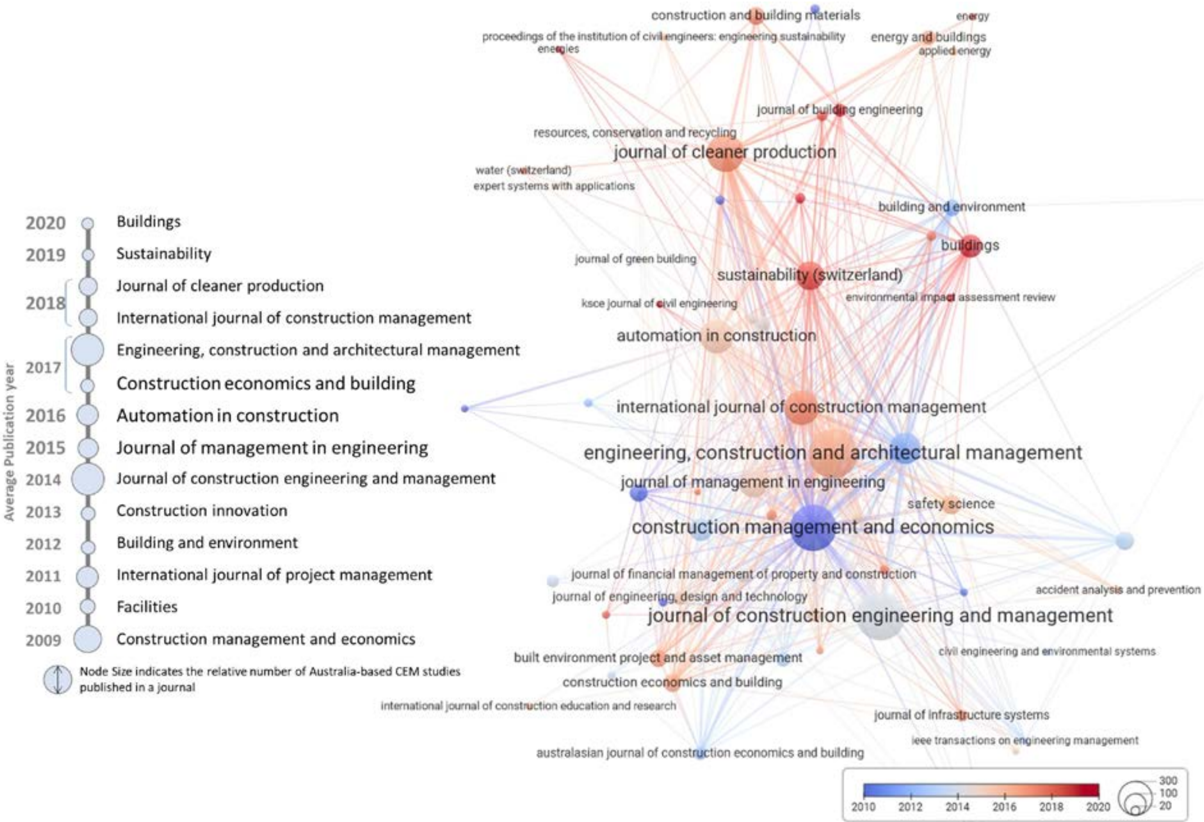

Figure 4: Network of prominent outlets (top 64) of CEM studies (Note: Scale indicates Average Publication Year)

In terms of the Average Publication Year (APY) values, the publication of Australian CEM research in Journal of Cleaner Production (APY=2018); Sustainability (APY=2019); Buildings (APY=2020); International Journal of Construction Management (APY=2018); and Engineering, Construction and Architectural Management (APY=2017), is relatively recent. On the contrary, Australian CEM research is being published for a reasonably long time in outlets such as Construction Management and Economics (APY=2009), International Journal of Project Management (APY=2011), Facilities (APY=2010), Construction Innovation (APY=2013), and Building and Environment (APY=2012).

3.5 Scientific collaboration: co-authorship analysis of documents

Being aware of existing networks of scientific collaboration in a field helps access to funding, specialty, and skills; increases productivity; and helps scientists reduce isolated efforts. This ultimately enhances scientific collaboration and contributes to scholarly communications

(Ding, 2011). By examining co-authorship networks, nearly every facet of scientific collaboration networks can be reliably tracked (Glänzel and Schubert, 2004). Co-authorship equates to scientific collaboration, and its lack in a scientific network indicates lower research productivity. Substantial evidence suggests that collaborative work has higher likelihood of being published in an outlet with a higher impact and receive more citations (Glänzel and Schubert, 2004). With this consideration, the following section analyses the co-authorship network of Australian universities involved in the subject area.

3.5.1 Active collaborations among institutes

Beside the collaboration of individual investigators, recognising the collaboration of institutes highly driven towards the subject area helps the field, especially by informing policy-making for research partnership (Ding, 2011). For the selected set of studies, the institute collaboration network was created for Australia-specific institutes (see Figure 5). Larger nodes indicate higher number of publications from an institute and vice versa. The maps in Figure 5 demonstrate the closeness of institutes in terms of collaboration and their prominence as CEM research hubs. The colour of the nodes shown in Figure 5 represents the Average Publication Year (APY) of the documents affiliated to different institutes. Among the institutes with high number of affiliated publications, Curtin University and Western Sydney University have high APY values indicating that for recent few years the publication volume from these institutes has dramatically increased.

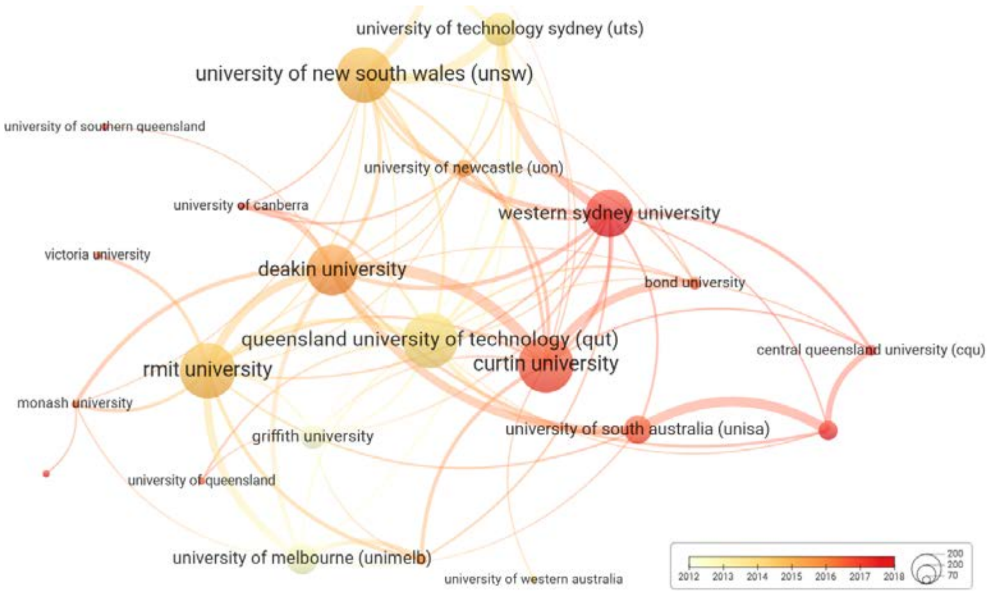

Figure 5: Institute-wide collaboration (Australian Universities) (Note: Scale indicates Average Publication Year)

3.5.2 Collaborating countries

A country-wide collaboration network is built to highlight the regions leading the research in subject area and to map their research collaboration. Basing the node size on the number of publications co-authored by a country, the map of collaborating countries is generated (see Figure 6). The colour of the nodes shown in Figure 6 represents the Average Publication Year (APY) of the documents affiliated to different countries. Regarding CEM research, Australia has largest collaboration with China, in terms of the number of joint publications. Australian and Chinese academics have collaborated on up to 1275 studies implying that 34% among all selected studies are result of Australia-China collaboration. Other than this, most notable collaborations of Australia are with the UK (n=361; 9.6%), USA (n=163; 4.3%), Malaysia (n=104; 2.8%), and Iran (n=98; 2.6%). Based on the APY values visualized in the map (Figure 6), it can be observed that the collaboration of Australia with China, UK, USA, and Singapore is not recent. On the contrary, the collaboration of Australia with Iran, Malaysia, and New Zealand is a relatively recent activity.

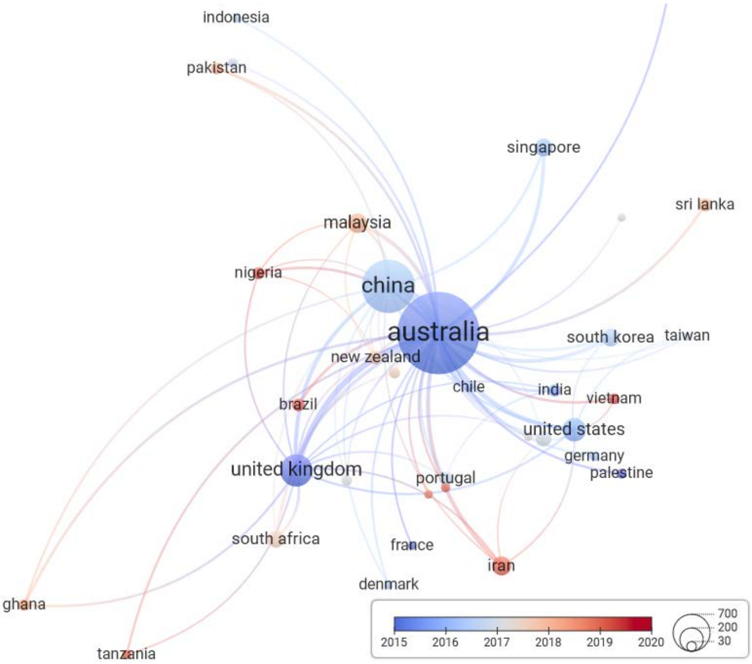

Figure 6: Country-wide collaboration (Note: Scale indicates Average Publication Year)

4 Suggestions

Based on the analysis of Australia-based CEM research presented in this study, some suggestions to improve future research activity are as follows:

- **Institutes:** Australia-based research in CEM has mostly been led by non-Go8 universities. Go8 universities in Australia are popular for their top world ranking as well as focus towards research. The lack of attention of these institutes towards CEM research is a matter of concern which can be addressed by aligning their research focus towards this domain. Also, some Australian institutes have high number of published studies but low citations (such as UNSW), and some others have low number of publications but high citations (such as Griffith University). Universities must enable a culture to conduct high impact research to benefit the practice as well as theoretical aspects of CEM.
- **Regional collaboration:** Other than the Australian collaboration with China, for CEM research Australia has weak collaboration with the rest of the world and most importantly with USA and UK which rank 2nd and 3rd in terms of the number of co-affiliated CEM research publications. The lack of Australian research collaboration with USA and EU can be resolved by conducting targeted conferences and initiating joint research programmes at regional level. USA and EU both boast highly mature construction markets, hence, reinforcing Australian research collaboration across these regions can be invaluable for Australian construction industry. Australian Universities can pool their resources to develop contemporary research labs becoming collaboration hubs for Australian as well as overseas universities.

5 Conclusion

To understand the research trends in CEM discipline across Australian institutes, this study has conducted a scientometric review of 3748 CEM-related publications from Australian universities. The review has shown that CEM academics in Australia have high degree of collaboration with China and UK-based academics. In terms of publication volume, Curtin University, UNSW, RMIT, QUT, and Deakin University have performed extraordinarily. While this review study provided a detailed understanding of the past CEM research trends in Australia, it also provided recommendations for future research development in Australian institutes. The findings of this review will be able to generate a discussion on the improvement of CEM research across Australian universities.

There are some limitations, however, regarding the review methodology used in this study. The filters applied to conduct review in this study ensured that only the research by CEM academics authoring 6 or more publications in construction, is selected for review. While this approach delivered highly relevant studies, it is likely to miss the CEM research by authors who published less (<6 studies in this field) and who did not co-author with senior academics in the CEM field. The review study is also limited in terms of a critical analysis of the research topics considered by CEM academics, in-depth analysis of the CEM academics responsible for the majority of publications, funding sources for Australia-based CEM research, and the comparison of Australian research with worldwide CEM research. Future reviews can help address these limitations.

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Impact of the Construction Computing Software (CCS) ‘Candy’ Course: Construction Management and Quantity Surveying Students’ Perceptions

John Smallwood[1*], Chris Allen[1] and Ashvin Manga[1]

[1]Department of Construction Management, Nelson Mandela University,
PO Box 77000, Port Elizabeth, 6031, SOUTH AFRICA

john.smallwood@mandela.ac.za; chris.allen@mandela.ac.za; ashvin.manga@mandela.ac.za
* Corresponding author

Abstract:
Students’ post-course perceptions provide insight relative to their understanding and appreciation of a module, including the impact thereof within the context of the wider course content and its enhancement of a candidate’s holistic knowledge. Hence the study reported on to determine construction management and quantity surveying students’ post course perceptions regarding a CCS ‘Candy’ course presented at a South African university. The students were surveyed via an e-mailed self-administered questionnaire at the completion of the course. The salient findings include: ‘planning – programming’ predominates in terms of the extent Candy training contributed to an increase in knowledge; estimating, costing, coordinating, and planning predominate in terms of an enhancement of skills; programming and scheduling predominate in terms of contributing to an improvement in students’ understanding and appreciation of seven activities of the planning function in an organisation, and; time predominates in terms of an improvement in students’ understanding and appreciation of the project parameters. Conclusions include that the CCS Candy course had an impact in terms of: an enhancement of both knowledge and skills aligned with the planning function; a better understanding and appreciation of the practice of construction management and quantity surveying, and students understand and appreciate the importance and role of the course in terms of greater knowledge development. It is recommended that the ‘add-on’ certificated CCS Candy course continue to be included and that the research be conducted annually.

Keywords:
CCS Candy course, Construction Management, Perceptions, Quantity Surveying, Students

1 Introduction

The Department of Construction Management at Nelson Mandela University is the only ‘pure’ Construction Management department in South Africa and therefore prides itself on providing the most relevant and learner centred education in the discipline. Specialist planning skills education was identified as an area that needed greater focus within the department and as a result it was decided to align the department with the most widely used planning and estimating package in the South African construction market, CCS Candy. Although students registered for the Construction Management 3 module receive planning theory lectures and must include a programme created in the most popular scheduling software, Microsoft Project, many Southern African contractors have been using CCS Candy for the better part of 40 years. This in turn, has led to graduates with such certification being able to secure employment not solely because of their degree, but because they completed a CCS Candy course.

The CCS Candy system is used to control a project’s construction process and financial performance from tender stage to the final account stage. Candy has a planning application but is much more than a planning and estimating package due to its dynamic link between money and time providing a wealth of information for both management and clients (RIB CCS, 2022). The subject matter of the course has become highly topical with greater emphasis being placed on the use of software for the planning and estimating of construction projects, with greater interest being shown from contractors in students having a practical certification of competency, alongside their theoretical knowledge garnered during their degree programme.

Furthermore, universities are increasingly focused on delivering a product fit for market and therefore realigning their programmes to best align with the needs of their students and industry. However, it was imperative that the department understand whether this new intervention was indeed adding value to the students' education and where in particular it was of assistance, to potentially consider opportunities to improve other subjects in the undergraduate programme. Given the abovementioned, all students registered for the CCS Candy course were surveyed immediately upon completion thereof to determine the extent to which the training contributed to an: increase in knowledge; enhancement of skills, and improvement in understanding and appreciation of the planning function and its seven activities, and the nine project parameters.

2 Literature Review

The following quotation has a bearing on the paper in that it We cannot always build the future for our youth, but we can build our youth for the future (Roosevelt, 1940).

Worldwide, navigating today's job market is challenging for university graduates (Nisha and Rajasekaran, 2018). Surveys indicate that 40 percent of employers believe there is a significant skills gap between what organisations consider are entry-level skills and that of skills owned by university graduates. In the same breath, the job market has become hyper-competitive (Finch *et al*., 2016). Research conducted to determine the cause generally attributes the skills gap to reduced quality of tertiary education (Tran, 2018). Graduates are facing an increasingly changing world resulting in university's becoming responsible for developing skills demanded by industry such as communication skills, self-learning, and self-management (Gilbert, Turner and Haass, 2022).

According to author Islam (2022) "employability is one's ability to gain either of the three statuses such as first employment, retain employment and obtain new employment". Islam (2022) highlighted that employment is dependent on knowledge, skills, and attitude. Another definition of employability is provided by authors Singh and Singh (2017) "employability depends upon his or her assets in terms of knowledge, skills, and attitudes; the manner in which these assets are used and deployed; presented to potential employers and the context within which the individual works (for example labour market and personal circumstances)". Researchers and practitioners have raised concern about the lack of employability skills and the impact this disconnect between skills supplied by universities and skills demanded by industry (Singh and Singh, 2017).

Employability skills or 'soft skills' can be defined as the personal traits and skills that employers look for in employees. In general, this includes communication skills, presentation skills, teambuilding skills, leadership skills, time management skills, interview skills, and interpersonal skills (Nisha and Rajasekaran, 2018). In developed nations, it has become common practice for higher education institutions (HEIs) to embed employability expectations and to enhance student learning outcomes especially at undergraduate level (Cheng *et al*., 2021). It is notable to mention that in recent years, higher education has been attempting to prepare students for jobs that do not yet exist, for using technologies that have yet to be invented, and for solving problems that nobody has yet thought of (Römgens, Scoupe and Beausaert, 2019).

As the approach of students to learning depends on their interest in the task and their previous experience of the area to which it integrates (Ramsden, 1997), enabling students to understand relevance, and provide sufficient motivation to them can be challenging. Students tend to lack experiences that allow them to relate theory to practice, which has led to an increased need to engage with students to create curricula that can “support student learning and personal development through providing a meaningful and motivational context” (Edström, 2012). “Motivation is an important factor in student learning” (Liu *et al*., 2012) and “self-motivation of students is a prime requirement for their active engagement” (Kamardeen, 2013), suggesting that course content needs to stimulate interaction within the study sessions and into other courses within each discipline’s course structure. “When graduates are equipped with necessary skills, they will become motivated and efficient in fulfilling their job tasks.” (Wickramasinghe and Perera, 2010), so appreciation of the courses’ ability to enhance their skills and determining its impact within the context of the wider course content, including its enhancement of a candidate’s holistic knowledge, is essential.

From an academic department standpoint, student engagement is regarded as a valuable exercise that contributes to improved learning, retention, equality / social justice, curricular relevance, and institutional benefits relating to reputation, marketing, and finance (Öz and Boyacı, 2021). Actively engaging with students is a key factor in students’ personal and academic development and several studies have found a positive association between school engagement and academic performance. While a variety of interventions for improving student engagement in higher education have been defined, it is noteworthy to mention that engagement is a complex and multifaceted concept, the exact nature of which is subject to debate. It is agreed, however, that engagement has behavioural, cognitive, and affective dimensions (Álvarez-Huerta, Muela and Larrea, 2021). Research supports the assumption that improving the educational experience students have through higher relationship quality, the more they will be engaged with their studies (Snijders *et al*., 2020).

One of the most widely used tools to empirically assess the quality of educational programs is student surveys. Students are a key stakeholder in the learning and teaching process and therefore have valuable data on how to improve the quality of education provided (Herbert, Fischer and Klieme, 2022). Given that the presenting department endeavours to improve the general perception of the CM course as a forward thinking, dynamic and reflective course for the workplace environment to be encountered by the students upon completion of their degree, giving them an opportunity to report on the intervention provides powerful proof of its willingness to engage openly thereby fostering stronger relationships ahead of Honours registration. “Higher educational institutions need to identify different working patterns that graduates might engage in and ensure that they possess employability skills that employers prefer them to possess.” (Wickramasinghe and Perera, 2010). Furthermore, the engagement of the department with the students through research surveys, influences the direction of the course through identifying areas of study that need enhanced attention.

3 Research Methodology

The two-day CCS Candy certificate course presented by a CCS representative is an annual additional intervention in the BSc (Construction Studies) programme relative to the subject Construction Management 3. The financial performance component in the course provides an opportunity to invite quantity surveying students to participate. They gain planning skills whilst engaging in more meaningful financial discussion with the construction management students. The topics addressed on the course include: quantity take off; estimating; planning; forecasting; cashflow; subcontractor management; valuations, and cost and allowable. The learning objectives include to: understand and appreciate the role of quantities, estimating, planning, and cost control in terms of managing resources on projects; determine quantities for a project; prepare a project estimate; prepare a project programme; prepare a project cashflow forecast; compile valuations for a project; assess subcontractor valuations, and manage project costs.

To assess the impact of the CCS Candy course, all students registered for the course were surveyed immediately upon completion thereof to determine the extent to which the CCS Candy training contributed to an: increase in knowledge; enhancement of skills, and improvement in understanding and appreciation of the planning function and its seven activities, and the nine project parameters. The questionnaire consisted of 7 closed-end questions and 97 sub-questions, and 1 open-end question. The closed-end questions entailed a response to a five-point 'extent' Likert scale: 1 = minor; 2 = near minor; 3 = some; 4 = near major, and 5 = major. The five points were preceded by an 'unsure' and 'did not' contribute option. Therefore, respondents effectively responded to a six-point Likert scale. Based upon the number of responses to the six points, a measure of central tendency in the form of a mean score (MS) was computed to enable a relative comparison and rankings. Given that there were effectively six points on the scale, the MS ranges between 0.00 and 5.00, the midpoint of the range being 2.50. To increase the generalisability of the findings, two years of findings were included - 19 No. in Year 1 consisting of 11 construction management, and 8 quantity surveying students, and 31 No. in year 2 consisting of 16 construction management, and 15 quantity surveying students, which equates to 50 students in total in terms of the sample size. All 50 students completed the questionnaire and their responses were included in the analysis of the data. Given that a 'captive' sample was surveyed, the sampling method can be termed 'convenience'.

4 Findings and Discussion

4.1 Knowledge areas

Table 1 presents a comparison of the extent to which the Candy training contributed to an increase in knowledge relative to thirty knowledge areas between construction management and quantity surveying students in terms of percentage responses to a scale of 1 (minor) to 5 (major), and MSs between 0.00 and 5.00. It is notable that 29 / 30 mean MSs are > 2.50, which indicates that the contribution of the Candy training to an increase in knowledge is major as opposed to minor. Given that effectively a six-point scale ('did not' linked to a five-point) was used, and that the difference between 0 and 5 is five, ranges with an extent of 0.83 (5 / 6) are used to discuss the degree of central tendency.

6 / 30 (20.0%) mean MSs are > 4.17 ≤ 5.00, which indicates that the Candy training made between a near major to major / major contribution to an increase in knowledge. Planning – programming predominates followed by estimating, project management, planning (strategic), subcontractor management, and cost control. Except for planning (strategic), the findings are not unexpected. Furthermore, the greatest MS difference is relative to project management, namely 0.54 in favour of the construction management students, which is probably attributable to project management not being an exit level outcome of the quantity surveying programme.

19 / 30 (63.3%) mean MSs are > 3.33 ≤ 4.17, which indicates that the Candy training made between a contribution to a near major / near major contribution to an increase in knowledge.

Furthermore, the greatest MS differences are relative to cash flow forecasting (0.61), followed by management (business) (0.46), and human resources (0.43), in favour of the construction management students. The difference relative to cash flow forecasting, and management (business) are notable as quantity surveyors prepare cash flow forecasts for clients and their practices in the case of the former, and have to manage practices in the case of the latter. However, cash flow forecasting is a critical knowledge area in terms of construction management in both the business of construction and projects.

5 / 30 (16.7%) mean MSs are > 2.50 ≤ 3.33, which indicates that the Candy training made between a near minor contribution to a contribution / contribution to an increase in knowledge. Furthermore, the greatest MS differences are relative to methods (civils construction) (0.49), in favour of the construction management students, and risk management (-0.23) in favour of the quantity surveying students. The difference relative to methods (civils construction) is not unexpected, as generally, QSs do not practice in the civil engineering sector of the construction industry. The difference relative to risk management is notable, as risk management is more diverse in practice in the case of construction management, than quantity surveying.

Table 1. Comparison of the extent to which the Candy training contributed to an increase in knowledge relative to thirty knowledge areas

Knowledge area	**CM**		**QS**		**Mean**		**CM -QS diff**
	MS	**Rank**	**MS**	**Rank**	**MS**	**Rank**	
Planning - programming	4.81	1	4.43	1	4.64	1	0.38
Estimating	4.63	3	4.18	3	4.43	2	0.45
Project management	4.63	2	4.09	5	4.38	3	0.54
Planning - strategic	4.52	4	4.19	2	4.38	4	0.33
Subcontractor management	4.44	5	4.18	4	4.33	5	0.26
Cost control	4.41	6	4.04	7	4.24	6	0.37
Information technology	4.11	11	4.04	6	4.08	7	0.07
Measuring (quantities)	4.15	9	3.95	9	4.06	8	0.2
Materials management	4.15	8	3.87	14	4.02	9	0.28
Materials	4.12	10	3.91	12	4.02	10	0.21
Procedures	4.00	12	3.95	11	3.98	11	0.05
Productivity	3.92	18	4.00	8	3.96	12	(0.08)
Training	3.96	16	3.95	10	3.96	13	0.01
Plant and equipment management	3.96	14	3.87	13	3.92	14	0.09
Contract documentation	4.00	13	3.59	17	3.82	15	0.41
Cost engineering	3.85	21	3.76	15	3.81	16	0.09
Financial management	3.92	19	3.62	16	3.79	17	0.3
Final accounts	4.25	7	3.19	29	3.76	18	1.06
Cash flow forecasting	3.96	15	3.35	23	3.69	19	0.61
Specifications	3.74	22	3.59	18	3.67	20	0.15
Purchasing	3.93	17	3.33	24	3.67	21	0.6

Management (business)	3.85	20	3.39	21	3.64	22	0.46
Methods (building construction)	3.69	24	3.36	22	3.54	23	0.33
Remuneration	3.62	25	3.45	19	3.54	24	0.17
Human resources	3.73	23	3.30	25	3.53	25	0.43
Work study	3.31	27	3.29	26	3.30	26	0.02
Risk management	3.20	30	3.43	20	3.30	27	(0.23)
Benchmarking	3.28	28	3.29	27	3.28	28	(0.01)
Design	3.26	29	3.24	28	3.25	29	0.02
Methods (civils construction)	3.44	26	2.95	30	3.23	30	0.49

4.2 Skills

Table 2 presents a comparison of the extent to which the Candy training contributed to enhancing twenty-seven skills between construction management and quantity surveying students in terms of percentage responses to a scale of 1 (minor) to 5 (major), and MSs between 0.00 and 5.00. It is notable that all the mean MSs are > 2.50, which indicates that the contribution of the Candy training to enhancing skills is major as opposed to minor. Given that effectively a six-point scale ('did not' linked to a five-point) was used, and that the difference between 0 and 5 is five, ranges with an extent of 0.83 (5 / 6) are used to discuss the degree of central tendency.

Seven out of 27 (25.9%) mean MSs are > 4.17 ≤ 5.00, which indicates that the Candy training made between a near major to major / major contribution to enhancing the seven skills. Estimating is ranked first, followed by costing, coordinating, planning, measuring (productivity), computer, and organising. There are three skills in which case the difference is greater than 0.50 in favour of the construction management students, namely planning (0.55), costing (0.54), and estimating (0.53). Furthermore, the difference in favour of the construction management students relative to coordinating is 0.39, and computer is 0.33. When deliberating the differences, it should be remembered that the candy system is construction focused. However, planning, costing, and organising skills are more relevant to CMs than QSs, and estimating and computer skills are equally important.

Fourteen out of 27 (51.9%) mean MSs are > 3.33 ≤ 4.17, which indicates that the Candy training made between a contribution to a near major / near major contribution to enhancing the fourteen skills. The difference relative to financial (0.62) in the favour of the construction management students is not unexpected as CMs manage finance on projects directly, as opposed to indirectly as QSs do.

Six out of 27 (22.2%) mean MSs are > 2.50 ≤ 3.33, which indicates that the Candy training made between a near minor contribution to a contribution / contribution to enhancing the six skills. Notable differences include the following. Motivating (0.78) in the favour of the QS students is possibly attributable to their interpretation, which may relate to QSs having to 'motivate' their project estimates and budgets. However, the aforementioned applies to CMs in terms of managing the business of construction. CMs, within the context of projects must motivate subcontractors and direct employees to achieve targets, and to remain within budget. Auditing (0.53), and communicating (written) (0.52) in favour of the CM students is possibly attributable to the role of Candy competency in auditing and enabling communicating in writing in terms of managing the construction process, programme, and finance.

Table 2. Comparison of the extent to which the Candy training contributed to enhancing twenty-seven skills

Skill	CM		QS		Mean		CM - QS diff
	MS	Rank	MS	Rank	MS	Rank	
Estimating	4.67	1	4.14	2	4.44	1	0.53
Costing	4.59	2	4.05	4	4.35	2	0.54
Coordinating	4.52	4	4.13	3	4.34	3	0.39
Planning	4.59	3	4.04	8	4.34	4	0.55
Measuring (productivity)	4.27	8	4.26	1	4.27	5	0.01
Computer	4.38	6	4.05	6	4.23	6	0.33
Organising	4.33	7	4.04	7	4.20	7	0.29
Measuring (quantities)	4.44	5	3.74	13	4.12	8	0.7
Procedures development	4.00	10	4.05	5	4.02	9	(0.05)
Controlling	4.04	9	3.91	11	3.98	10	0.13
Technical	3.70	15	4.00	9	3.84	11	(0.30)
Training	3.67	17	3.95	10	3.80	12	(0.28)
Financial	4.00	11	3.38	20	3.73	13	0.62
Supervisory	3.70	14	3.74	12	3.72	14	(0.04)
Communicating (graphic)	3.85	13	3.52	17	3.70	15	0.33
Administrative	3.89	12	3.43	19	3.69	16	0.46
Decision making	3.70	16	3.65	16	3.68	17	0.05
Statistical	3.56	18	3.67	15	3.60	18	(0.11)
Systems development	3.48	20	3.67	14	3.56	19	(0.19)
Negotiating (subcontractors)	3.56	19	3.35	21	3.46	20	0.21
Initiating	3.46	22	3.33	22	3.40	21	0.13
Negotiating (plant hire)	3.41	23	3.19	23	3.31	22	0.22
Auditing	3.48	21	2.95	25	3.25	23	0.53
Work study	3.11	25	3.05	24	3.08	24	0.06
Motivating	2.70	27	3.48	18	3.06	25	(0.78)
Communicating (written)	3.30	24	2.78	26	3.06	26	0.52
Plan reading	3.04	26	2.74	27	2.90	27	0.30

4.3 Planning function and activities

Table 3 presents a comparison of the extent to which the Candy training contributed to an improvement in understanding and appreciation of the planning function and its seven activities in the form of forecasting, developing objectives, programming, scheduling, budgeting, developing procedures, and developing policies, between construction management and quantity surveying students. It is notable that all the activities have mean MSs > 2.50, which indicates that the extent of the contribution is major than minor.

It is notable that 3 / 7 (42.9%) activities have mean MSs > 4.17 ≤ 5.00, namely programming, scheduling, and forecasting, which indicates that the extent of the contribution is between near major to major / major. Given the focus of the Candy system, this finding is not unexpected. Furthermore, the differences which are all in favour of the construction management students range between 0.30 and 0.41, which is possibly attributable to the construction management students' programme being more focused on planning than that of the quantity surveying students, in addition to the subject Construction Management 3, which addresses planning.

The remaining 4 / 7 activities' mean MSs are > 3.33 ≤ 4.17, namely developing objectives, developing procedures, budgeting, and developing organisation structure, which indicates that the Candy training made between a contribution to a near major / near major contribution. The major differences are relative to budgeting (0,64), and developing procedures (0.45) in the favour of the construction management students, and developing organisation structure (0.37) in favour of the quantity surveying students.

Table 3. Comparison of the extent to which the Candy training contributed to an improvement in the students' understanding and appreciation of the planning function and its activities

Activity	CM		QS		Mean		CM - QS diff
	MS	Rank	MS	Rank	MS	Rank	
Programming	4.73	2	4.43	1	4.60	1	0.30
Scheduling	4.77	1	4.38	2	4.60	2	0.39
Forecasting	4.46	3	4.05	11	4.28	3	0.41
Developing objectives	4.08	7	4.24	5	4.15	5	(0.16)
Developing procedures	4.35	4	3.90	14	4.15	6	0.45
Budgeting	4.35	5	3.71	18	4.06	7	0.64
Developing organisation structure	3.73	12	4.10	9	3.89	12	(0.37)

4.4 Project parameters

Table 4 presents a comparison of the extent to which the Candy training contributed to an improvement in understanding and appreciation of nine project parameters in the form of client satisfaction, cost, customer satisfaction, developmental objectives, environment, health and safety, productivity, quality, and time, between construction management and quantity surveying students. It is notable that all the parameters have mean MSs > 2.50, which indicates that the extent of the contribution is major than minor.

It is notable that 3 / 9 (33.3%) parameters have mean MSs > 4.17 ≤ 5.00, namely time, cost, and productivity, which indicates that the extent of the contribution is between near major to major / major. Given the focus of the Candy system, this finding is not unexpected. Furthermore, the difference relative to cost (0.49) in favour of the construction management students is possibly attributable to the construction management students realising how cost is impacted upon by performance relative to the other parameters and the benefits of the Candy system.

Thereafter, 4 / 9 (44.4%) mean MSs > 3.33 ≤ 4.17, , which indicates that the extent of the contribution is between a contribution to a near major / near major contribution.

The remaining 2 / 9 (22.2%) mean MSs are > 2.50 ≤ 3.33, which indicates that the Candy training made between a near minor contribution to a contribution /.

Table 4. Comparison of the extent to which the Candy training contributed to an improvement in the students' understanding and appreciation of nine project parameters

Parameter	CM		QS		Mean		CM -QS diff
	MS	Rank	MS	Rank	MS	Rank	
Time	4.70	1	4.65	1	4.68	1	0.05
Cost	4.62	2	4.13	4	4.39	2	0.49
Productivity	4.22	3	4.13	3	4.18	3	0.09
Quality	3.65	6	4.39	2	4.00	4	(0.74)
Client satisfaction	3.96	4	4.04	5	4.00	5	(0.08)
Customer satisfaction	3.44	7	3.86	6	3.63	6	(0.42)
Developmental objectives	3.81	5	3.78	7	3.80	7	0.03
Environment	2.59	8	3.48	8	3.00	8	(0.89)
Health and Safety	2.41	9	3.30	9	2.82	9	(0.89)

5 Conclusions, recommendations, and further research

The only limitations of the study are that the way the course contributed to an increase in knowledge, enhancement of skills, and an understanding and appreciation was not interrogated, which would require in-depth interviews. However, the extent was quantified.

Conclusions include that the CCS Candy course had an impact in terms of: an enhancement of both knowledge and skills aligned with the planning function; an improvement in understanding and appreciation of the planning function and its seven activities and the nine project parameters, and an understanding and appreciation of the practice of construction management and quantity surveying, albeit to varying degrees. The enhancement of certain knowledge and skills indicates that the learning objectives were achieved. Furthermore, the students understand and appreciate the importance and role of the CCS Candy course.

The implications of the findings are that other institutions should consider offering the CCS Candy course if they are not offering it, and furthermore, if they do, they should interrogate the impact thereof.

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Using 360-Degree Virtual Tours to Teach Construction Students

Susan Mander[1]*, Vishnupriya Vishnupriya[1] and Ruggiero Lovreglio[1]

[1]School of Built Environment, Massey University,
Private Bag 102904, North Shore, Auckland 0745, NEW ZEALAND

S.Mander@massey.ac.nz; P.Vishnu@massey.ac.nz; R.Lovreglio@massey.ac.nz
* Corresponding author

Abstract:
The COVID-19 pandemic restrictions made it necessary to move learning activities online, requiring educators to think outside the box to create authentic and experiential learning activities for students. This paper describes how virtual field trips were developed to actively engage construction students and evaluates the impact of the pedagogical technique on students' learning experiences through qualitative analysis. This exploratory study focused on understanding student experiences within a virtual learning environment. Off-the-shelf tools were used to develop online 360-degree virtual site tours to teach construction students at Massey University's School of Built Environment. Student feedback was collected to assess their perspectives on their learning after the virtual tour. The student responses indicate a high perceived impact on students' authentic learning and engagement within construction education. The research contributes to the growing knowledge base on the implementation of virtual tours in education and in supporting students in experiential learning. Our findings highlight enhanced students' experiential and authentic learning experiences in a remote learning environment.

Keywords:
360-degree virtual site tours, Construction education, Sustainable Development Goals (SDGs), Virtual classrooms, Virtual field trips

1 Introduction

In many university programs, class field trips are beneficial to bridge the gap between academia and industry. Such trips transform classroom knowledge into real-life application by allowing students to encounter and explore in an authentic setting (Djonko-Moore and Joseph, 2016). Through observation and interaction, students can reinforce their understanding of processes, operations, and spatial relationships (Nikolic *et al.*, 2009).

Despite the many benefits of field trips, they were impossible during the COVID-19 pandemic, as compulsory government lockdowns isolated populations, and students had to remain in their homes. The pandemic forced educators to rethink their curriculum and find new solutions that allowed students to undertake experiential learning and continue applying their knowledge to practical situations (Tadesse and Muluye, 2020). Initially, this involved rapid improvisation, as the educators were likewise housebound. However, as restrictions eased, these temporary online solutions were refined and replaced by more sophisticated tools.

This work aimed to prototype and test 360-degree ("360") Virtual Field Trips (VFTs). This goal was achieved by creating online tours for Massey University's construction students to replace in-person visits during the COVID-19 pandemic using off-the-shelf tools. As such, the proposed tours were developed using an existing 360 editor tool and tested for two courses in the university's curriculum. The testing assessing student experience was carried out through anonymous surveys, which registered student feedback.

2 Literature Review – Virtual Field Trips

The increasing presence of computers and cell phones in classrooms and homes has opened the world of VFTs to students. In their simplest form, VFTs resemble a child's read-along storybook (Kundu, 2016). In this scenario, students interact with electronic images accompanied by page-by-page commentary. Nowadays, advanced technologies provide educators with many more immersive and non-immersive VFT options beyond the simple storybook. These may include simple online platforms and downloadable applications through to more sophisticated virtual and augmented reality tools.

VFTs allow students to attend field trips unhindered by distance, weather and time constraints (Çalişkan, 2011). They give access to previously inaccessible places, such as dangerous building sites or hidden service ducts. VFTs offer unlimited capacity in locations with restricted space, such as electrical and mechanical plant rooms. Multiple images can be used to show construction progress (Kim *et al.*, 2019). A further advantage of VFTs is the opportunity they provide for revision, as students can view the material more than once (Sun *et al.*, 2022).

Importantly, VFTs are a step toward the United Nations' Sustainable Development Goal 4 (SDG4) to provide inclusive and equitable education (United Nations, 2022). Through VFTs, in-person attendance is possible regardless of distance, family responsibilities and other impairments, as sites can be accessed from anywhere in the world. Such opportunities for distance learning overcome many barriers to education (Pozdnyakova and Pozdnyakov, 2017).

VFTs have been applied in various educational disciplines, such as geosciences (Fung *et al.*, 2019) and hospitality education (Patiar *et al.*, 2017). Such trips have been shown to improve attitudes toward learning in students (Klippel *et al.*, 2020). In addition, digital technologies can enhance teaching effectiveness in terms of the desire to learn and knowledge retention (Lovreglio *et al.*, 2021; Rupp *et al.*, 2019).

When considering VFT delivery options, traditional VR tools may be unfeasible due to the development costs required to construct a virtual world (Pham *et al.*, 2018). An affordable alternative to traditional VR is captured-reality 360 technology (Wen and Gheisari, 2020; Wolf *et al.*, 2021). Captured reality uses simple panoramic photos and videos in a virtual environment to make VR more accessible and highly realistic in content.

The implementation of VFTs in construction education has been low (Pham *et al.*, 2018). In one example, Wolf *et al.* (2021) created a 360 model of a waterworks plant, which students explored through self-directed learning. This research found that the VFT supported student learning. In another example, Pham *et al.* (2018) developed a tool known as VIFITS (VIrtual FIeld Trip System) to provide construction site safety training. VIFITS contains three modules that are used to give training, provide VFTs and test student knowledge through gaming simulations. Results showed that students scored significantly higher in post-testing after the VFT compared to an in-person field trip. Both Wolf *et al.* (2021) and Pham *et al.* (2018) utilised experts to create their tools. Research on creating construction-based VFTs by those who are not IT or audio-visual specialists is lacking.

This paper aims to advance knowledge in the growing area of VFTs by illustrating how those with elementary IT abilities and no prior programming training can create engaging VFTs using off-the-shelf products.

3 Prototyping

3.1 Technology

This section aims to illustrate the steps required to develop VFTs using 360 photos that can be visualised using both non-immersive (i.e., computer or smartphone screens) and immersive devices (i.e., virtual reality headsets). The steps as illustrated in Figure 1 and explained in the following paragraphs.

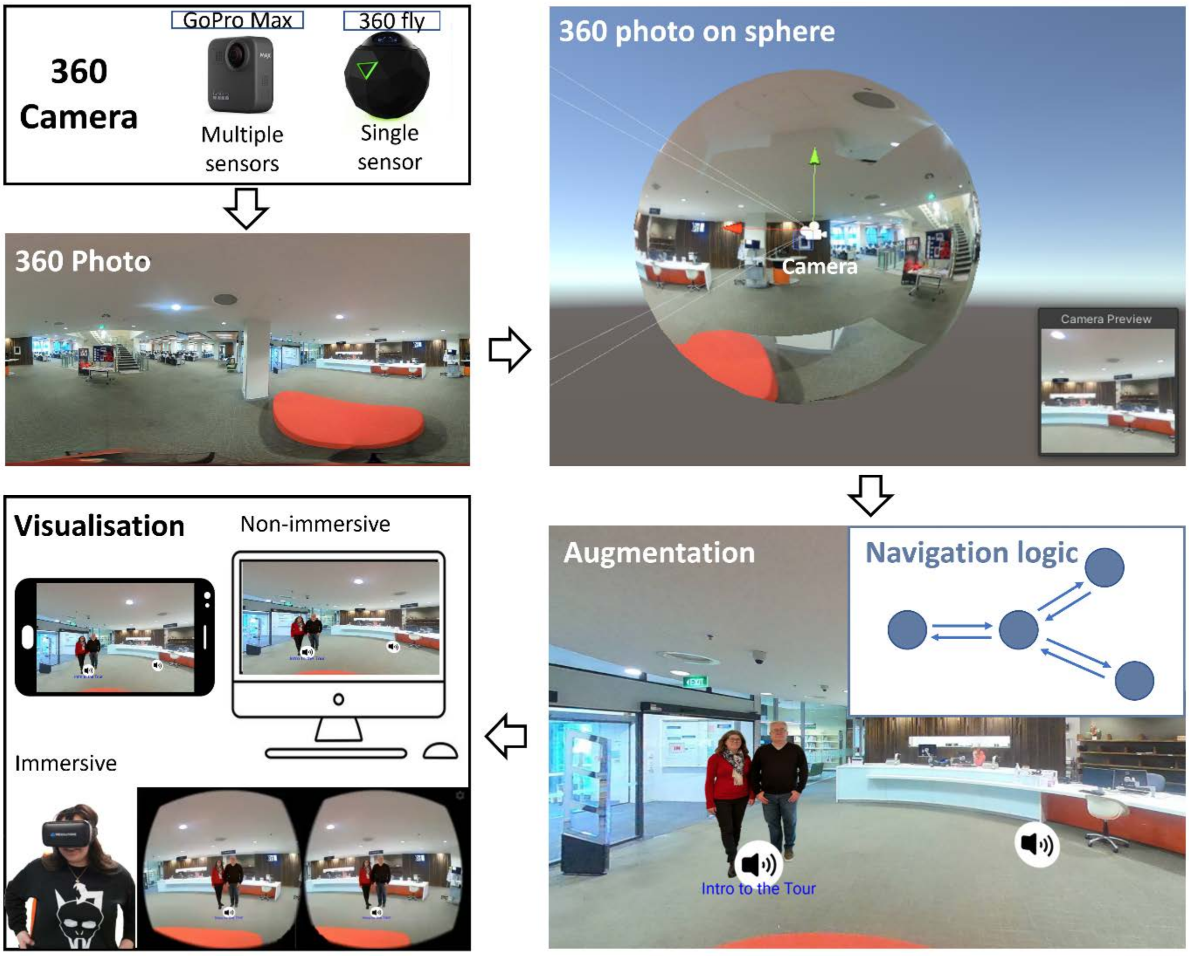

Figure 1. Prototyping steps to develop a VFT using 360 photos

A 360 photo is a wide-angle panoramic image capturing the space surrounding the original point from which the shot was taken. These photos can today be taken using different types of affordable hardware. There are two types of specialised cameras for 360-photos, which use either a single sensor or a combination of sensors. The former solution consists of a single sensor combined with a fisheye lens (see, for example, the 360 fly camera in Figure 1). In this case, the sensor is generally directed upwards while collecting pictures. The latter solution is used by cameras having two or more sensors combined with fisheye lenses. In this case, the camera is calibrated to combine the photos taken from the individual sensors and stitches them together to generate a single 360 image (see, for example, the GoPro Max).

360 photos can be viewed as traditional rectangular photos. However, when they are projected on a sphere with a viewing camera at its centre, it is possible to have a 360 experience. In this case, the viewer can decide to interact with the picture by changing their viewpoint in any direction of the sphere.

360 photos can be taken in different locations of a building. These photos can then be connected, and navigation tour logic is used to allow the users to pass from one 360 view to another. The 360 images can be augmented by adding icons enabling audio information, links to webpages or transition from one 360 photo to another. It is also possible to augment the 360 photos with text and traditional pictures. Once the tour is created, this can be hosted on a website, and it can finally be visualised using both immersive and non-immersive devices. However, when using an immersive VR device, the perception of 'depth' is limited and artificial as the 360 photos are recorded with a mono viewpoint. In this case, the 360 photos are still projected on a sphere, and the software uses two offset cameras (one for each eye) to give a sense of depth to the image projected on this sphere. This represents the main limitation of the existing 360 cameras; however, new generations of stereoscopic 360 cameras will solve this issue in the future.

All these steps to create a tour can now be done using a simple tour editing application, which enables educators to create tours using a set of 360 photos, augmenting them and creating a navigation logic. In this work, we adopted one such editing tool: kuula (https://kuula.co). Users upload their images into kuula and use simple 'drag and drop' icons to provide navigation or link to more information. Many media are supported, including simple text and images, website links, and audio-visual items.

3.2 Pilot study 1 – MU Library Tour

Pilot Study 1 was designed for students of MU's lighting programme and aimed to show how to evaluate the lighting in a commercial space (see Figure 2). In this study, students complete two self-directed tours through MU's Auckland campus library. At strategic points in the VFTs, clickable icons are used to direct the student's attention to critical information via audio commentary. Initially, the commentator focuses students' attention on specific scenes and asks them to record targeted reflective comments about the lighting. An informative tour follows this reflective component, in which the students follow the same route but are given the instructor's expert opinion at each location.

Figure 2. Library lighting tour

3.3 Pilot Study 2 – Plant Room Tour

For Pilot Study 2, Bachelor of Construction students toured a plant room at MU's Auckland campus (see Figure 3). This VFT was designed to reinforce classroom learning on mechanical and electrical services and show each piece of equipment in its typical environment. Installation techniques and interconnecting elements (such as ducts and cable ladders) can also be observed. Significant items are labelled using clickable icons, which provide additional information, such as written definitions or images showing the device's internal structure. Green and blue fonts are used to distinguish between mechanical and electrical services, respectively. Students can 'move around' through the plant room by clicking on markers on the floor. Demonstrations and clear instructions are provided to students to help them use the tool and navigate the plant room.

Figure 3. Plant room tour for construction students

4 Testing

4.1 Testing Procedure/Protocol

This section focuses on Pilot Study 2, which was accompanied by a student survey. This plant room tour was introduced as an optional activity for 204 second-year students of the university's *Construction Technology and Services* course and was available via a link on the course's online learning site.

Qualitative research methods were used in this study to understand students' perceptions and experiences with virtual technologies in education. To achieve this goal, we used an anonymous online survey to collect data regarding the students' experience. Due to the exploratory nature of this study, we used open-ended questions to gather responses from students as they are insightful and allow participants to explain the reasoning behind the responses elaborately. The intention was to gather insights into the ease of use of the tour, perception of learning improvement, and overall experience.

The survey questions specific to the site visit were:

(i) Was the virtual tour easy to use?
(ii) Would you like virtual tours for other topics too?
(iii) What was beneficial about the tour?
(iv) Did the virtual tour help you with your studies? If so, how? If not, why not?

4.2 Feedback Results

Feedback from 21 respondents from Pilot Study 2 was used as a basis for qualitative analysis. None of the questions were compulsory.

All responses to “Was the tour easy to use?” were “yes”, confirming the application’s ease of use. No further comments were provided for this question.

In response to the question, “Would you like to have virtual tours for other topics too?” all students responded affirmatively by typing “yes”. The relevant comments are given below:

- *I would love to have more virtual tours for other topics.*
- *Yes. I would like virtual tours for other topics as I found it quite fun and interesting to learn*

The responses for questions (iii) and (iv) were more descriptive in format and are given below. The feedback was categorised using qualitative codes for the most common themes identified from the analysis of the responses (Farrow and Wetzel, 2022). The qualitative codes were not predetermined and were not available to students while taking the survey.

Analysis of the comments indicated that the students’ feedback was based on the categories of learning improvement, experience, benefits over traditional learning and site tours, and assessments. The recurring themes in the comments indicate which factors may be important to students regarding virtual tours.

<u>Learning improvement</u>

- *Virtual tour helped to visualise how it all goes together.*
- *Helpful putting theoretical knowledge into the practical environment.*
- *Gave more understanding of how everything works together.*
- *The virtual tour helps make the lecture easier to understand and apply in real life.*
- *I have a visual impression of the equipment.*
- *It was really helpful to understand what each HVAC unit looks like.*

<u>Experience</u>

- *Awesome application of technology.*
- *It was interesting since I have never been in such a room before.*
- *Learning is becoming an experience.*
- *It was interesting to see a real-life situation rather than just seeing photos of slides all the time.*
- *The tour is detailed, like being personally on the scene.*
- *It assists me in observing the circumstance of the internal and directly demonstrates the equipment.*

<u>Benefits over traditional learning and site tours</u>

- *It is even better than having an actual site walk –as this could be reviewed and clicked on at any time during revision.*
- *It’s better than the 2D view, easy to interact and more attractive.*
- *I have been able to understand the system without having physical contact with others.*
- *Very useful tool, especially for distance students.*

Assessments

- *Not really, other than it being used in the tests etc.*
- *I do not know if this was ultimately relevant to the specific questions that popped up in my test so far.*

The survey response confirms the students' positive attitudes towards the virtual tour. The responses show enthusiasm for learning subjects using virtual tours. These comments highlight the value of VFTs in putting learning into context. The importance of revision and review is also evident for student learning which is available through virtual tour learning.

No detailed survey comments were received on the ease or difficulty of using the virtual tour beyond the simple affirmative answers. Specific questions in the survey could have provided more detail on the ease of navigation or other aspects of the user experience. Future studies could gather such feedback to evaluate the software and hardware tools in more detail.

Given that the pilot studies were implemented when COVID-19 restrictions were in place, none of the students experienced an in-person field trip to provide a comparison. However, students enjoyed the prototypes, and research suggests improved learning outcomes from VFTs. Despite these positive results, Clark (1983) advises that perceived gains in learning may be due to the novelty of the new learning aid, which wears off with familiarity. Thus, the novelty effect of implementing VFTs for construction also needs to be studied. Longitudinal studies could capture the possible effects of this phenomenon.

The VFTs described in this paper were optional activities designed to enhance students' understanding of lighting, electrical and mechanical services. Hence student learning from the tours was not evaluated in summative assessments such as course tests or exams. Though the literature suggests that digital technologies can improve both the desire to learn and knowledge retention, it is evident from the comments that some students perceive learning to be achieved when the activity is linked to their assessments. Therefore, an activity might be perceived as insignificant if it is not evaluated through summative assessments. As experiential and authentic learning is important in construction education, assessing the learning from site tours may emphasise the activity's importance. Hence, further studies are required to explore using assessments to test the learning from VFTs.

5 Conclusion and Further Research

This study explored students' perception of the use of 360-degree virtual tours for teaching construction students and illustrated the implementation of Virtual Field Trips using 360 photos. Such applications were originally difficult to develop as they required the use of game engines (e.g. Unity or Unreal). Today, all of the steps described in Section 3.1 can easily be carried out using off-the-shelf software tools, enabling many more users (without programming experience) to create customised Virtual Field Trips. In this work, the research team used one of these existing software tools to develop the two tours described in Sections 3.2 and 3.3 and did not encounter any issues.

The qualitative feedback shows a high interest in authentic and experiential learning experiences. The interactive 'walk around' feature of the Virtual Field Trips enabled students to feel personally present at the site. The availability and accessibility of the virtual tour for distance students and revision were important to students.

The material presented in this paper was provided under COVID-19 conditions that required emergency remote teaching. Following the success of these initiatives, Virtual Field Trips will become a permanent fixture in Massey University's teaching curriculum to enhance learning for both online and blended-learning students. This paper illustrates that simple but impactful tours can be prepared by anyone, not just those skilled in digital technologies.

Further, this paper identifies that a longitudinal study is required to investigate the novelty effect of VFTs, which is a future focus of the research team.

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Taxonomy of Digital Skills Needed in the Construction Industry: A Literature Review

Fida Hussain Siddiqui[1*] Amir Abdekhodaee[2] and Muhammad Jamaluddin Thaheem[3]

[1]Department of Civil and Construction Engineering, School of Engineering, Swinburne University of Technology, Hawthorn, VIC 3122, AUSTRALIA
[2]Department of Mechanical Engineering and Product Design Engineering, School of Engineering, Swinburne University of Technology, Hawthorn, VIC 3122, AUSTRALIA
[3]School of Architecture and Built Environment, Deakin University, Geelong, VIC 3220, AUSTRALIA

[*]fsiddiqui@swin.edu.au, fida_siddiqui@hotmail.com; aabdekhodaee@swin.edu.au; jamal.thaheem@deakin.edu.au

* Corresponding author

Abstract:
The construction industry is currently on the pathway to digitalisation as per the ongoing fourth industrial revolution and post-COVID needs. However, it has been quite slow in doing that. One of the foundational causes of the lack of digitalisation or its slow adoption in the construction industry is the lack of adequate understanding of digital skills amongst the stakeholders. This study aims to develop a taxonomy of digital skills needed to digitalise the construction industry. Following the methodology of systematic literature review, Scopus and Web of Science databases were mined to assess the relevant literature and map the skills currently utilised or needed for this digitalisation. Mainly, the digital skills were extracted and categorised into automation and robotics, communication, design, drafting and engineering, etc. The developed taxonomy will help stakeholders to plan holistically and strategically for the digital skills needed in the upcoming graduates joining the workforce. The outcome also benefits academia by aiding the stakeholders to develop tailored pedagogical approaches and relevant curricula improvements to accommodate the need for digital skills. Digitalisation is the future and educational institutions can support this movement by providing the relevant skills to existing and returning students.

Keywords:
Construction Industry, Digital Skills, Digitalisation, Systematic Literature Review, Taxonomy

1 Introduction and Background

Digitalisation is defined as the process of organising and transforming data into a distinct digital format, understandable and processable by computers or any other digital devices. It is about working with information and communication technology (ICT) tools, processes, and practices. Whereas digital technologies have a broad, diverse, complex, and contextual definitional concept and could mean different to different people as per the needs and situations and relations they are in with the digital technologies, such as in the case of Building information modelling (BIM), Augmented reality (AR), Virtual Reality (VR) etc. As they are a combination of hardware and software, can be used multi-purposely and be utilised in various phases of a construction project (Puolitaival *et al.,* 2019).

All the major industries including manufacturing, banking, and retail have recognised the benefits of digitalisation (Osunsanmi *et al.*, 2018). However, the construction industry is yet to fully embrace this concept and get the benefits (Kaufmann et al., 2018). The globally existing and fast-paced digitalisation in the context of Industry 4.0 or the digital revolution (García de Soto *et al.,* 2019) is urging the construction industry to transform rationally for efficient performance (Hassan e*t al.*, 2021). Disruptive changes have happened in the construction sector and one of the changes started with the transition from 2D to computer-aided drawings and then to BIM. Other digital technologies including the Internet of Things (IoT), AR, VR, Artificial intelligence (AI), drones, laser scanning, 3D Printing, big data analytics, Geographic information systems (GIS) and robotics are the applications of the Industry 4.0 concept (Balogun *et al*., 2021) and are up to a certain extent existing in the construction sector. These technologies help in eliminating many of the inefficiencies of complex construction projects (Suprun *et al*., 2019), improving the performance of the construction projects *(*Nassereddine *et al.,* 2021) such as safety and quality issues (Kamaruddin *et al*., 2016) etc.

Researchers claim that in implementing digital technologies and related Industry 4.0 concepts, lack of skills, knowledge, expertise and experience are the major barriers (Fitriani and Ajayi, 2021; Sriyolja *et al*., 2021; Suprun *et al*., 2019) which in turn affect the individual's and firm's performance (Tayeh *et al*., 2020). This is evident from research work which indicated that roughly 7.5% of time loss occurs due to malfunctioning of the ICT devices only as a result of a lack of ICT skills among the workers (van Deursen & van Dijk, 2014). Furthermore, Francis and Paton-Cole (2021) stated about a survey conducted by the Victorian government highlighted that approximately 75% of construction industry employers believe technical and job-specific skills are lacking in the industry (Department of Education and Training, 2017) and it was affecting the project costs and the productivity. Several other authors such as Becker et al., (2017), and Djumalieva and Sleeman (2018) also point out that digital skills are and will be required for the majority of jobs.

It is clear from the above literature that the skills requirements for the construction industry have changed over time. Stakeholders have tried to assess the workforce skills requirements every decade to acknowledge the criticality of issues due to the skills shortage and to continuously propose and implement skills development strategies and practices (Akyazi *et al.*, 2020; Cicco, 2018). Hence further research can be conducted about the preparation of current graduates for relevant digital skills and competencies development. Consequently, this research work aims to synthesise the state of the literature on the digital skills, which are used or needed in the broader construction industry domain and to develop the taxonomy (*i.e*., list) of digital skills as per the construction industry needs.

2 Research Methodology

This section briefs about the methodology to carry out the current research work. This study utilised a systematic literature review. This type of review uses methods that are replicable to identify, screen and evaluate the studies on the undertaken research area (Lima *et al*., 2021). As there is an enormous amount of research produced for each research area progressively and to delineate a fine line between what is done and the possible research gaps, SLR can be utilised to collate the existing works for a particular research question or aim in a comprehensive manner (von Danwitz, 2018; Siddaway, 2014; Tawfik *et al.*, 2019). The SLR procedure usually comprises the stages i.e., scoping, planning, searching, screening, eligibility, research syntheses and representation of the results (Siddaway, 2014).

In the scoping and planning phases, the research focus statement was formulated i.e., to develop a taxonomy (viz grouping, classification or categorisation) of the digital skills currently needed or utilised in the construction industry. Based on this research theme, search keywords were brainstormed and grouped under the categories 'Construction Industry', 'Digital Skills', 'Digitalisation', 'Systematic Literature Review', 'Taxonomy', 'Education', and 'Stakeholders'.

The entire list of keywords utilised in the searches can be requested from the corresponding author(s). The preliminary inclusion criteria were set out to consider only those publications which mention the digital competencies, roles or skills related to digitalisation of the construction industry utilised or needed within the architecture, construction engineering and management industries.

Well-thought and logical keyword combinations were then formed to be searched amongst renowned databases i.e., Scopus and Web of Science (WoS), utilising Title, Abstract and Keyword search criteria. Boolean operator "AND" was used between different keyword groups while "OR" was used to control the scope within each group. A total of 471 records were found through the searches. After downloading the relevant records from the two databases into the MS Excel format, the records were merged, duplicates (353) were removed, and non-English language records (5) were also removed. With the title and abstract screening process, 34 articles were discarded.

Furthermore, in the detailed screening phase of the SLR, while sifting through the full versions of the 79 articles, 46 records were discarded based on the detailed inclusion and exclusion criteria. Either, the articles did not consider the "digital skills" related discussion, did not mention the need and/or current utilisation of the research-themed skills, or were related to only teaching and learning or full-text unavailability. Only 33 articles were considered for the final synthesis. Figure 1 virtually summarises the above steps in the form of the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) model.

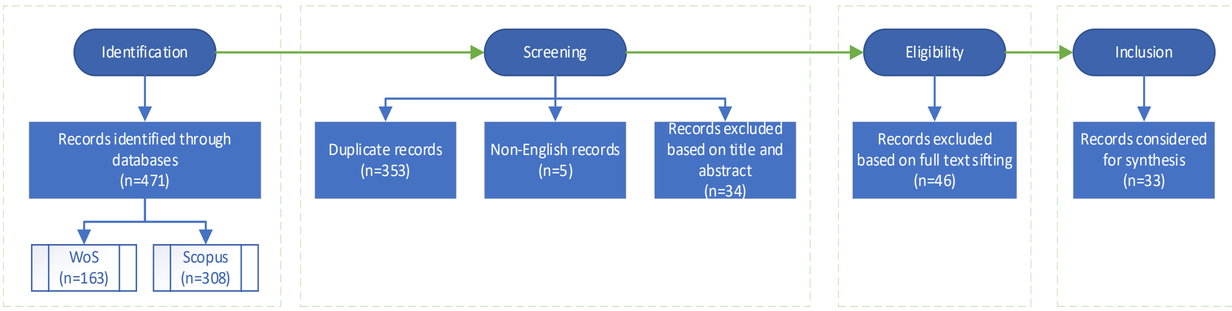

Figure 1. PRISMA Flowchart

3 Findings and Discussion

The construction industry is undergoing the process of digitalisation globally. Technological changes in the construction industry help in improving the processes and tools on-site and in the office used for the management of projects during various project lifecycle phases (Puolitaival *et al.*, 2019). The possibilities are limitless, including automation of construction sites (Elzomor & Pradhananga, 2021), digitization of design documents, utilisation of Big Data for enormous data fetching and management processes etc. Based on these and many other digital technologies' increasing utilisation in the construction sector, the relevant digital skills need has also gradually intensified (Balogun *et al.*, 2021). Any ability that involves the computer, and/or the internet can be broadly termed under the umbrella of "digital skills" (Career, 2021). Whereas the concept of 'digital skills' is defined as a combination of digital mindset, knowledge, competence/skill, and attitude (Gekara *et al.*, 2017). Engineers with digital skills are expected to be more productive and beneficial for organizations (Koretsky & Magana, 2019).

Different terminologies were used to refer to a particular digital skill in the literature. Hence grouping or categorisation of these skills is done in this research for easy understanding. Again, it is important to note that there could be numerous categorisations possible, even overlapping as well, based on a researcher's approach and the scope of the study i.e., a few of the digital skills in this research paper might be in a different category than the original category in the selected references. Though a generic and broad term can be used for almost all the mentioned skills i.e., "digital technological skills". Table 1 represents the digital skills, categories and relevant terminologies utilised in the literature. Different categories i.e., Automation & Robotics, Coding & Programming, Communication, Design, Drafting & Engineering, Digital Literacy, Digitisation & Virtualisation, Modelling & Simulation, and Planning & Estimation as presented in Table 1 were formed partially based on inspiration from (Oesterreich & Teuteberg, 2016; Tayeh *et al*., 2020) and authors' mutual brainstorming sessions.

Automation & Robotics: Growing advancements in the sector recently, has increased the usage of several tools and methodologies such as 3D printing, automation-based technologies, autonomous vehicles, offsite construction and manufacturing, drones/unmanned aerial vehicles (UAVs) (Hossain *et al.*, 2020; Li & Liu, 2019; Siddiqui *et al.*, 2019). The integration of automation and robotics technologies in the construction sector has resulted in improvements in cost, safety, quality and productivity (García de Soto *et al*., 2019). New roles and responsibilities are established whenever new technologies are introduced. Robots and automation in construction will create new opportunities and roles, specifically during the transition phase of human-machine interaction. Gerbert *et al.* (2016) depict that the new roles would be more digital e.g., digital fabricator, digital coordinator, digital manager and digital programmer (García de Soto *et al*., 2019). Recently, a debate was initiated by García de Soto *et al*. (2019) to emphasise the fast-approaching digital construction era in which the use of digital technologies and the need for digital skills are evident.

Coding & Programming: The machine learning algorithms and AI concepts are mainly based on programming skills. Construction students are rarely introduced to such advanced developed curricula (Elzomor & Pradhananga, 2021) and hence the literature emphasises the need for digital skills related to generic programming languages for future employment *(Alexander et al.,* 2019).

Communication: Today, numerous tools and devices are linked to the Information technology (IT), ICT and IoT systems i.e., radio-frequency identification (RFID), smart sensors and smart wearables and help in the communication of essential information amongst different systems (Barro-Torres *et al*., 2012; Li, CZ *et al*., 2018; Zhong *et al*., 2017).

Design, Drafting & Engineering: Knowledge and expertise in various drafting software such as AutoCAD, Revit, etc and structural design software systems leading to technical solutions have been deemed important in the construction industry. Engineering and designing modern materials including nanotechnologies and their relevant applications support the building construction sector (Shayakhmetov *et al.*, 2021). Possessing these skills has been linked with the digital literacy of the prospective candidates (Alberdi Celaya *et al.*, 2016; Fitriani & Ajayi, 2021) and are the minimum requirement for construction jobs these days (García de Soto *et al*., 2019).

Digital Literacy: Digital literacy is the knowledge and utilisation of the available digital devices for tasks. The ongoing dynamic paradigm of digital technologies requires the construction personnel to be digitally literate to be able to use several computational tools and techniques such as Microsoft office in general and for accounting purposes; possessing an awareness of and basic knowledge to use state-of-the-art construction technologies and software (Agyemang & Fong, 2019; van Laar *et al*., 2017; Pugacheva *et al*., 2020). Being digitally literate makes construction-related students eligible for prospective construction jobs (Department of Education and Training, 2017).

Digitisation & Virtualisation: Due to the digitalisation trends, an enormous amount of data is produced during the project lifecycle. To collect, store, manage, map, analyse and visualise such huge data, concepts and tools such as big data, blockchain, cloud computing and collaboration, data analytics, GIS, laser and lidar scanning are utilised (Bello *et al*., 2021; Çetin *et al.*, 2021; Li *et al.*, 2019; Oesterreich & Teuteberg, 2016; Patel *et al.*, 2021; Suprun *et al.*, 2019).

Modelling & Simulation: One of the most important and popular digital skills required today are related to BIM design, modelling and simulation, Mixed Reality (MR), AR, VR etc. BIM has been adopted in the construction industry for a long time now and almost in all phases of projects (Azhar *et al.*, 2012). AR and VR have been also very useful in educating the personnel and preventing plentiful quality and safety issues (Li *et al*., 2018). More recently, the Digital twin concept has also been established in the construction industry (Austin *et al*., 2020) aiding a lot in the monitoring and facility management phases.

Planning & Estimation: Planning, scheduling and cost estimation and optimisation, via programming, technology and software e.g., Navisworks, Primavera, MS Project, and Vico schedule planners lead to productivity improvement (Hsu *et al*., 2018; Hwang *et al.*, 2014; Liu and Lu, 2018; Moselhi and Alshibani, 2007; Zayed and Halpin, 2005).

Table 1. Categorisation of Digital Skills

S. No	**Category**	**Skills related to the use of**	**Reference**
1	Automation & Robotics	3D printing	(Balogun *et al.*, 2021; Elzomor and Pradhananga, 2021)
2		Automation based technologies	(Elzomor and Pradhananga, 2021)
3		Autonomous vehicles	(Balogun *et al.*, 2021)
4		Digital fabrication	(García de Soto *et al.*, 2019)
5		Digital fabrication Managing and Coordinating	
6		Drones/UAVs	(Balogun *et al*., 2021; Elzomor and Pradhananga, 2021; Ryan *et al*., 2019)
7		Offsite construction and manufacturing	(Balogun *et al.*, 2021)
8		Robotics	(Balogun *et al*., 2021; Elzomor and Pradhananga, 2021)
9	Coding & Programming	AI	
10		Computer programming techniques	(Elzomor and Pradhananga, 2021; Fitriani and Ajayi, 2021; Suprun et al., 2019)
11		Digital fabrication Programming	(García de Soto *et al.*, 2019)
12		Machine Learning	(Balogun *et al*., 2021; Elzomor and Pradhananga, 2021)
13	Communication	IoT	
		Smart sensors	
14		IT/ICT/computer information systems	(Agyemang and Fong, 2019; Jayawickrama *et al.*, 2020; Madanayake *et al*., 2020; Mondragon Solis *et al.*, 2015; Nguyen *et al.*, 2008, 2009; Ozumba and Shakantu, 2009; P.E. and Hanus, 2014; Pariafsai and

S. No	Category	Skills related to the use of	Reference
			Behzadan, 2021; Vaganova *et al.*, 2020; Villegas-Quezada *et al.*, 2007)
15		Smart wearables	(Balogun *et al.*, 2021)
16	Design, Drafting & Engineering	AutoCAD	(Fitriani and Ajayi, 2021; García de Soto *et al.*, 2019; Mondragon Solis *et al.*, 2015)
17		Nanotechnologies	(Shayakhmetov *et al.*, 2021)
18		Structural design/software systems designing technical solutions	(Fitriani and Ajayi, 2021; Vaganova *et al.*, 2020)
19	Digital Literacy	Computational tools/techniques; Computer skills; Microsoft office; Construction software usage; Awareness of and knowledge to use state-of-the-art construction technologies	(Agyemang and Fong, 2019; Alberdi Celaya *et al.*, 2016; Fitriani and Ajayi, 2021; Jayawickrama *et al.*, 2020; Madanayake *et al.*, 2020; Maghiar *et al.*, 2019; Mandičák *et al.*, 2020; Mondragon Solis *et al.*, 2015; Pariafsai and Behzadan, 2021; Ryan *et al.*, 2019; Urias *et al.*, 2015; Vaganova *et al.*, 2020; Windapo, 2021)
20	Digitisation & Virtualisation	Big data	(Agyemang and Fong, 2019; Balogun *et al.*, 2021; Suprun *et al.*, 2019)
21		Blockchain	(Balogun *et al.*, 2021)
22		Cloud computing and collaboration	
23		Data analytics	(Balogun *et al.*, 2021; Suprun *et al.*, 2019)
24		Data driven digitalisation	(Fitriani and Ajayi, 2021)
25		GIS	(Suprun *et al.*, 2019)
26		Laser scanning	(Balogun *et al.*, 2021)
27		Lidar survey scanner	
28	Modelling & Simulation	BIM design & modelling	(Agyemang and Fong, 2019; Anderson *et al.*, 2020; Azhar and Fadzil, 2021; Balogun *et al.*, 2021; Elijah and Oluwasuji, 2019; Fitriani and Ajayi, 2021; García de Soto *et al.*, 2019; Hore, 2008; Jayawickrama *et al.*, 2020; Karampour *et al.*, 2021; Liu and Hatipkarasulu, 2014; Mandičák *et al.*, 2020; Mesároš *et al.*, 2016; Pariafsai and Behzadan, 2021; Sriyolja *et al.*, 2021; Suprun *et al.*, 2019; Urias *et al.*, 2015; Vaganova *et al.*, 2020)
29		Digital twin	(Balogun *et al.*, 2021)
30		MR/AR/VR	(Agyemang and Fong, 2019; Balogun *et al.*, 2021; Elzomor and Pradhananga, 2021; Sasi *et al.*, 2018)
31		Revit	(Mondragon Solis *et al.*, 2015)
32		Simulation	(Panas *et al.*, 2014)
33	Planning & Estimation	Productivity planning apps/software	(Balogun *et al.*, 2021)
34		Scheduling & cost estimating/management via technology and software e.g., Navisworks	(Fitriani and Ajayi, 2021; Mandicak *et al.*, 2020; Mondragon Solis *et al.*, 2015; Pariafsai & Behzadan, 2021; Urias *et al.*, 2015)

4 Implications and limitations

The construction industry has been quite slow in the adoption of digital technologies in comparison to others. One of the reasons is the lack of relevant skills and true understanding. This research work contributes to the list and categorization of digital skills in the literature. It helps in the improvement of relevant pedagogical tools and methodologies to develop digital skills amongst the construction and allied discipline students. Furthermore, the 'contribution to practice' is that this would aid company-wide skills review of the existing staff base. It shall be noted that the scope of this research work was set down to identify the digital skills only from the articles which either explicitly or implicitly mention the need or current utilisation of the digital skills or skills related to digitalisation in the construction sector. Therefore, there may be several other skills not shortlisted due to considered search keywords.

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Perceptions of Architecture Degree Students towards Sustainability in Buildings

Tayyab Ahmad[1*] and Christhina Candido[2]

[1]Department of Civil and Architectural Engineering, Qatar University, QATAR
[2]Faculty of Architecture, Building and Planning, The University of Melbourne, Parkville, Victoria, 3010, AUSTRALIA

tayyab@qu.edu.qa

* Corresponding author

Abstract

For sustainable development and operation of buildings, architects have a critical role in converting the intangible project requirements into tangible reality. The industry-driven transition towards sustainability requires architects to have the necessary skills, knowledge, and experience to create sustainable buildings. Owing to the multidimensional nature of sustainability, and the multitude of challenges driving the sustainability agenda, the students of architecture may have varying opinions regarding sustainability attributes in buildings. Evaluating their viewpoint can give an essence of how future architects think about building sustainability. Accordingly, this study aims to provide a detailed account of the building sustainability perception of graduate-level architecture degree students at the University of Melbourne. Data was collected through two separate student activities. In the first activity, one cohort of students identified the attributes of sustainable and healthy buildings. In the second activity, a different student cohort indicated their agreement regarding a list of attributes for building sustainability. Interviews with three professional architects were also conducted to investigate the role of architects towards sustainable buildings. The outcomes of the activities reported in this study will help identify the shortcomings in the sustainability awareness of students and will help revisit the architecture degree curriculum to ensure high degree of sustainability understanding among students.

Keywords

Architecture student, Building, Sustainability attributes, Sustainability awareness

1 Introduction

Buildings are intrinsically a part of human society. They protect humans from the undesirable effects of nature, while providing places to live, work, and rejoice. However, their overarching role in society comes at an environmental cost. The environmental impact of buildings is not limited to the construction stage only as buildings continue to impact the environment in their operational life (Zuo and Zhao, 2014). The development and the operation of buildings are associated with a significant environmental and economic burden, accounting for one-sixth of freshwater, one-quarter of wood harvest, and two-fifth of material and energy flows worldwide (Chan *et al.*, 2009; Gottfried, 1994; Rodman and Lenssen, 1996). Across the globe, building-driven carbon emissions are speculated to reach 42.4 billion tonnes in 2035, that is 43% above 2007 levels (Zuo and Zhao, 2014). Negative impacts of buildings may also include traffic congestion, dust, noise, waste disposal, and water pollution during the construction stage. Due to its contribution to the largest portion of landfill wastes and consumption of about half of mineral resources, the building sector is compelled to improve in sustainability terms. Owing to urbanization, an unparalleled growth in building development is observed worldwide. The International Energy Agency has predicted that by 2050, the number of commercial and institutional buildings will increase by two times (WBCSD, 2010). Hence, sustainable practices incorporated into building construction can make substantial contributions in the future.

When it comes to sustainable development and the operation of buildings, architects have a significant role to play. Architects are the professionals who convert intangible project requirements into tangible reality defined by spaces, floors, roofs, walls, doors, and windows. Although building projects purposely developed to pursue sustainability agenda typically involve ESD or sustainability consultants, the sustainability-related awareness, motivation, and commitment of architects still contributes significantly to the project's performance.

Sustainable development is a complex issue which prevails at many different scales including building, neighbourhood, regional, national, and global-level. Also, it is hard to define sustainability in absolute terms and there is a lot of green-washing practices in built environment which corrodes the understanding of sustainable development basics. All these issues can lead to misunderstanding, misinformation, and biasness in the sustainable development-related viewpoints of general public as well as built environment experts such as architects. To date, building sustainability-related opinion of architecture-degree students is not addressed well in literature. While some studies with similar scope have been conducted previously, there is still a need to conduct such studies periodically and for different institutes. To address this research need, this proof-of-concept study aims to investigate the viewpoint of architecture degree students regarding key sustainability attributes in buildings. Following objectives will help fulfil this aim:

1. To identify the role of future architects in building sustainability.
2. To develop a list of key sustainability attributes in buildings
3. To study the viewpoint of architecture degree students towards key sustainability attributes in buildings

2 Literature Review

Determining the awareness of university students regarding sustainability is a growing topic of interest. For instance, to understand the degree of sustainability-related perception and knowledge of students, Damico, Aulicino, and Di Pasquale (2022) conducted a survey on a 1063 students enrolled in the faculties of Agricultural, Economic, and Social Sciences of the National University of Lomas de Zamora, Buenos Aires. Some studies have used survey-based data collection to gauge the sustainability awareness of architecture degree students in higher education institutes. For instance, Martínez-Ventura, de-Miguel-Arbonés, Sentieri-Omarrementería, Galan, and Calero-Llinares (2021) developed a close-ended questionnaire survey instrument for architecture students measuring the students' perception of their sustainability learning outcomes, their learning experience, and the connection between. For energy efficient buildings, YILDIZ, KARTAL, and ÖZBALTA examined the opinions, requirements, and awareness of 460 students from Balikesir University and Trakya University. In a study conducted by Brzezicki and Jasiolek (2021), 48 students were surveyed after the *Interdisciplinary Hybrid Factory Design (HFD)* course was carried out at the Faculty of Architecture, Wroclaw University of Science and Technology, Poland. Among other key findings, the survey also revealed a significant disproportion between students' expectations and experience regarding sustainable and ecological design aspects. In a study conducted by GÖKUÇ , 107 students from the Department of Architecture at the University of Balıkesir, were surveyed to determine their awareness of sustainability. One of the key findings of the study was that the architecture students lacked knowledge of sustainable architecture. Another important study in this regard is by Boarin, Martinez-Molina, and Juan-Ferruses (2020), which provided survey findings of over 300 student from the University of Auckland, New Zealand; the University of Texas at San Antonio, USA; and the CEU Cardenal Herrera University, Spain. The study analysed the students' understanding of sustainability in buildings (see Figure 1) and correlated student responses with the educational programmes offered by the institutions.

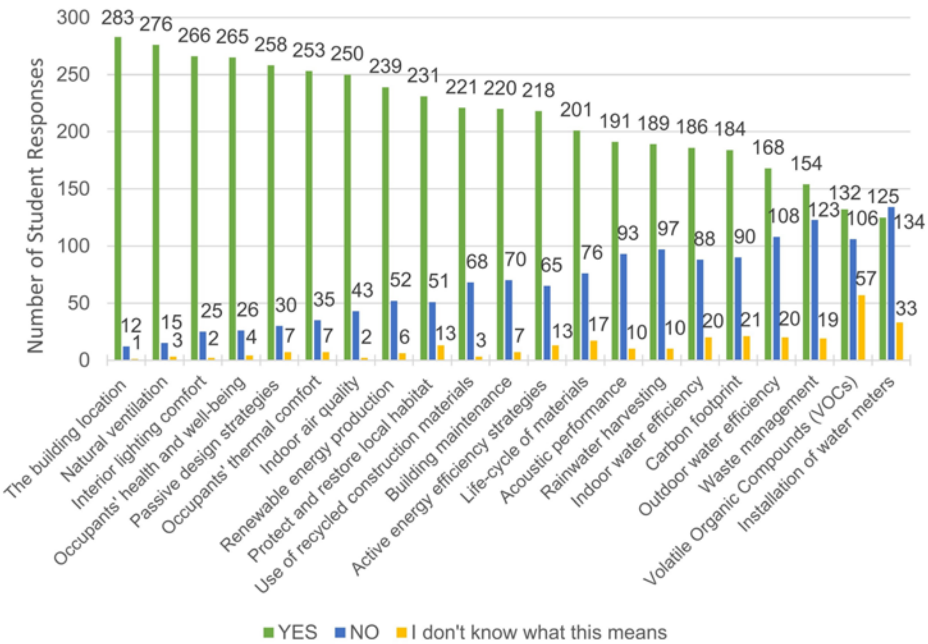

Figure 1. Students' opinion regarding sustainability aspects considered in building design (Source: Boarin e*t al.* (2020))

When assessing student awareness of sustainability, the previous studies on the subject matter reported above have focused mostly on the environmental attributes and in most instances have ignored the social attributes associated with building sustainability. The study reported in this paper will follow a similar methodology as used by Boarin *et al.* (2020), however, instead of developing the list of sustainability attributes from literature, this study will rely on the responses from students to develop an exhaustive list of both environmental and social attributes related to building sustainability.

3 Methodology

In terms of methodology, this proof-of-concept study follows a mixed methods approach. To assess the role of architects in building sustainability (obj-1), the study uses findings of semi-structured interviews conducted with practicing architects. For this purpose, three interview participants were engaged including an Australia-based, Hong Kong-based and Singapore-based architect with 8, 24, and 22-year professional experience, respectively.

To develop a list of key sustainability attributes in buildings (obj-2) and study the viewpoint of architecture degree students towards key sustainability attributes in buildings (obj-3), the study has used data from survey of students enrolled in the Master of Architecture degree programme at the University of Melbourne. The student activities informing the data collection in this study were conducted early in the offering of a graduate-level course[1] to ensure that the student learning from the course will not affect the outcomes. As part of the first assignment for the course, students are given the activity to define Sustainable and Healthy Buildings. As a result

[1] Details of the course and student-related details are kept anonymous to comply with research ethics

of this exercise sustainability attributes are indicated by students which are analysed and reported in this study (see Figure 1).

The attributes of Sustainable and Healthy Buildings identified in one course offering in academic year 2021 were used to develop an online survey activity for students which was conducted in the subsequent offering of the same course in academic year 2022. Hence, the findings from one cohort of students helped develop the online survey which was conducted for another cohort of students in a subsequent academic year (see Figure 1). The online survey listed the key attributes of Sustainable and Healthy Buildings indicated by prior students in their assignments. A Likert Scale was used to register the agreement of students regarding the relevance of attributes to Building Sustainability. The survey was conducted online and the participation in it was voluntary resulting in the participation of 44 students. The key findings of this study are listed in the next section.

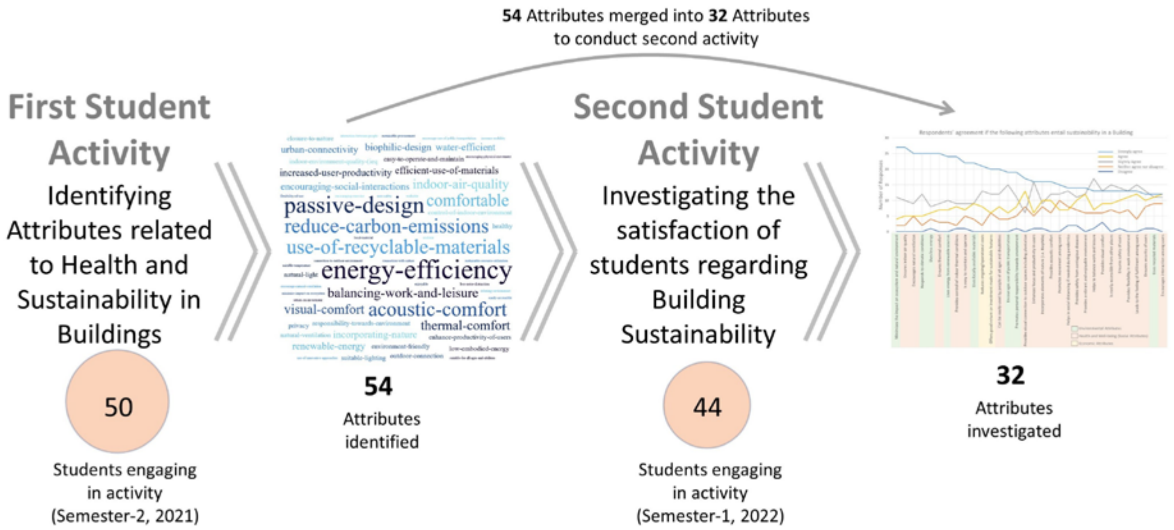

Figure 2. Student activities and their outcomes

4 Results

4.1 Role of Architects towards building sustainability

Professional architects participating in the semi-structured interviews responded to the theme of architect’s role in building sustainability. Architectural profession has started to pay increased attention towards building sustainability, as an Australia-based architect stated:

> *“Some young architects are particularly motivated and concerned towards sustainability as they care for environment ……. Architects have a huge role to play in building design and they have a lot of stuff to think about as they design a building and historically they did not need to think about sustainability….. In case an architect has not already considered sustainability aspects in a building design then under the requirement of sustainable development, he has to make an extra design effort.”*

Sustainability in buildings is ensured by high-performance designs. Developing these designs require an effort by multiple decisions. For architects to facilitate and lead the design efforts toward high-performance, it is necessary to facilitate collaborative efforts. Regarding this, a Hong Kong-based interview participant stated:

> *"We do not operate as a traditional architectural practice. With my own training and experience, we are recognized for performance-based design. We know the practices in other disciplines when it comes to Green Building projects. So, when the other specialists carry out their simulations or systems design, we understand the process and knowledge behind. This way we can cooperate in a very integrative manner. By having this approach, we distinguish our practice from the silo approach. When we encounter a certain problem or challenge, we can quickly work together and think about solutions together. This way it is not just a solution by the architect. It is a solution by everyone around the table and facilitated by us. This way everyone contributes. Since we understand other disciplines to a good extent, we can collaborate in an effective manner."*

Architects need to be highly motivated towards sustainable development to convince project clients about sustainability value. Sustainability in buildings may not readily seem profitable and to develop a better justification for sustainability based on factual data, architects need to make a rigorous effort. While indicating the practices of highly motivated and committed architectural consultants, the Singapore-based interview participant stated:

> *"Through our designs we want to change the world and you must be ready to deal with the profit-oriented clients ……. As architects, we don't blame the clients, we blame ourselves. If a project is unsuccessful, then we think that it is because of us. If the property developer can drive you to design something based on the numbers he has got, then there is something terribly wrong. This would lead to some fundamental flaws in design as spaces maybe too tight for the people to use. We have to know how to challenge it. As architects it is up to us to convince the whole team to follow the brief."*

While emphasizing on the need of Architect's knowledge of sustainable building solutions, the Singapore-based interview participant stated:

> *"As architect you must be the driver, you must know your stuff, you must have numbers with you. You cannot conquer a market when you don't have the numbers, or technical knowhow. You need to have these fundamentals first and only then you can talk about sustainability. If you just talk about green and miss the fundamentals, then people may think that you are crazy. If you don't provide people with a useful green alternative to a non-green practice, you will be wasting people's time. I have the constructivist viewpoint in this regard as I always try to look for some new solution, try to get people to buy-in, give them alternatives, explain to them our journey, etc. These things are really important."*

4.2 Outcomes of Student Activities

In the first activity conducted in 2021, students were expected to indicate what Sustainable and Healthy Buildings were comprised of, in their own understanding. Responses collected from 50 students were analysed and coded into sustainability attributes and practices (see Table 1 and Figure 3).

The list generated from the first-student-activity comprised of many Health and Well-being-related attributes emphasising on comfort, leisure, productivity, work-life balance, social interactions, safety, security, and physical movement of building users. Indoor Environment Quality (IEQ) was also indicated as a key attribute. Few students also reflected on recent pandemic-related developments and the needed role of buildings to help avoid the spread of contagions. Students also indicated some practices to ensure Health and Well-being in Buildings such as providing connections with nature and incorporating nature using Biophilic Design, connecting users to outdoor environment, encouraging exercise and physical movement, introducing natural ventilation, incorporating natural lighting, providing users control over indoor environment, and even providing good furnishing to ensure a relaxing and comfortable environment.

Figure 3. Word cloud indicating sustainability attributes and practices (outcome of first activity assigned to students)

The list is also comprised of many environmental sustainability-related attributes which are about reducing impact on ecosystem, reducing carbon emissions, reducing embodied energy, improving water and energy efficiency, ensuring urban connectivity of the building, and instilling environment-related responsibility in users. Practices to ensure environmental sustainability were indicated which most importantly comprised of the use of Passive Design and the use of recyclable materials. A number of other practices to implement environmental sustainability were also suggested (see Table 1).

Table 1. Sustainability attributes and practices identified from first activity assigned to students

Sustainability attributes and practices		Frequency
Attributes related to Health and Well-being	Comfortable	5
	Increased user productivity	5
	Indoor Environment Quality (IEQ)	2
	• Acoustic comfort	7
	• Indoor Air Quality	4
	• Thermal comfort	5
	• Visual comfort	4
	Balancing work and leisure	4
	User privacy	2
	Encouraging social interactions	5
	Enjoyable	1
	Walkable	1

Sustainability attributes and practices		Frequency
	Suitable for all ages and abilities	1
	User security	2
	User safety	4
	Helps protect from contagious diseases	2
	Relaxing environment	1
	Vibrant	2
Practices to ensure Health and Well-being	Can easily adopt social distancing in pandemics	1
	Connection with nature	1
	Connection to outdoor environment	3
	Encourage exercise	1
	Encourage physical movement	1
	Incorporating nature/Closure to nature	5
	Biophilic design	3
	Natural Ventilation	3
	Suitable lighting	2
	Use of natural light	2
	User's control over indoor environment	2
	Good Furnishing	1
Attributes related to Environmental Sustainability	Minimise impact on ecosystem	1
	Urban connectivity	3
	environment friendly	2
	Reduced Carbon Emissions	6
	low embodied energy	2
	Water efficiency	3
	Energy efficiency	8
	Responsibility towards environment	2
Practices to ensure Environmental Sustainability	Efficient use of materials	3
	Passive Design	8
	Sustainable procurement	1
	Sustainable Resource Utilization	1
	Use of recyclable materials	6
	Use of local materials	1
	Renewable energy	3
	Easily accessible	1
	Easy to operate and maintain	2
	Flexibility of use	1
	Use of innovative approaches	1
	Resilient	1
	Encourage use of public transportation	1
	High degree of usability	1
Economic Attribute	Return on investment	1
	Reduced operational costs	1

The list of sustainability attributes and practices identified from the first-student-activity helped conduct the second-student-activity in which a different cohort of students was asked their agreement regarding a number of sustainability attributes (see Figure 4).

Some of the key findings of the second-student-activity are as follows:

- There is a tendency to associate environmental attributes much strongly to Building Sustainability than social attributes. Most of the respondents strongly agreed that Building Sustainability is about reducing impact on ecosystem, responding to climatic conditions (an aspect closely related to passive design), using less energy, using renewable energy, and using locally available materials. There was a slightly low degree of agreement that Building Sustainability is about encouraging public transportation and promoting personal responsibility towards environment. There was a very low degree of agreement that Building Sustainability is about using recycled materials.

- After environmental attributes, students also tend to strongly associate economic attributes to ‘Building Sustainability’. Respondents strongly agreed that Building Sustainability can entail reducing operational costs and achieving good ROI from sustainable features.

- Some of the social attributes have also received a high degree of agreement from respondents. These attributes are about ensuring IAQ, incorporating natural ventilation, ensuring thermal comfort, providing control of indoor thermal conditions to building users, and having an easy to maintain and operate building. Hence, respondents have a high level of agreement that IEQ-related social attributes define building sustainability.

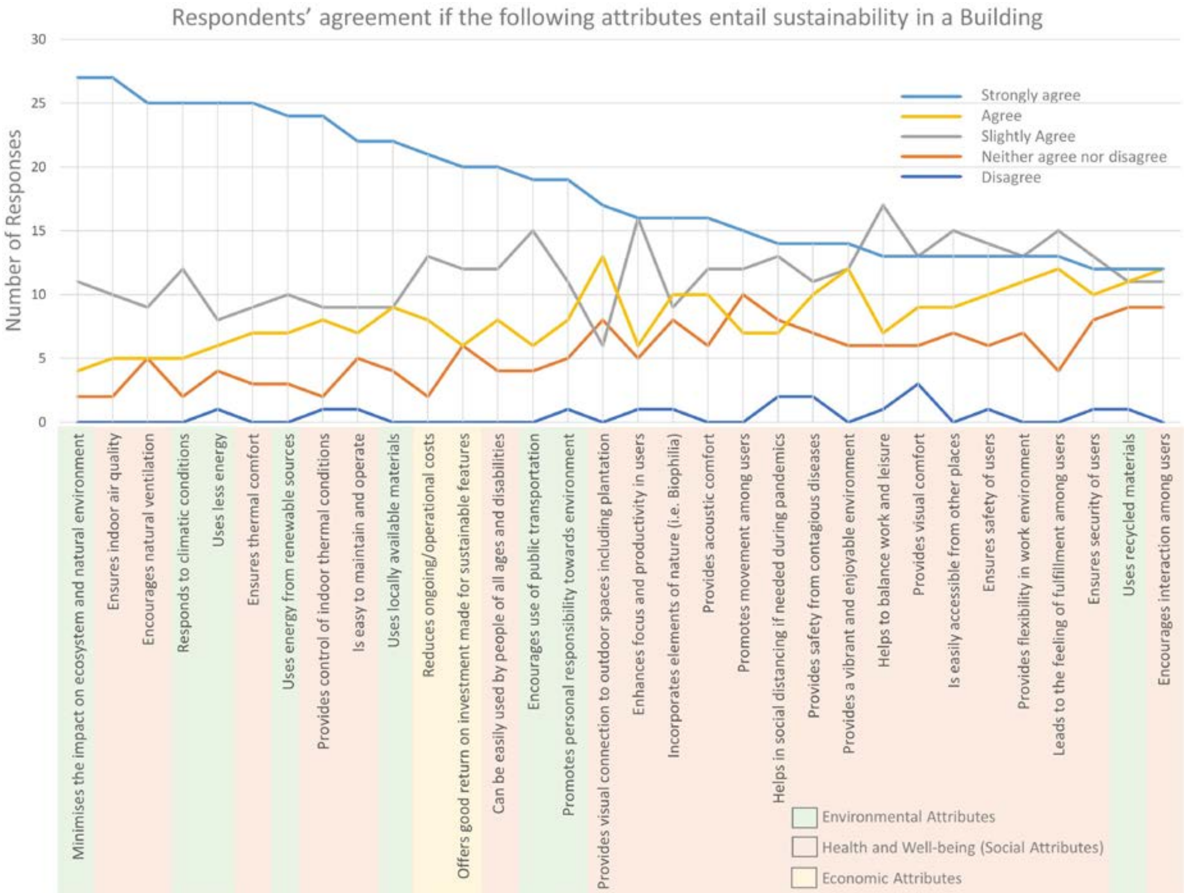

Figure 4. Students’ level of agreement regarding sustainability attributes and practices (outcome of second activity assigned to students)

The inclination of students towards social attributes was different across the two activities since in the first activity students had strong inclination towards social attributes while in the second activity this inclination was reduced. A key reason for the difference in inclination is because of the way questions were specified across the two activities. In the first-student-activity students were asked to identify attributes of *sustainable and healthy* buildings. These attributes were then introduced as *building sustainability* attributes in the second-student-activity and students were asked to show their agreement (whether the attributes entailed sustainability in buildings). In second activity, a relative lack in student agreement towards social attributes may be because the students in some instances may not be able to associate some of the social (health and well-being-related) attributes with building sustainability.

5 Discussion

According to practicing architects, architectural profession has started to pay attention towards the needs and challenges of sustainable buildings. To contribute towards sustainable buildings, an architectural graduate needs to have a commitment towards sustainable outcomes. Moreover, the architect's knowledge of sustainable solutions and the personal ability to understand and facilitate collaborative design process can play a significant role in successful achievement of sustainable outcomes.

The concept of Sustainability in Buildings has grown from the usual environmental focus to User Health, and Economic well-being. Students of Architecture are able to identify what environmental sustainability entails and what health and well-being (social attributes) in buildings entail. However, to some degree students are not able to associate social attributes under the same umbrella of building sustainability where environmental sustainability lies. Closing this gap is important for architectural pedagogy because ensuring sustainability in buildings is often challenging for the reason that achieving environmental goals may compromise user comfort and ROI and vice versa.

In case social attributes are agreed upon as intrinsic elements of building sustainability, finding optimum solutions (i.e., not compromising environmental or social values for each other) may become easier. For instance, a well-designed building envelope can reduce the need of mechanical air conditioning while also introducing natural ventilation. Hence, such an architectural design intervention not only helps improve IAQ (social attribute) but also reduces dependence on non-renewable energy (environmental attribute) and meanwhile helps save operational costs (economic attribute). On the contrary, in case sustainability is only considered in environmental terms, incorporating social (health and well-being) attributes in design may seem more as a luxury than necessity, a mindset which should be shifted considering the intrinsic relationship between built environment and health. For instance, an uncomfortable building can become an unliveable building, and can eventually become obsolete and become an environmental burden as it may require resource-intensive refurbishment or even a reconstruction. Instilling such mindset among future professionals of architecture discipline is critical. Course curriculum can be adjusted to reflect social attributes in buildings as sustainability elements, an approach increasingly being embraced by certification/rating such as the Living Building Challenge and Well certification.

6 Conclusion

For sustainable development and operation of buildings, architects have a critical role in converting the intangible project requirements into tangible reality. This study provides a detailed account of the architects' role in building sustainability and the perception of architecture degree students regarding sustainability. Semi-structures interviews with professional architects have informed the role of architectural graduates towards building sustainability. Student perception-related data is collected through two separate student activities. In the first activity, one student cohort has identified the attributes of sustainable and healthy buildings. In the second activity, a different student cohort has indicated their agreement regarding a list of building sustainability attributes.

To contribute towards sustainable built environment, the skillset for architectural degree graduates need to include collaborative design thinking, rigorous data collection, and good understanding of sustainable solutions. Students are able to associate environmental attributes more strongly to building sustainability as compared to social attributes. Alongside environmental and social attributes, students have also agreed that good ROI and savings in operational costs contribute to building. Overall, a high degree of sustainability-related awareness is noticeable among architecture degree students. A key finding of this study is that architecture students have a good understanding of what health and well-being in buildings mean, however, they lack agreement on the notion that building sustainability is not merely about environmental aspects but also about health and well-being. The outcomes of the activities reported in this study will help revisit the architecture degree curriculum to ensure high degree of sustainability understanding among students. Further study is required to differentiate the sustainability awareness of undergraduate and graduate-level architecture students. Conducting such surveys at the start and end of relevant courses can also help see how the lessons learnt from different courses affect students' awareness of sustainability. This proof-of-concept study will lead to a detailed study aspired to provide an in-depth sustainability understanding of architecture degree students from different institutes across multiple regions.

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Retention over Attraction: A Review of Factors Affecting Women's Experiences in the Australian Construction Industry

Amir Ghanbaripour[1*], Roksana Jahan Tumpa[2], Riza Yosia Sunindijo[3], Weiwei Zhang[1], Parinaz Yousefian[4], Ranka Novak Camozzi[1], Carol Hon[4], Nima Talebian[1], Tingting Liu[5], Mina Hemmati[6]

[1]Faculty of Society and Design, Bond University, Gold Coast, QLD 4226, AUSTRALIA
[2]School of Engineering and Technology, Central Queensland University, Sydney, NSW 2000, AUSTRALIA
[3]School of Built Environment, UNSW Sydney, Sydney, NSW 2052, AUSTRALIA
[4]School of Architecture and Built Environment, Queensland University of Technology, Brisbane, QLD 4001, AUSTRALIA
[5]Cities Research Institute, School of Engineering and Built Environment, Griffith University, Southport, QLD 4222, AUSTRALIA
[6]Faculty of Business and Accountancy, University of Malaya, Kuala Lumpur, MALAYSIA

aghanbar@bond.edu.au; roksanajahan.tumpa@cqumail.com; r.sunindijo@unsw.edu.au; wzhang@bond.edu.au; parinaz.yousefian@qut.edu.au; rnovakca@bond.edu.au; carol.hon@qut.edu.au; ntalebia@bond.edu.au; tingting.liu@griffith.edu.au; hemmati.minaum@gmail.com
* Corresponding author

Abstract:
Despite substantial investments and efforts by governments, construction organisations, and researchers, the construction industry remains one of the most male-dominated industries in Australia, with women being underrepresented numerically and hierarchically. Efforts to attract and retain women in construction have been implemented inconsistently on an ad hoc basis. As part of a larger research project that focuses on retaining women in the Australian construction industry, this research conducted a systematic literature review (SLR) in accordance with the PRISMA guidelines to identify the major factors that influence women's careers and their experiences in the Australian construction industry. The SLR revealed that excessive and rigid work hours, gendered culture and informal rules, limited career development opportunities, and negative perceptions of women's abilities are the main factors and issues that cause women to leave the industry. Among these, rigid and long work hours seem to be the foremost factor to be prioritised. Although long work hours can affect women more due to their family responsibilities, addressing this issue can lead to better work-life balance and mental well-being, which can benefit everyone. Understanding the roles of key variables in driving this cultural change is important to ensure that concrete progress is made. The findings are anticipated to inform future efforts to evaluate the effectiveness of current initiatives to retain women and develop a framework for enhancing women's experiences and retaining them in this profession.

Keywords:
Australia, Career experience, Construction, Retention, Women.

1 Introduction

Women certainly must be resilient and develop their technical, interpersonal and coping skills to have a successful career in the construction industry. However, this view individualises the problem, focuses on short-term solutions to 'fix women', and dismisses the need to transform the industry culture and provide a safer working environment for women (Turner *et al.*, 2021).

As a male-dominated workplace, the percentage of women in construction is low, between 9 and 13%, and has stayed relatively constant throughout the years despite efforts to diversify the workforce (Norberg and Johansson, 2020). U.S. Labour Force Statistics show that female labour force participation was 9.9% in 2018 and 10.9% in 2021. In Germany, Belgium, Italy, Spain, and Portugal, approximately 9% of construction workers are female, whereas the corresponding statistics for Canada and the United Kingdom are below 14% (Taiebi, 2022).

Being the third largest industry in Australia, construction is forecast to increase at a 2.4% annual rate through 2023, making it the second largest sector with the greatest expected employment growth (10%) (AISC, 2020). The participation rate of women in this key economic sector is extremely low, dropping from 17% in 2006 to 12.9% in 2020 (Wang *et al.*, 2021). The need for more female participation in the construction sector has been highlighted to address the labour shortage, promote equality, and increase productivity (Norberg and Johansson, 2020).

Australia's federal and state governments have initiated and implemented numerous initiatives to attract and retain women in this profession. The Queensland Government, for instance, actively encourages women to enter the industry and sets a target to surpass the National Association of Women in Construction's 11 per cent target for women in construction-related occupations (DEPW, 2022). Similarly, the Victorian Government introduced a new policy mandating greater female participation in the construction industry and allocated $5 million to promote the policy's implementation.

Despite government, industry, and educators' efforts to attract women into these jobs, they show limited success (Rosa *et al.*, 2017; Women in construction, 2021). Australia's construction industry, one of the country's leading sectors, faces an impending labour market shortage, causing the industry to overheat nationwide (ACA, 2022). The sector is missing out on a large number of talented individuals who do not engage or pursue a career in this sector. Hence, women represent an underutilised resource for meeting the labour requirement in this industry (Oo *et al.*, 2022). This is not a new problem in this industry; in fact, there is strong evidence that tackling the gender disparity has been necessary since the latter half of the 20th century (Carnemolla and Galea, 2021).

Even though several studies have explored the education, recruiting, and retention of women in the sector, the reasons for women being underrepresented in construction are still not entirely understood (Galea *et al.*, 2015, 2020; Sang and Powell, 2013). The underutilisation of women's skills and abilities is a compelling reason for scholars worldwide to investigate women's attraction, retention, and experiences in the construction industry (Oo *et al.*, 2022). Hegarty (2020), for instance, examined how women in New Zealand's construction industry entered, progressed through, and eventually left the profession between 2010 and 2018. Perrenoud *et al.* (2020) evaluated the most relevant elements in attracting and retaining women in managerial occupations in the U.S. construction industry. They surveyed 686 construction sector managers and found that women enter the field later than men. Also, women in executive positions had much less vocational training than their male counterparts.

In Türkiye, Çınar (2020) conducted qualitative field research consisting of in-depth interviews with 32 construction workers. The findings show that by defining construction labour in terms of physical capacity, a consequence of the labour conditions shaped by the practice of subcontracting, construction work has become naturalised as a male occupation. The findings also suggest how construction brings a wide range of masculinities that intersect with a working-class perspective based on men's traditional roles as heads of households and protectors of their families. In Brazil, 17 employees and engineers who work/have worked at construction sites were interviewed (Regis *et al.,* 2019). Their research found that women are typically engaged near the end of the construction period, which raises the issue of the gendered division of labour. The effects of the glass ceiling and the leaky pipeline phenomena, together with harassment, discrimination, and sexism, were apparent. Hickey and Cui (2020) examined engineering and construction executive leadership jobs in the U.S and found that women hold 3.9% of executive engineering positions. Their findings suggest that most of these organisations lack gender diversity in their leadership cultures and mission statements.

Australia's struggle to solve this severe gender disparity has given a good case study for researchers and organisations attempting to address this issue. Early research by Lingard and Lin (2004) evaluated the effect of various family and work environment variables on women's careers in construction. Loosemore and Galea (2008) found fewer conflicts would occur if more women worked in construction in Australia.

Since then, additional studies have been undertaken to uncover the difficulties experienced by Australian women in this industry. Nevertheless, our research is based on a recommendation made by Zhang *et al.* (2021), who conducted 19 interviews to investigate the transition experiences from university to work for early career female professionals. They suggested that "if retention, not simply attraction, is the key to increasing female participation in construction, workplace structure, gender fairness, and rigid work practises must be reconsidered" (Zhang *et al.,* 2021, p. 683). It is essential to understand what happens to women after being introduced to the profession to eradicate impediments to retention. This situation has been dubbed the "leaky pipeline", implying that a large number of women in construction get filtered out throughout the career pipeline, leaving only a handful at the other end (Turner *et al.,* 2021; Zhang *et al.,* 2021).

This study is part of a broader, ongoing project that intends to assist governments and policymakers by improving the effectiveness of programmes and projects implemented in Australia and their influence on the retention of women in the construction industry. As stated before and indicated by the project's title, the primary objective of this project is to improve the environment of the Australian construction industry in order to retain women who have commenced or established a career in this field. We believe that these improvements will result in fewer women leaving the profession, a more positive image of the industry, and a more diverse and inclusive workplace. Additionally, this will encourage more women to join the sector.

The information presented in this paper is based on a review of prior studies and lays the groundwork for a more extensive and in-depth investigation of the factors and issues that affect women's retention and career advancement in the construction industry in order to develop a framework for evaluating the initiatives and policies in place to retain women in this industry.

2 Methodology

Using systematic literature reviews (SLRs), researchers may reliably and openly pinpoint the most pertinent material and follow consistent review processes (Thomas and Harden, 2008). SLRs provide readers with a comprehensive overview of the literature and help them discover research gaps in the field. Thus, an SLR can be considered a platform for advancing knowledge. An SLR was conducted to identify major issues that influence women's careers and their experiences in the Australian Construction industry based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines consisting of four phases:

identification, screening, eligibility, and inclusion for review (Page *et al.*, 2021). The process is shown in Figure 1.

In the identification phase, Scopus and ProQuest were selected as the preferred databases for collecting existing articles. Keywords chosen in this study were related to 'construction industry', 'women', 'retention' and 'Australia'. Two search strings were developed focusing on different synonyms:

- Female* OR women OR woman OR girl* OR feminist* OR "gender diversity" AND "construction industry" OR "building industry" OR "construction management" OR "construction companies" OR "construction company" OR "property industry" OR "built environment".

- Female* OR women OR woman OR girl* OR feminist* OR "gender diversity" AND "construction industry" OR "building industry" OR "construction management" OR "construction companies" OR "construction company" OR "property industry" OR "built environment" AND Retention or Retain.

The search strings were applied to Scopus and ProQuest, where 4071 documents were identified. While Google Scholar provides very low-precision search results and does not support many of the features required for systematic searches (Wang *et al.*, 2021), it was used to find results that may not have been found elsewhere due to the limited research in this field in the Australian construction context. 723 documents were identified in Google Scholar.

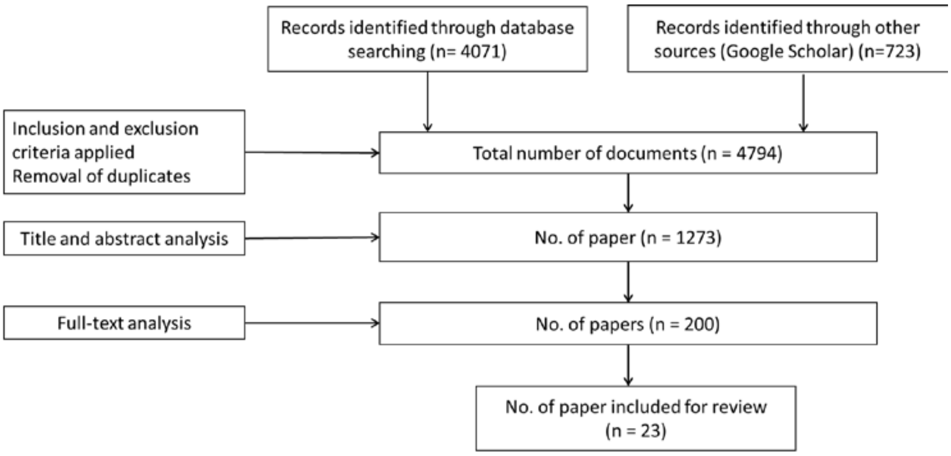

Figure 1. PRISMA flowchart of selected articles (prepared by the authors)

In the screening phase, criteria were established to choose relevant articles. The inclusion criteria included articles published in peer-reviewed journals, available in full text, written in English, published in the last 30 years and researched in the Australian context. Duplications were removed among Scopus, ProQuest and Google Scholar at this stage, thus resulting in 1273 articles. The titles and abstracts of these 1273 articles were screened to identify relevant articles. Only 200 articles were deemed eligible at this stage. These 200 articles were read thoroughly (full text) in the eligibility stage to determine if they met the inclusion criteria. Only 23 articles met the inclusion criteria and were included for data analysis, forming the inclusion for the review phase.

The research was conducted in two phases to strengthen the validity of the findings. The first author studied and analysed each of the reviewed papers. Second, all authors used a shared spreadsheet to modify, refine, and finalise the structural dimensions and analytical categories utilised to build the study's conceptual framework. Wijewickrama *et al.* (2021) employed a similar method to improve the quality and dependability of the content analysis in the SLR.

3 Results

The results were categorised into two sections. A descriptive analysis was carried out to shed light on the sources of publications and annual trends of the reviewed articles. A content analysis was undertaken to examine the selected 23 papers.

3.1 Descriptive Analysis

As shown in Table 1, the first bibliometric study examines the distribution of articles by publication source.

Table 1. The number of articles published in journals and conference proceedings

Source Name	No. of Articles
Journals	*22*
Construction Management and Economics	7
Construction Economics and Building	4
Gender, work, and organisation	2
Journal of Construction Engineering and Management	1
Australian Journal of Civil Engineering	1
Equality, Diversity, and Inclusion	1
Australian Journal of Management	1
Journal of Management in Engineering	1
Construction Innovation	1
Work, Employment and Society	1
Buildings	1
International Journal of Construction Management	1
Conferences	*1*
IOP conference series. Materials Science and Engineering	1

All articles except one were journal publications, with the *Construction Management and Economics* journal constituting the most prominent source with seven articles. This was followed by the *Construction Economics and Building* and *Gender, Work, and Organization* journals. Also, Figure 2 presents the distribution of these 23 articles from 1998 to 2022.

Although annual publications remained below three from 1998 to 2019, the numbers indicate a modest rise to eight by 2021. It is noteworthy that more than half of the articles were published after the Covid-19 pandemic began in 2020. The upward trend of articles implies that scholars are becoming increasingly interested in the field, which is expected to continue.

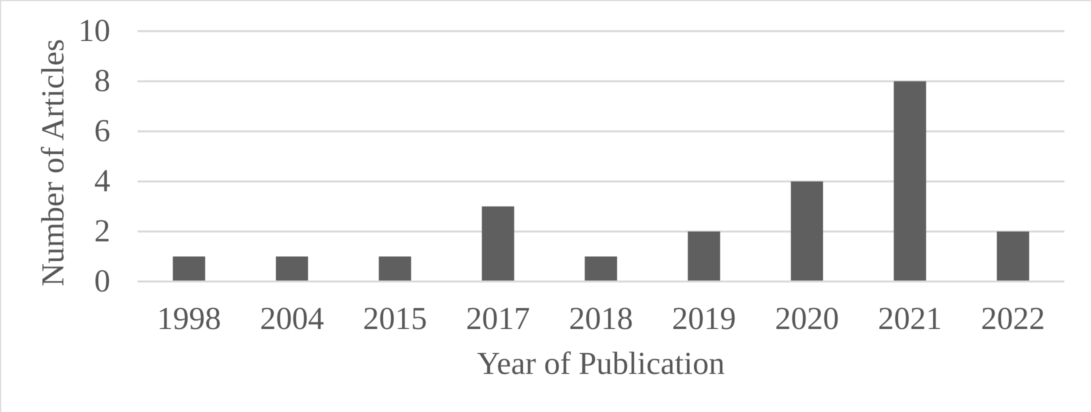

Figure 2. Annual distribution of articles throughout 1998–2021

Table 2 includes that factors and issues identified in the literature and the main categories which comprise almost all the issues will be discussed in the next section.

3.2 Content Analysis

Several challenges and factors influencing women's retention and engagement in Australia's construction sector have been discovered through the SLR. While little research has been conducted to evaluate the effectiveness of government policies in retaining women in this sector, researchers have made significant progress in identifying the primary obstacles that would cause women to leave this industry or seek employment elsewhere, as discussed in the following sections. It should be noted that while the emphasis is solely on the Australian construction sector, international research will also be utilised to contextualise the results for the general readership and to inform the next phases of the larger project, which involve investigating these concerns in other countries with comparable cultural environments to Australia.

3.2.1 Work Hours and Family

It is evident from the interviews conducted in Lingard and Lin's (2004) research that the construction industry is infamously known for its rigid and long work hours. This characteristic has been identified as the greatest barrier to gender equality in the Australian construction industry across almost all research efforts. The sector clings to restrictive work norms such as long work hours and tight timetables. It establishes expectations of "presenteeism" and absolute availability, which are seen as the way things have always been (Galea *et al.*, 2020). One interviewee in Zhang *et al.* (2021) stated, "*There was a time last Christmas I was doing 80 hours a week, and I just can't maintain that. I can't maintain that with a family, which I'm hoping to have, but there's expectations*" (Zhang *et al.*, 2021, p. 679).

Table 2. Mapping the factors and issues affecting women in the Australia construction in the literature

Factors \ Citations	Bryce *et al*. (2019)	Baker and French (2018)	Salignac *et al*. (2018)	Rosa *et al*. (2017)	Francis (2017)	Galea *et al*. (2015)	Lingard and Lin (2004)	Pringle and Winning (1998)	Oo *et al*. (2019)	Loosemore et al. (2020)	Baker *et al*. (2021a)	Oo and Lim (2021)	Baker *et al*. (2021b)	Turner *et al*. (2021)	Perera *et al*. (2021)	Zhang *et al*. (2021)	Galea *et al*. (2020)	Bridges *et al*. (2020)	Oo *et al*. (2020)	Galea *et al*. (2022)	Oo *et al*. (2022)	Oo *et al*. (2021)	Wang *et al*. (2021)
Institutionalised work practices		*																*					
Lack of flexible working solutions/long hours	*	*						*	*	*		*			*		*			*		*	
Lack of available roles/ career opportunities	*								*										*		*		
Lack of senior female mentors	*																				*		
Gender discrimination	*		*					*															
Work/life responsibilities	*	*		*								*			*							*	
Lack of career support	*	*					*	*		*				*	*								
Workplace culture/informal rules/industry culture	*	*		*		*		*	*	*			*	*		*	*	*		*		*	
Stereotypes about females' abilities				*				*		*								*					
Stress									*											*			
Family					*							*										*	
Policies						*	*				*		*					*					
Masculine culture			*						*														
Inability to fit in										*													
Health needs										*										*			
Human capital/ resilience/personal growth				*	*									*	*	*			*				*

According to Galea *et al.* (2020), working on Saturdays regardless of level, responsibility, or set work hours has been an unwritten norm in the Australian construction sector. Due to long working hours, women quit or have considered leaving the construction profession (Bryce *et al.,* 2019). A participant in their study stated that "*the standard working day is ten hours plus travel and it is exhausting. I am working towards leaving the industry because the hours are simply too much*" (Bryce *et al.,* 2019, p. 4). In Baker and French's (2018) study, one female project manager said: "*The industry is used to you answering your phone at 6 a.m. in the morning when [the] manager gets onsite, and they're used to the manager calling you at 7 o'clock at night when they're still in the office so you just sort of have to be available"* (Baker and French, 2018, p. 804). It is important to note that this phenomenon is not exclusive to women, but men have also struggled due to these work norms, as reflected by the high occurrence of poor mental health.

3.2.2 Gendered Culture and Informal Rules

In the construction sector, aggressive and competitive behaviours are gendered since they are founded on hegemonic male norms and rules of conduct, what Chappell (2006) refers to as a "gendered logic of appropriateness". Francis (2017) surveyed 463 women in professional or management positions in the Australian construction sector and discovered that the less masculine the organisation, the more women progress in their careers. As a result of the cultural pressures of portraying masculinity in male-dominated professions, many employees feel they must hide or ignore their mental health problems in order to demonstrate their "toughness", "self-reliance", and "reliability" (Wong *et al.,* 2017). As a consequence of being rewarded, these restrictions become ingrained, whereas feminine behaviours (such as exhibiting emotions) are usually sanctioned (Galea *et al.,* 2021).

According to Oo *et al.* (2020), the sector's culture is seen as one of the most significant hurdles to women's participation in the construction sector. Organisations and their leaders frequently fail to consider organisational culture and structural inequalities in the industry when implementing diversity initiatives, even though doing so would go a long way towards addressing the core causes of inequality and bringing about permanent change (Baker *et al.,* 2021a). To address these cultural issues, Bridges *et al.* (2020) argue that businesses should conduct workplace education programmes that focus on cultural change to promote harassment and bullying-free workplaces for women.

3.2.3 Career Opportunities and Available Roles

In the construction sector, the shortage of transparent professional prospects has been one of the primary obstacles to women's career advancement (Bryce *et al.,* 2019; Zhang *et al.,* 2021). According to research, women are less likely than men to actively plan their careers, focusing more on surviving in their current job (Francis, 2017). Men are afforded better possibilities for job advancement, such as working on and managing high-profile projects, while women must contend with prejudices and assumptions that they will quit the sector or scale down their employment to pursue motherhood (Salignac *et al.,* 2018; Sang and Powell, 2013). Half of the people surveyed in a study by Baker and French (2018) on gender bias and other structural barriers to career development in Australia's project-based construction industry, expressed scepticism about the openness, credibility, and fairness of internal appointments and promotions that seemed to be based on informal selection and gender bias. One respondent explained: "*If you are a female … the only way you really progress is [if] someone older or more senior than you takes you under their wing and that person is typically a male. If you are a male … they seem to just progress much easier"* (Baker and French, 2018, p. 806).

Turner *et al.* (2021) argue that women are often denied professional advancement possibilities in addition to their skill sets being underutilised. For example, one of their research participants commented: "*I have been looked over for higher roles, leadership roles, because I'm a girl and I've been openly told you were the best candidate for this position, but boys won't … listen to you*" (Turner *et al.,* 2021, p. 845).

3.2.4 Perception of Women's Ability

In a series of interviews conducted 24 years ago, Pringle and Winning (1998) discovered that around one-fourth of tradespeople and builders believed that lack of strength and inability to operate equipment made some fields inappropriate for women. They made statements such as, "Women lack the intrinsic capacity to handle tools", "They lack the men's natural understanding of construction" and "Women are not built to lift heavy materials". Despite several initiatives and measures, this problem persists. While men are assumed competent in the construction industry, women's professional ability is scrutinised, questioned, or discounted (Turner *et al.*, 2021). When a woman messes up, it's called a problem with "female capacity" rather than her own incompetence (Galea *et al.* 2018). Zhang *et al.* (2021) state that males in the construction industry instinctively assume that women lack the necessary skills and abilities to execute their jobs. This mindset is at odds with the efforts of the business world as a whole to expand the number of women in the workforce. One of their research interviewees explained that: "*Well, even in a meeting, most of the subcontractors prefer to talk with the men in the room rather than the ladies* " (Zhang *et al.*, 2021, p. 678).

4 Discussion and Conclusion

This study aims to lay the groundwork for a large-scale investigation evaluating the effectiveness of initiatives and policies that resolve the gender imbalance that hinders women's retention in the Australian construction sector. The most significant impediments have been identified through the SLR on the variables and challenges affecting women's careers and experiences in this Australian construction sector. The results reveal that women in the construction industry have been marginalised and have challenged several stereotypes and informal rules intrinsic to the profession.

Most articles identified institutionalised work practices, such as rigid and lengthy work hours, as the most significant barrier to women's professional advancement in the construction industry. Long working hours are hazardous for both men and women, although women are often affected more (Wang *et al.*, 2021). Several women with families find it challenging to balance their careers and family responsibilities, especially when they return from maternity leave and find themselves without assistance. For women trying to return to their prior project responsibilities part-time, the demands of full-time employment and the absence of part-time work opportunities pose substantial obstacles (Baker and French, 2018). The Australian construction sector has long had policies and regulations in place promoting gender equality. However, a culture of subtle denial and hostility to gender equality hinders the proper implementation of legislation and regulations (Wang *et al.*, 2021). Based on past research, addressing this issue should be the foremost priority for the industry to retain women. Changing this culture can also lead to better work-life balance and mental health for both men and women.

Other significant issues for women to leave this profession include the gendered culture, informal rules, limited career prospects compared to males, and a negative view of women's abilities in some areas. Therefore, to increase worker well-being, these informal, commonly accepted, and gendered regulations must be broken (Galea *et al.*, 2021). If this is not done, informal norms will likely continue undermining official regulations, such as government policies and efforts regarding gender disparity using public funds.

Throughout the years, Australian state and federal governments have developed and implemented several initiatives and policies to tackle gender disparity in the construction industry, yet studies indicate that only minimal improvements have been accomplished. This suggests a potential study path to analyse further and evaluate these initiatives' outcomes and implementation. A systemic viewpoint is necessary to identify the various variables/stakeholders/factors and their interrelationships to detect the leverage points (Meadows, 1997; Zhang *et al.*, 2016) and archetypes within the system in order to design the most effective policies and initiatives that can make a real difference. Indeed, these approaches will aid in making the sector more appealing to and inclusive of women (Baker *et al.*, 2021a).

According to Galea *et al.* (2015), efforts and policies addressing gender imbalance in construction must be robust and adaptable. Otherwise, the above-mentioned informal norms would impede the successful implementation of such initiatives, making it difficult for these policies to 'stick'. The findings of the SLR are consistent with their research, which implies that gendered norms and behaviours, such as long work hours, must be prioritised when establishing a gender equality policy. The historical experience with comparable difficulties and the presence of such informal regulations imply that more obligatory and focused actions are likely to be more successful (Loosemore *et al.*, 2020).

Few Australian studies have examined the retention of women in this sector through improving the work environment and the policies. Consequently, the government will need to provide robust assistance by formulating policies. This will encourage researchers to conduct a systematic review of the system's variables and causal relationships, resulting in the development of a framework that will aid governments and policymakers in designing the most effective initiatives that will make a significant difference and evaluating the success and effectiveness of such initiatives. This will boost employee well-being (Galea *et al.*, 2015) and benefit the whole industry.

This study contributes to the discussion on the variables influencing the retention rate of women in the construction industry and the need for more effective strategies to boost it. It serves as a stepping stone for the next part of the study, which attempts to provide a framework for evaluating the efficacy of such efforts.

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Skill Transformation: Future Requirements, Implementation, and Academic Implications in Quantity Surveying and Construction Management Professionals in the New Zealand Construction Industry

Kam Yuen Cheng[1*] and Cecily Zhou[2]

[1]Engineering and Architectural Studies Department, Ara Institute of Canterbury,
130 Madras Street, Christchurch, NEW ZEALAND
[2]TOPA Partner Ltd (TOPA Electrical)
1/10 Musgrove Close, Wigram, Christchurch, NEW ZEALAND

Kam.cheng@ara.ac.nz; Cecily_0707@hotmail.com
* Corresponding author

Abstract:
The construction field is currently experiencing a profound transformation driven by technological evolution, climate changes, and wellbeing, especially after the disruption due to the pandemics in 2020, which highlights the importance of preparing students for the types of careers that will be available to them in the future. Construction and quantity surveying programmes in New Zealand are typically at the diploma level taught in polytechnics; there is no existing research about skill transformation in the New Zealand construction industry. This study aims to identify future skill requirements to investigate how the academic curriculum will be transformed in response to changes in their employability demand by the industry over the coming three to five years and set the graduates up for future success in New Zealand. The study consists of questionnaires sent to academics and practitioners and subsequent thematic analysis of the result is performed under smart competencies, resilience competencies and sustainability competencies. The study shows that data analytics and STEM knowledge, teamwork and communications, energy management and circular economy under the three thematic categories and their interactions with one another hold information that can lead to recommendations for the design of construction and quantity surveying programmes.

Keywords:
Construction, Future skills, Higher education, Sustainability, Transformation

1 Introduction

The construction industry is one of the largest sectors in the global economy, but its productivity has had an average growth of 1% per annum over the last twenty years. The construction sector needs to change significantly to improve its low productivity context. New technologies and smart approaches can respond better to current and future demands. Artificial intelligence (AI), design automation, robotics, the Internet of Things (IoT), and the advent of information and technologies are revolutionising the construction transformation and bringing the construction process to a new level. Key skills for future construction requirements will be skewed towards the system thinker, data-driven decision-making, and STEM background practitioner (RICS, 2020).

2 Literature Review

The advanced construction operation management system successfully converts the paperwork into the computer and subside business costs and labour. Compared with traditional construction methods, integrated industrialised construction (IC) requires professional teams to perform more installation, assembly, and coordination activities by leveraging the benefits of offsite technologies. IC system connects the design to the making process through innovative and integrated techniques (RICS, 2020). A new terminology - intelligent or smart construction presents the full use of digital and industrialised manufacturing technology to strengthen productivity, cut back the overall expenses of the sector, and improve sustainability to optimise the resources of the entire industry. The competencies of the three themes are summarised in Table 1.

Table 1. Summary of future skills identified

	Theme 1: Smart Competencies	**References**
1	Data Analysis and Leadership	(Haupt and Naidoo, 2016)
2	STEM Knowledge	(Smith, 2011)
3	Modelling and Simulation	(Tang *et al.*, 2019)
4	IoT, Images and CV	(Maskuriy *et al.*, 2019)
5	Design Automation	(Council, 2021)
6	AR/VR	(Council, 2021)
7	AI	(Chernyshev *et al.*, 2023)
8	AMT	(Li *et al.*, 2017)
9	Managing Robots and Drones	(Council, 2021)
	Theme 2: Resilience Competencies	**References**
1	Teamwork/Collaboration	(Knight and Yorke, 2003)
2	Excellent communication for complex problem-solving	(Knight and Yorke, 2003)
3	Critical thinking	(Borg and Scott-Young, 2020; Demaria et al., 2018)
4	Project management	(CITB, 2018)
5	Resilience and perseverance	(Ellis *et al.*, 2014)
6	Quality and consistency assurance	(Demaria *et al*., 2018; Pang *et al.*, 2019)
7	Emotional intelligence	(Knight and Yorke, 2003)
8	Systematic thinking	(Borg and Scott-Young, 2020; Demaria et al., 2018)
9	Excellent Presentation	(Council, 2021)
10	Integration of Resources	(Vohmann and Frame, 2016)
11	Production management	(Council, 2021)
12	Creativity and Innovation	(Olawale, 2015)
13	Proactive learning	(Maxwell and Armellini, 2018)
14	Personal work & life experience	(McGunagle and Zizka, 2018)
15	Computer programming mindset	(CITB, 2018)

	Theme 3: Sustainability Competencies	References
1	Energy management	(McLaughlin, 2012)
2	Circular economy	(Dean, 2019)
3	Sustainable insight	(Agapiou *et al.*, 1995)
4	Carbon footprint	(Council, 2021)
5	Climate change	(RICS, 2020)

2.1 Smart Opportunities

Intelligent or smart construction presents the full use of digital and industrialised manufacturing technology to strengthen productivity, cut back the overall expenses of the sector, and improve sustainability to optimise the resources of the entire industry. The meaning of "smart" in the construction section refers to the development and improvement through collaborative partnerships among each link of design, construction, and operation. In other words, relying on modern competency to streamline the building cost (Tang *et al*., 2019) and to satisfy the current growing market to upskill the productivity of the sector.

Data analytics is a key to digital transformation. Because with the improvement of streamlined data entry and management presentation, the work becomes easier and more competitive, enhancing productivity and competitive advantage (Haupt and Naidoo, 2016). Conversely, saving more time on repetitive processes, for instance, daily business activities, upgrading the social image of the organisation. Furthermore, it benefits decision-making (Ibironke *et al*., 2011) and boosts the quality of the service provided and the speed of the execution of tasks (Haupt and Naidoo, 2016). The new technology allows for applying digitisers for measurement and eliminates various situations by directly extracting quantities from expert files (Smith, 2011). Therefore, the professional system can be transferred quantities and costs more efficiently through digital techniques and take advantage of scaling services related to time-consuming, resolution, and cost planning. The realisation of a smart system requires the industry to cooperate with tertiary educators or skill training providers to upgrade existing offerings and develop new upskilling routes aimed at existing practitioners and new entrants (Council, 2021)). In addition to existing professionals or experts in the construction sector, highly trained, multi-skilled, and digitally literate technicians will be new stars in the construction human sources market.

2.2 Resilience over skills

Understanding and knowledge before the construction industry are crucial (CITB, 2018). Construction students are familiar with academic knowledge within particular modules rather than skills development. Resilience and adaptability in the construction sector rely on individual cognition and experience. It is an achievement with capabilities, consciousness, and personal attributes (Maxwell and Armellini, 2018). This skill set is reconceptualised as "Skill Plus" by (Knight and Yorke, 2003). Future construction talents regard communication, teamwork, and technical construction knowledge as three critical elements of transferable and improved skills (Borg & Scottand -Young, 2020; Demaria *et al.*, 2018). Collaborative abilities are the most sought-after skills demanded (Olawale, 2015) because good quality work relationships help to learn on the job. Therefore, some researchers sustained that verbal and written communications emerge as one of the leading skills, and team-working is the most important future capability in the construction industry that evokes contribution from diverse specialists (Olawale, 2015).

To produce competitive, innovative solutions to real business issues, construction professionals can be responsive, initiative-taking, adaptable, and creative. Their personality and individual experiences are beyond academic knowledge, which can be applied in the workplace (McGunagle and Zizka, 2018). Such high-performance resilience and collaboration will be essential skills necessary to deliver future smart construction projects (Council, 2021). The need to enhance future construction talent's skill transformation is identified by (Vohmann and Frame, 2016) since construction learners frequently work in complex dynamic environments and often in construction practitioners' professional courses. There may be an assumption that they develop both subjects' specific knowledge and appropriate professional future competence (Vohmann and Frame, 2016). This point is supported by other scholars who agree with integrating capability within the curriculum (Knight and Yorke, 2003), but the assessment becomes the weakest part of their learning experience.

Construction learners are more aware of industry expectations regarding transferable competence and made significant headway in their transferable abilities (Demaria *et al*., 2018). But most of the learners reflect that assessment is effective at building transferable skills because they are most confident with their analytical skills and flexibility/adaptability rather than creativity/innovation and leadership (Olawale, 2015).

The construction sector expects critical thinking ability and responsibility (Demaria *et al.*, 2018; Pang *et al.*, 2019) and considers value-based attraction factors (CITB, 2018). Besides that, the ability to use the computer and technology to process the task; writing and listening; problem-solving capability are also employers' perspectives (Ellis *et al.*, 2014).

2.3 Sustainable Development

Current researchers' theories assist us in understanding how to process analysis and policy toward identifying the crucial factors affecting a person's possibility of achieving a new career and providing a strong framework for a prosperous labour market model. With a sustainable view, the skills of future practitioners are unlikely to be strengthened by training schemes that only satisfy the industry demands. Many construction organisations have this issue and are interested in upgrading and improving their human resources competence to counter persistent skill shortages (Agapiou *et al.*, 1995). Apart from essential individual training needs, group and personal training can strengthen practitioners in a highly competitive place and create a systematic way to address emotional behaviour and achieve quality communication (Dean, 2019). It is named "DEMO Strategy", which involves four stages: assembling resources – engaging learners – working together – building confidence(McLaughlin and Mills, 2012). The market trends prove that working experience is more highly considered as evidence of job readiness than a degree in three aspects (Ferns et al., 2019): (1) Work placement integrated learning has emerged as a critical pedagogical strategy to raise students' research and develop professional capability; (2) Partnership between education and industry is a more extensive and intensive framework; (3) Professional accreditation promotes services to educators as a marketing strategy appealing to incoming students. Some researchers set up a framework to support this view – Active Blended Learning (ABL). It is taught through student-oriented programmes that support the improvement of subject knowledge and understanding, self-learning, and digital fluency (Maxwell and Armellini, 2018). Sustainable construction development will demand industry talents to operate on-site installation and offsite facility-based manufacturing in different environments. Technically, they can manage product integration and logistics alignment (Council, 2021). Following the transformation and adoption in the industry, new IC-related teams have emerged. The experts highlight that these teams' creations make construction a more attractive industry for the next generation (RICS, 2020).

3 Research Methodology

The study in New Zealand used a quantitative research approach to determine future construction talents. The research technique included a focused review of the literature, conversations with subject-matter experts, data collection, statistical pre-testing of the data, and data analysis. A literature review was conducted in order to find potential future skills. Scopus and Web of Science were used to find relevant papers. Section 2 describes how relevant papers were evaluated in order to discover prospective future capabilities. The study's target population includes the New Zealand Institute of Building (NZIOB) and the New Zealand Institute of Quantity Surveyors (NZIQS), which represent construction professionals, councils, contractors, suppliers, consultants, property developers, designers, subcontractors, manufacturers, and academics. Practitioners are the ones who determine which changes should be implemented inside an organisation. Registered construction practitioners are people who are knowledgeable and skilled in the New Zealand building sector. Their forecasts for future capability provide perspective for the New Zealand building sector. Because the sample comprises persons from diverse professions in the construction industry, the research findings are impartial and trustworthy for future reference and study. The analysis is performed under three themes – Smart competencies, Resilience competencies and Sustainability competencies.

4 Findings and Discussion

4.1 Characteristics of respondents

From August to September 2022, 40 electronic survey questionnaires were sent through email, phone, and social media. (For example, Facebook and WeChat). Eighty per cent of the surveys sent were returned, with 32 valid replies. This is greater than the typical response rate for surveys in the construction sector, which is 30% (Yap and Skitmore, 2018), and is considered excellent.

The summary of respondents' attributes in Table 2 demonstrates that the four groups of respondents are equally distributed. Almost 40% of the practitioners are experts in their field and have worked in the construction business for at least five years.

Table 2. Demographic profile of respondents (N=32)

Working Experience	Client	Contract	Suppliers	QS	Others	Total
0-5 years	5	6	1	2	5	19
6-10 years		3	2	1	3	9
10-20years	1	2				3
21 years and above		1				1
Total	6	12	3	3	8	32

4.2 Results

4.2.1 Smart Competencies

The nine variables are reliable, with a Cronbach's alpha value of 0.840. Table 3 displays the average scores. The three most important talents are data analysis and leadership, STEM knowledge, and modelling and simulation, with mean scores of 4, 3.688, and 3.688, respectively. The overall mean scores vary from 2.6884 to 4, with these three abilities ranking highest. Controlling robots and drones is placed last.

Table 3. Average scores of smart competencies

Competency	Mean	Ranking
Data Analysis and Leadership	4	1
STEM Knowledge	3.688	2
Modelling and Simulation	3.688	3
IoT, Images and CV	3.625	4
Design Automation	3.563	5
AR/VR	3.156	6
AI	2.688	7
AMT	2.656	8
Managing Robots and Drones	2.344	9

4.2.2 Resilience Competencies

Cronbach's alpha is 0.679 for the 15 variables, suggesting a good level of dependability. The average scores are shown in Table 4. The three most important qualities are teamwork/collaboration, good communication skills, and critical thinking, with mean scores of 4.844, 4.656, and 4.552, respectively. The overall mean scores vary from 3.46 to 4.844. Surprisingly, the computer programming mindset is the last to be described.

Table 4. Average scores of resilience competencies

Group 2: Resilience	Mean	Ranking
Teamwork/Collaboration	4.844	1
Excellent communication for complex problem-solving	4.656	2
Critical thinking	4.531	3
Project management	4.469	4
Resilience and perseverance	4.438	5
Quality and consistency assurance	4.281	6
Emotional intelligence	4.281	7
Systematic thinking	4.250	8
Excellent Presentation	4.219	9

Integration of Resources	4.219	10
Production management	4.063	11
Creativity and Innovation	3.875	12
Proactive learning	3.656	13
Personal work & life experience	3.625	14
Computer programming mindset	3.469	15

4.2.3 Sustainability Competencies

Cronbach's alpha value is 0.777 for the five variables studied, showing strong internal consistency reliability. Table 5 shows the importance of each skill's ranking, mean scores, and standard deviation. Energy management and circular economy are the two most essential sustainability competencies, with total mean scores ranging from 2.219 to 3.781. Climate change is one of the least important sustainability competencies.

Table 5. Average scores of sustainability competencies

Group 3: Sustainability	**Mean**	**Ranking**
Energy management	3.7813	1
Circular economy	3.6875	2
Sustainable insight	3.2813	3
Carbon footprint	2.4688	4
Climate change	2.2188	5

4.3 Discussion

Smart competencies, which include "data analysis and leadership, STEM knowledge," are the key skills with the highest mean scores in Group 1 of Table 1. Employee domain knowledge and analytic skills are a mix of knowledge and abilities that may help effectively execute data analysis tasks (Draganidis and Mentzas, 2006). A vast volume of data is meaningless unless it is utilized to enhance the firm performance have invested in data analytics to help translate it into business insights. Still, the human side of this process has received little attention (Waller and Fawcett, 2013). Paying attention to other related company features (such as human resources) makes corporate assets more difficult for rivals to copy(Helfat and Peteraf, 2003). As a result, in the context of this research, it is critical to concentrate on people's strengths in decision-making via the use of data analytics.

Integrating BIM data, management goals, and stakeholder connections are essential for successful decision-making and the creation of intelligent systems. Thus, IoT-enabled artificial intelligence (AI), machine learning (ML), and other innovative technologies may be adopted while keeping data safety and cyber security in mind (Woodhead *et al.*, 2018). To acquire a competitive edge, the firm should convert into a digital organization led by top management and supported by financial stakeholders (Chen, 2017). The firm also needs to continue to educate itself on developing technologies such as construction ERP, e-procurement, and so on (Santos *et al.*, 2017). Like any other organization, the removal of any impediments to the construction industry's digitalization will occur despite social, political, technical, ethical, and legal obstacles (Kravchenko, 2019).

Group 2 - Resilience: The following are the top basic/core attributes "teamwork/collaboration" and "communication skills." A team is "a distinct kind of group in which members work interdependently to accomplish a goal" (Yaman et al., 2018). However, as Tarricone and Luca (2002, p. 56) point out, "teamwork demonstrates that people work in a cooperative atmosphere toward a shared objective by sharing knowledge/skills and being adaptable to complete a range of duties." Given this reasoning, teams often comprise individuals with specialized knowledge of their duties in activities aimed toward a shared goal (Halvorsen *et al.*, 2019; Tarricone and Luca, 2002). Successful "team players" must have both task-specific and interpersonal abilities. As a result, they are forming high-performance teams and maintaining and optimizing chemicals for superior results.

Employee communication is critical for maximizing productivity on the job site. Effective communication occurs when the recipient understands the sender's message. Drawings, specs, notes, letters, memoranda, models, catalogues, instructions, and photos must be preserved, retrieved, and shared throughout construction. Poor communication has caused delays, cost overruns, poor quality, health and safety hazards, pollution, and sustainability challenges in New Zealand's construction industry (Kumar *et al.*, 2021; Sanni-Anibire *et al.*, 2022). Poor communication is directly responsible for rework, non-uniformity, and wasteful resource utilization in the construction industry. Workplace bullying, worker resentment, unethical behavior, poor productivity, low employee morale, discrimination, insecurity, workplace violence, and limiting creativity and originality are further adverse consequences. Excellent communication is key to finishing a job. Appropriate information helps consumers make educated financial choices, ensures material and labour availability, and ensures exact construction project planning and scheduling.

In Group 3 – Sustainability, Energy management and circular economy are the top basic/core competencies. Because each construction project is unique and the construction business is complicated, building professionals may find it difficult to adopt new technology and processes (Almansoori *et al.*, 2021). To understand the causes of the variance in energy management knowledge and application levels in the local construction sector, it is necessary to examine the barriers that restrict its acceptance(Siddique *et al*., 2022). The government advocates energy conservation measures, such as taxes, financial support from financial markets, and subsidies for energy-saving projects; these may boost construction's adoption of energy management. (Enshassi *et al*., 2018).

The largest hurdle to energy management in building projects is the industry's inability to integrate sustainable solutions. Both the amount and quality of human resources contribute to this inability. Top management commitment is the most critical aspect of an energy-management programme's successful adoption and administration (Capehart et al., 2020). Effective energy management necessitates using tools and processes that allow strategic decision-making in selecting feasible and ecologically desirable energy-saving methods (Koutsandreas *et al*., 2022). Lack of investment, information and transaction costs, profitability barriers, a skilled labour shortage, and other market obstacles are just some of the impediments to investment in energy management and greenhouse gas emission reduction that need to be addressed by industrial-sector policies and programmes.

5 Conclusion and Further Research

Quantity surveyors (QSs) in the New Zealand construction sector will need future abilities to fulfil and manage their professional tasks. Client needs become more demanding and getting more difficult. To stay competitive, the QS profession's existing obligations must evolve and be well-prepared for changing corporate settings. The industry must recognize the core abilities that are the foundation of present and future commercial success in the built environment. Some of the previous qualifications for a QS may have been superseded by the competencies described in this research in the future. In this regard, the necessity of training and education on those above fundamental/core and emergent skills to adapt and future-proof QSs' professional growth cannot be overstated. The QS education of the next generation must be tailored to the market's requirements. Professional organizations, councils, and associations can help with curriculum creation, accreditation, professional competency evaluation, and continuous professional development.

The finding of this paper will aid academic institutions in upgrading the quantity surveying programme curriculum. According to the literature, professional organizations for quantity surveying will need to integrate newly recognized talents and abilities in their lists of competencies and skills necessary for quantity surveyors to carry out their different responsibilities in the future. The research continues this idea by identifying the various QS occupations in high demand and the knowledge and abilities needed to perform those activities. This study makes a significant theoretical contribution by redefining the work tasks of a professional QS to reflect contemporary trends in the construction sector. It also adds to the corpus of current knowledge by setting a baseline for the level of expertise and abilities anticipated by professional QS to carry out the provided responsibilities. Limitations should be considered as the sample size is relatively small (32) and the small number of QS respondents (3). Future academics may do more studies on developing practical techniques for assessing QSs' skills and knowledge about the content of tasks for which they are accountable, as well as implementing systems to remedy any discrepancies. However, due to factors such as technological improvements, the chosen occupations will only be effective for the next ten years. The order of the various jobs varies depending on the nation.

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A Review of Immersive Technology Applications in Occupational Health and Safety Training in the Construction Industry

Arka Ghosh[1*] and Abid Hasan[2]

[1]School of Information Technology, Deakin University,
Geelong, VIC 3220, AUSTRALIA
[2]School of Architecture and Built Environment, Deakin University,
Geelong, VIC 3220, AUSTRALIA
ghoshar@deakin.edu.au; abid.hasan@deakin.edu.au

* Corresponding author

Abstract:
Training of the workforce is an integral component of the occupational health and safety (OHS) management system on construction sites. However, the traditional training styles have been criticised for their failure to capture the complexities of the construction site environment, potential accident scenarios and workers' responses or behaviour. Immersive technologies like AR (Augmented Reality), VR (Virtual Reality) and MR (Mixed Reality) could change the content and delivery of OHS training in the construction industry. The present study reviews 42 journal articles published on the application of immersive technology in OHS training in the construction industry. It illustrates various applications of immersive technologies, along with prominent researchers, organisations and countries active in this research area. Furthermore, it offers insights into four major research clusters of immersive technology applications: (1) improved risk management, (2) efficient resource usage, (3) computer-based hazard simulation, and (4) better OHS decisions.

Keywords:
Construction workers, Immersive technology, Safety, Training, Virtual reality

1 Introduction

The construction industry in many countries has started to recognise the growing pervasion of digitalisation in other sectors, such as manufacturing and retail. As a result, it is gradually adapting work practices and environments to inculcate various emerging technologies that promise to revamp the industry's traditional working style and productivity. Previous studies show that using various emerging technologies for workforce training could improve training delivery and learning outcomes by overcoming the shortcomings of traditional training programs (Afzal and Shafiq, 2021; Xu and Zheng, 2021).

Some of the limitations of traditional occupational health and safety (OHS) training methods are a two-dimensional or paper-based and theoretical approach that fails to capture the entire site environment and project reality. There are also limited opportunities for workers to visualise OHS hazards and practice working safely in hazardous conditions before performing the task in real-world situations. On the other hand, virtual and immersive environments could simulate the task and actual site conditions. Many researchers discuss the potential applications and use of immersive technologies like AR (Augmented Reality), VR (Virtual Reality) and MR (Mixed Reality) to improve the OHS training of the construction workforce (Wang et al., 2018; Afzal and Shafiq, 2021; Opoku *et al.*, 2021; Xu and Zheng, 2021). For instance, Ferrada et al. (2019) argued that workers must be provided with a real-world context to ensure their behaviour while performing the actual task remains the same. Furthermore, Adami *et al*. (2021) concluded that virtual learning environments increase construction workers' knowledge, operational skills, and safety behaviour. Therefore, these technologies can positively impact OHS training outcomes due to increased worker motivation, self-efficacy, situational awareness and authentic experiences.

The growing use of simulated virtual learning environments can revolutionise how construction workers are trained on construction sites. These technologies have been found to promote active learning and impart practical skills better than widely used traditional training approaches in the construction industry. In addition, many researchers argue that immersive technologies and simulated site environments could lead to the active engagement of experienced workers and trade unions, especially in the context of apprenticeship training (De Freitas and Neumann, 2009; Abdel-Wahab, 2012; Wang *et al.,* 2018).

Immersiveness can be understood as the functionality of a tool to seamlessly blend the 3D augmented visuals with the perceived real-world environment (Yuen *et al*., 2011). In a classroom setting, an immersive three-dimensional (3D) experience can also facilitate students understanding of critical concepts (Turkan *et al.*, 2017). Furthermore, researchers believe that immersive technology helps alleviate the mental workload and cognitive load of participants and workers and enables smoother learning (Lin and Seipel, 2018; Chu *et al.*, 2018; Chalhoub and Ayer, 2019b). However, there is another line of thought among some researchers that immersive technologies could increase the cognitive load (Kang *et al.,* 2017) instead of improving cognitive performance (Wang et al., 2018). The diverse views may be a result of the specifics of the implementation of immersive technologies.

Since immersive technologies in the OHS training of construction workers is an important and emerging field of research, it is imperative to understand the research landscape on their applications and benefits in OHS management in the construction industry. Therefore, the present study reviews journal articles on immersive technology applications in OHS training to examine the research trends and identify major research themes. It also shows various platforms and environments developed by the researchers to create immersive OHS training environments and experiences. The findings offer new insights into the existing research to facilitate future research efforts.

2 Review Approach

Scopus was selected as the source database for identifying published journal articles on immersive technology applications in OHS training in the construction industry. Scopus has a broader coverage of recent publications and a faster indexing process and lists reputed publication outlets (Abioye *et al.,* 2021). The initial search (Step 1) for the relevant papers in the Scopus database resulted in 545 publications. Next, the period of the analysis was limited from 2010 to 2021. Moreover, to filter out quality research outputs, the document type was refined to include only peer-reviewed journal articles, the rationale being that journal articles represent research studies with a high impact (Wijewickrama *et al.*, 2021). At this stage, papers published in conferences and trade journals, review articles, book chapters, books, theses, etc., were removed. Furthermore, only articles published in the English language were retained. As a result, 230 articles were shortlisted after Step 1. After manually screening the title, abstract and keywords to filter out irrelevant articles in Step 2, 42 journal articles were retained for further analysis and discussion. Figure 1 shows the stepwise search results and the overall review approach.

Next, bibliometric analysis was performed using *VOSviewer* because it provides easy mapping and visualisation of research networks. It is increasingly used by researchers in the domain of construction management (Li *et al*., 2021). The intention was to evaluate emerging themes in immersive technology applications in OHS training in the construction industry and provide concise information on these themes. The analysis also reveals information on researchers affiliated with institutions from different countries assisting research efforts in this field. Additionally, the shortlisted papers were reviewed to provide information on various platforms and environments developed by the researchers to create immersive OHS training programs.

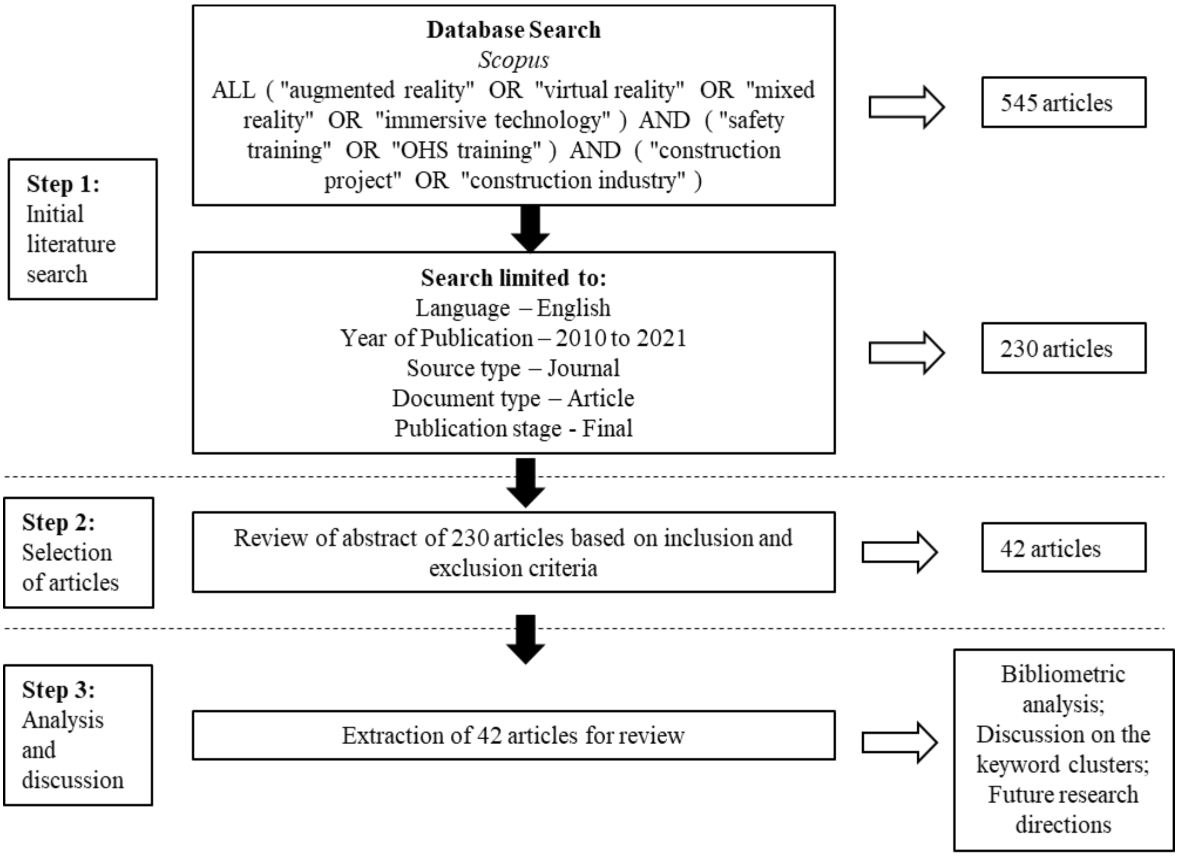

Figure 1. Stepwise search results and review approach

3 Review Findings

3.1 Publication Trends

Figure 2 depicts the year-wise trend of research on immersive technology applications in OHS training in the construction industry. While very few articles were published annually between 2010-2019, the number of publications in this field has increased considerably since 2019, with the highest number of articles (*i.e.*, 19 articles) published on this topic in 2021. The publication trend could be explained by the increased affordability and availability of these technologies in recent years resulting in more research and broader applications in OHS training in the construction industry.

The general distribution of the primary discipline source of the analysed articles revealed that most of the articles come from Engineering journals (41%). Additionally, there are significant contributions from Computer Science (15%), Business, Management and Accounting (12%), and Social Science (10%), which demonstrate the multi-disciplinary nature of research in this field.

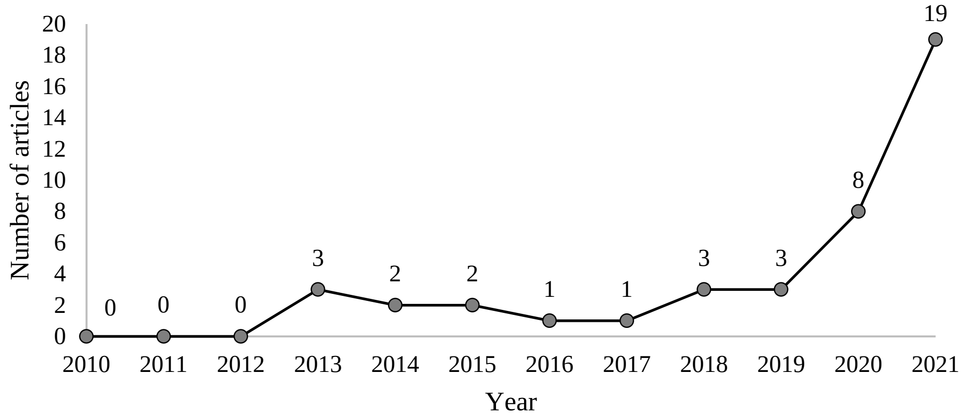

Figure 2. Year-wise publication trends on immersive technology applications in construction OHS training (2010-2021)

3.2 Leading Publication Outlets, Authors, Institutions and Countries

Among leading research outlets actively publishing research in this field, Automation in Construction published nine articles, followed by the Journal of Construction Engineering and Management (six articles), Advanced Engineering Informatics (four articles), Safety Science (four articles), and Engineering Construction and Architectural Management (three articles).

For conducting an analysis of prominent authors in VOSviewer, the type of analysis was set to co-authorship, the unit of analysis was set to authors, and the counting method was fractional to determine the major authors. Of the 161 authors, 29 met the criteria of a minimum of two documents per author. Of these, Albert, A., Ahn, C.R., and Park, C.S. had three publications each.

Among leading institutions illustrated in Figure 3, Virginia Polytechnic Institute is the leading research institution in this field with six publications, followed by the University of Florida (United States) and Chung-Ang University (South Korea) with four publications each.

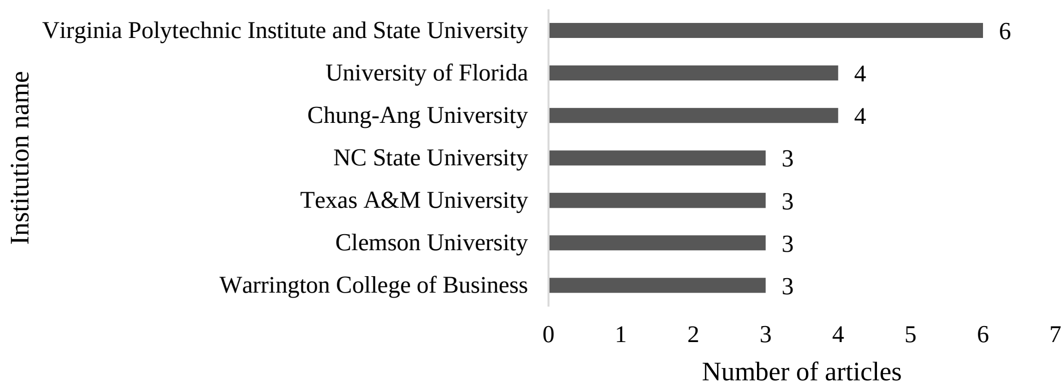

Figure 3. Institution-wise research distribution of research on immersive technology applications in construction OHS training (2010-2021)

Among countries leading the research on immersive technology applications in OHS training, as illustrated in Figure 4, the United States (US) has the maximum number of publications (i.e., 20 publications), followed by Australia and South Korea (5 publications each). The review found that there are more research contributions from developed countries than from developing nations. The scarcity of research in developing countries could be due to the limited financial capacity of construction institutions and construction organisations and the slow adoption of new technologies in these countries (Iqbal *et al.*, 2021; Opoku *et al.*, 2021).

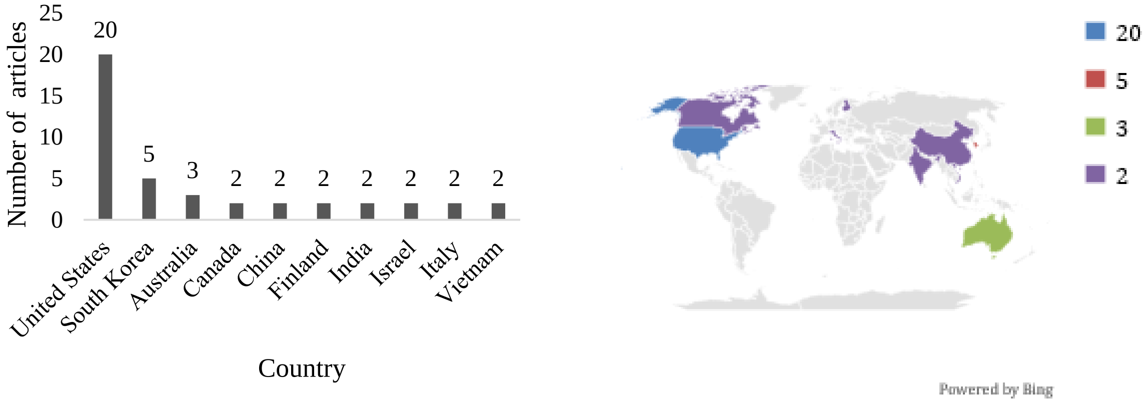

Figure 4. Country-wise research distribution of research on immersive technology applications in construction OHS training (2010-2021)

3.3 Immersive Technology Platforms and Environment

Table 1 summarises the immersive technology or environment used for OHS training in 42 reviewed articles. It can be seen that AR has been used in more than 80% of the reviewed articles though in combination with other technologies or processes. For instance, Afzal and Shafiq (2021) and Getuli *et al.* (2021) discuss BIM-enabled VR simulations for OHS training. Similarly, few studies have discussed the application of VR training modules incorporating sensors for eye-tracking, motion tracking and physiological data (Shi *et al*., 2019; Comu *et al.* 2021; Subedi *et al.*, 2021).

Table 1. Technology and platform used in reviewed articles

Technology	Platform/Environment description	References
Virtual Reality (VR) – 34 studies	VR simulated environment	Zhao and Lucas, 2015; Lu and Davis, 2016; Kim *et al.*, 2017; Lu and Davis, 2018; Sacks *et al*., 2019; Vahdatikhaki *et al*., 2019; Nykänen *et al.*, 2020a; Adami *et al*., 2021; Dhalmahapatra *et al.*, 2021; Han *et al.*, 2021; Kim *et al.*, 2021; Mora-Serrano *et al.*, 2021; Xu and Zheng 2021
	Integrated real-time location tracking and 3D immersive data visualization technologies	Teizer *et al.*, 2013
	Virtual construction site using a 3-sided virtual reality CAVE	Perlman *et al.*, 2014
	Online social VR system framework	Le *et al*., 2015
	Interactive Augmented Photoreality platform integrating virtual photoreality with 3D-virtual reality	Pham *et al*., 2019
	Multi-user VR system with a motion tracking feature	Shi *et al.*, 2019
	Cyber-physical postural training environment using wearable sensors, Vive trackers, machine learning and virtual reality	Akanmu *et al.*, 2020
	VR-based proprioceptive training	Cyma-Wejchenig *et al*., 2020

	Combined virtual environment with realistic environments (stereo-panoramic scenes)	Jeelani *et al.*, 2020
	Immersive VR and combined immersive VR and human factor	Nykänen *et al.*, 2020b
	4-D BIM-enabled VR simulations	Afzal and Shafiq, 2021
	Mobile VR game-based module and the virtual tour-based module	Bhagwat *et al.*, 2021
	Eye movements-based VR platform	Comu *et al.*, 2021
	Immersive storytelling within digital 360-degree panoramas	Eiris *et al.*, 2020
	Training protocol based on BIM-enabled VR activity simulations	Getuli *et al.*, 2021
	A reliable and responsive VR simulator for assessing ironworkers' gait performance and fall risk	Habibnezhad *et al.*, 2021
	VR module developed using Unity3D and Visual Studio joint platforms and can be interfaced with using the Oculus Rift/Oculus S	Joshi *et al.*, 2021
	Combined Electroencephalograph and eye-tracking technologies in an immersive virtual environment using machine learning techniques. Workers wear a VR head-mounted device equipped with an eye-tracking sensor.	Noghabaei *et al.*, 2021
	Building site VR model and a 3D video tutorial implemented using a VR Head-Mounted Display	Osti *et al.*, 2021
	Crane simulator system developed in the VR environment integrated with a database of comprehensive lift studies and a detailed crane path planning system	Pooladvand *et al.*, 2021
	VR user interaction based on a task-centred methodology	Raimbaud *et al.*, 2021
	Physiological sensors in a 3D simulation of a real construction site	Subedi *et al.*, 2021
Augmented Reality (AR) – 5 studies	A framework/prototype integrating building information modelling (BIM), location tracking, AR, and game technologies.	Park and Kim, 2013
	High-fidelity augmented virtual environment (System for Augmented Virtuality Environment Safety)	Albert *et al.*, 2014
	Vision-based hazard avoidance system displaying augmented hazard information on a wearable device	Kim *et al.*, 2017
	Platform using augmented 360-degree panoramas of reality (PARS)	Eiris *et al.*, 2018
	Interactive constructive safety education using Web-based panoramic virtual photoreality technology	Pham *et al.*, 2018
Mixed Reality (MR) – 3 studies	Immersive mixed-reality environment (i.e., virtual reality and passive haptics)	Hasanzadeh *et al.*, 2020a
	Passive haptics in a mixed-reality environment in a CAVE-like display system	Hasanzadeh *et al.*, 2020b
	Holographic mixed reality learning environment	Ogunseiju *et al.*, 2021

3.4 Keyword Cluster Analysis

For the keyword cluster analysis, the type of analysis was set to co-occurrence. The unit of analysis was set to all keywords. The counting method was set to full counting to form clusters in VOSviewer. Of 733 keywords, 63 were selected when the minimum number of occurrences was set to 3. Some keywords were omitted due to being too generic or repetitive, as shown in Table 2.

Table 2. Examples of omitted generic or repetitive keywords from keyword cluster analysis

accidents	adult	article	augmented reality	building industry	safety engineering
construction safety	construction workers	priority journal	visualization	construction	risk management,
occupational accident	human	controlled study	mixed reality	construction industry	safety
occupational health	young adult	design/methodology/approach	virtual reality	construction projects	safety management
occupational risks	male	students	virtual construction site	construction sites	safety training
occupational safety	female	surveys	wearable sensors	construction environment	training

The final keyword network map was organised into four major clusters depicted in Figure 5 and discussed briefly in the following sections.

3.4.1 *Cluster 1: Improved risk management*

This cluster mainly focuses on improved risk management in construction projects, primarily in the planning stage of construction projects, through the use of immersive technologies for workforce OHS training. Better capturing critical information about a proposed project through immersive technologies could facilitate better strategic and risk management planning, especially in small and medium-sized enterprises (SMEs) (Adami *et al*., 2021). Since effective communication and consultation with a multilingual construction crew is a challenging risk management process, Afzal and Shafiq (2021) simulated job-site safety instructions using 4-D BIM-enabled VR simulations. They found a significant improvement in workers' ability to understand safety instructions and mitigate hazards. Critical sharing of information and better technology transfer constitute essential aids in safety training and briefing the personnel before the actual commencement of work (Kim *et al*., 2021). Immersive technology could also provide intuitive tools like e-learning platforms for improved risk perception and assessment (Han *et al.,* 2021). Moreover, through immersive learning systems, inculcated development of self-concept and motivation among workers for improved risk management could be obtained (Hasanzadeh *et al.,* 2020a).

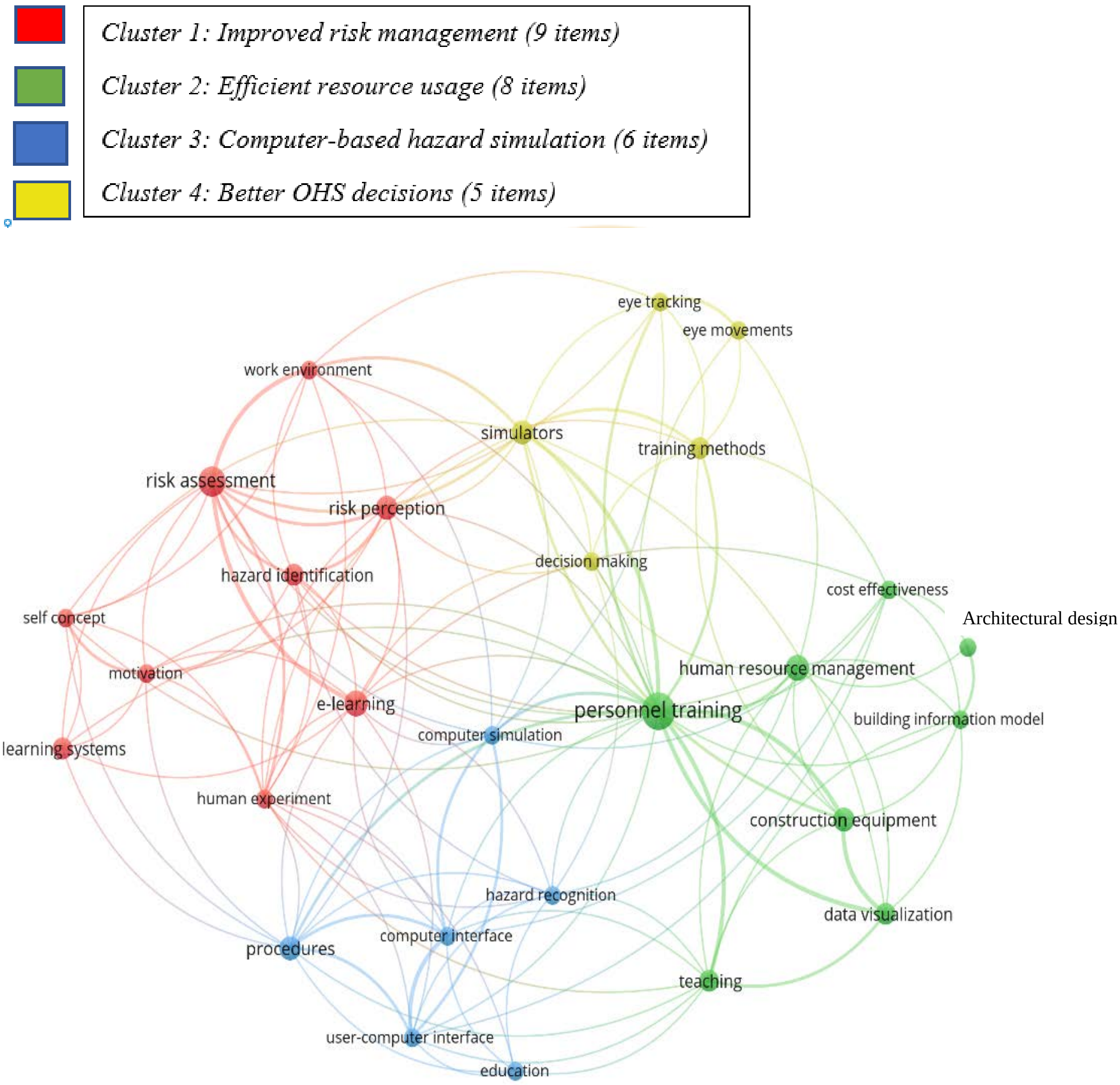

Figure 5. Text data overlay map of co-occurrence of research areas

3.4.2 Cluster 2: Efficient resource usage

This cluster focuses on improved resource usage in OHS training through better visualisation and data acquisition. BIM-enabled immersive tools to improve design and planning training and collaboration are also an essential corollary of this cluster (Getuli *et al.*, 2020). Previous researchers have outlined appropriate data collection and the development of robust data-to-agent and data-to-physics methods as the two most important factors responsible for effective safety training (Vahdatikhaki *et al.*, 2019). In addition, researchers have devised automated data acquisition and visualisation tools through immersive technologies to enhance safety monitoring and training at worksites. Creating a virtual training environment using immersive technologies could reduce the cost of training by simulating various OHS risk scenarios, creating virtual models of expensive equipment or dangerous environments, reducing travel costs and chances of injuries during the training (Zhao and Lucas, 2015). For instance, Pooladvand *et al.* (2021) developed a crane simulator system crane that operators and lift engineers could use to gain hands-on experience before the actual operation and, thus, reduce the risks of potential accidents. Xu and Zheng (2021) developed an immersive and interactive multiplayer-based training platform to improve workers' safety awareness and experience hazardous situations without being physically injured.

3.4.3 Cluster 3: Computer-based hazard simulation

This cluster focuses on computer-based hazard simulation as an essential tool to promote OHS procedure training. Immersive technologies provide realistic scenarios for interactive and authentic construction workforce training (Bhagwat *et al*., 2021). Previous researchers have created computer-based systems for training workers such as equipment operators, maintenance crew workers and electricians (Zhao and Lucas, 2015). For instance, Albert *et al*. (2014) created a high-fidelity augmented virtual environment to help workers develop hazard signal detection skills in construction field settings. However, the long-term impact of simulated training on workers' learning retention and behaviour is unknown.

3.4.4 Cluster 4: Better OHS decisions

This cluster focuses on improved decision making by reducing occupational risks through better eye-tracking and blind spot removal. Using mobile eye-tracking systems during and after training sessions in real construction sites could analyse group patterns and help develop prevention measures. Eye-tracking glasses have also been found helpful in evaluating the impact of mental fatigue on construction equipment operators' hazard recognition ability (Li et al., 2019). In contrast, traditional safety training programmes fail to capture the failure of construction workers to identify safety hazards (Jeelani *et al.,* 2020). The virtual training environments could also facilitate knowledge transfer between experienced and novice workers as the latter can learn from the behaviour and actions of the former when confronting a hazardous situation. Lu and Davis (2016) tested a virtual construction simulator to investigate the effect of noise on safety decisions.

4 Discussion and Conclusion

The present study aimed to enhance the understanding of the existing research on immersive technology applications in OHS training in the construction industry. The study found that research on immersive technology innovations and applications in OHS training in the construction industry is an emerging research area, as evidenced by increased research outputs in the last two years. The multi-disciplinary nature of this field of enquiry was also observed in the analysis, indicating it is an important and relevant area of research across different disciplines. The review identified the four major research clusters of technological applications in OHS training in the construction industry as (1) improved risk management, (2) efficient resource usage, (3) computer-based hazard simulation, and (4) better OHS decisions.

The review also identified a few gaps in the existing literature. For instance, research in developing countries is lacking, although poor OHS performance is a significant concern. Therefore, more collaboration with researchers from leading institutions and countries could facilitate applications of immersive technology in developing economies. Similarly, studies on OHS hazard analysis and mitigation are limited as most existing studies focus on hazard detection only. Fuller *et al.* (2021) found a lack of technological applications to facilitate health promotion programs in the construction industry. Therefore, how immersive technology could be utilised to improve construction workers' physical and psychological health demands further attention. Moreover, examining the impact of using immersive technology for OHS training on workers' cognitive load is another important research area. Finally, studies evaluating the business case for investment in immersive technology for OHS training could encourage SMEs to adopt these technologies.

The findings must be considered within limitations. First, the results are limited by literature analysis ranging from 2010 to 2021. Second, using multiple databases could have identified more relevant articles. For example, a similar study could be conducted in databases like Web of Science, ScienceDirect or ProQuest to gauge the research trends in those indexing methods. Third, bibliometric analysis suffers from certain limitations. Being a data-driven approach, it is an empirical and objective approach to analysing knowledge domains. However, there could be subjective biases while interpreting obtained results which could be minimised by consulting with independent domain experts (Li *et al.*, 2021). Finally, research quantity and other quantitative indicators do not necessarily represent the quality of the research work. Therefore, quantity should not be considered the sole criterion for judging the research contributions of various researchers and institutions active in this research area.

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Application of Immersive Technologies in Construction Education: An Experimental Study of Project Scheduling

Muhammad Sami Ur Rehman[1], Narmin Abouelkhier[1], and Muhammad Tariq Shafiq[1*]

[1]Department of Architectural Engineering, College of Engineering, United Arab Emirates University,
15551, Al Ain, Abu Dhabi, UAE.

202090209@uaeu.ac.ae; 700039609@uaeu.ac.ae; muhammad.tariq@uaeu.ac.ae
* Corresponding author

Abstract:
The advent of immersive technologies, such as Virtual Reality (VR) headsets, enabled a unique experience of the physical world in a virtual and interactive environment. Such distinct interactive experiences have opened a plethora of possibilities for immersive learning by bringing real-world situations to a virtual interactive environment. Similarly in education, immersive learning enables students to experience real-world scenarios in a convenient and controlled environment that otherwise may not be feasible and safe. The integration of immersive technologies in mainstream technical education delivery is still in its infancy and limited research is available on its ability to effectively deliver technical content in a classroom environment. This experimental research study aims to gauge the effectiveness of immersive technologies in delivering technical concepts to the participants of the undergraduate-level construction project planning course. This study reports the findings of an experiment that recorded undergraduate students' learning and understanding of construction sequencing and scheduling by using a set of two-dimensional construction drawings and a Critical Path Method (CPM)-based construction schedule to identify any scheduling setbacks. The same test case was repeated with the use of an immersive environment by carefully monitoring the activity-based layers. The findings of this study suggest that the comparative analysis of traditional teaching methods and technologically advanced immersive methods showed a significant difference in students' ability to understand technical concepts and highlight any errors in the construction sequence. The paper presents the details of the experiment and a comparative analysis of both approaches in terms of student learning and understanding of project planning, sequencing, and scheduling.

Keywords:
Construction education, Construction scheduling, Immersive technologies, Project planning, Virtual reality

1 Introduction

Engineering education integrates related research and technical education to accelerate technological and education innovation to improve problem-solving and creativity among fresh graduates entering the technical workforce. According to the United Arab Emirates (UAE) degree survey 2019 by the Ministry of Education (MoE), engineering was at the top of the list of 'Most in-demand degrees by subject'. The Knowledge and Human Development Authority (KHDA) – MoE reported that more than 9000 engineering students are enrolled in various institutions across the UAE, and this figure is expected to rise exponentially (Ministry of Education, 2019). This highlights the significance of technical workforce requirements and the necessity of quality engineering education in the UAE.

Traditional engineering instruction offers a learning environment that mainly conveys field-specific knowledge from the instructor to the students in a classroom environment with limited exposure to field activities (Hersam *et al.*, 2004). This can leave a gap in students' understanding of real-world situations, especially in adverse weather environments such as in the UAE. (Wang and Degol, 2015). In addition, typical methods of teaching engineering courses heavily rely on non-intuitive documents, for example, construction management students use 2D drawings and related project documents to review, analyze, and plan, and various aspects of project planning including the development of project activity sequencing, schedules, safety plans, cost estimate, etc. Such traditional methods are non-intuitive, error-prone, and difficult to understand for young construction students without any industry experience.

The emergence of Building Information Modeling (BIM) has offered numerous opportunities for the industry, and academia, to transfer the current document-oriented practices into data-driven 3D model-enabled engineering processes and workflows (Russell *et al.*, 2014). Also, advancements in the realm of immersive and reality-based technologies brought out extremely effective tools like Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). Applications of BIM and VR are increasingly being used in the construction sector to improve construction sequencing and planning (i.e., 4D BIM and virtual construction). VR is the technology that enables the user to completely immerse in a virtual environment through computer-generated simulations (Whisker *et al.*, 2020). With these symbolic representations, VR helps the user visualize and better understand the project (Goulding *et al.*, 2012). Thus, the actual project can be visualized through VR simulation, giving the decision-makers a chance to visualize, evaluate, and mitigate any errors that might hinder the project's actual execution. The integration of BIM and immersive technologies have been studied, and multiple studies have utilized such integrations to improve the construction management process (Afzal *et al.*, 2021; Afzal and Shafiq, 2021; Wang *et al.*, 2018). This advanced visual communication can significantly improve the ability of students to comprehend, learn, and gain experience with reviewing designs for constructability and planning the construction of building and infrastructure projects. In addition, the use of advanced visualization techniques will engage students in an active learning process. However, very few studies have focused on the potential of these technologies in improving engineering education.

This research aims to study the application of IVR in construction management courses being taught at the University level. To achieve this aim, this research investigated the integration of IVR into traditional construction management education, for courses related to construction project planning and control, and tested IVR effectiveness in learning project sequencing and planning with architectural engineering students at the UAE University. The research developed a comparative experiment that gauges the effectiveness of the 2D project data and the application of the IVR to understand the construction project sequence and find potential errors and irregularities by the students. The results of this research study intend to advance the existing knowledge available on the integration of advanced technologies in construction education and also motivate course instructors to integrate IVR into their teaching methods. This research study comprises the following steps: 1) developing a simplified Gantt chart and 3D Revit model for IVR application 2) experimenting with construction management students 3) assessing their experience by conducting a post-experiment survey and 4) analyzing the outcome of the survey.

2 Research Methodology

First, a case study project was selected, and necessary documentation was acquired including 2D construction drawings and a construction schedule. A modified construction baseline schedule was prepared by the researchers to present only the execution-related activities in the Gantt chart. The Gantt chart was prepared using Microsoft® Project™, a project management software to develop and manage construction schedules. This simplification of the baseline schedule was necessary to avoid over-burdening the students who already had little or no knowledge of construction sequencing. Furthermore, the 2D drawings were converted to a detailed 3D structural model using the licensed version of Autodesk® Revit™ 2022. The 3D Revit model was carefully divided into several pre-arranged phases as per the activities present in the simplified construction baseline schedule. Once the 3D Revit model was developed as per the testing requirements, the next step was to transform it into the IVR environment using the Enscape™ plug-in. The Oculus™ Rift S headset was used as the IVR gear to allow the users to experience the 3D constructability of the case study building and assess its correctness.

Second, the experiment was conducted by randomly splitting the class of an undergraduate course 'ARCH 450 - Construction Project Planning and Control' into two groups i.e. Control Group and the Test Group. Both, the control and the test group, comprises 11 students each, and all the users were tested and assessed individually. This sample size is similar to Wang and Dusnton's (Wang and Dunston, 2006) study who experimented with 16 students and Chu et al.'s (Chu *et al.*, 2018) experimental study with 20 participants. The control group corresponds to those students who were tested using the 2D set of drawings and the baseline schedule (Gantt Chart). Every single user in the control group was briefed about the aim of the research followed by a complete description of the task expected from them. A laptop was provided to all the users to review the provided documents and a piece of paper was also provided to record their observations during the experiment. On the other hand, all the users in the test group were briefed about the experiment and a 10-minute session was arranged to train them on how to use the Oculus™ Rift S headset gear and also navigate through the IVR environment on a sample 3D model. After the necessary training, all the users of the test group were exposed to the test IVR model and their feedback was recorded. The IVR simulation includes phases from laying out the foundation, through framing every floor to the completion of the frame structure of the case study building.

Third, a survey questionnaire was designed to capture the experience of the users. The survey questionnaire was divided into three distinct sections. The first section was aimed at the characterization of users and comprises 6 questions to capture the demographics and provide the researcher with valuable insight into the experience and prior understanding of the users. The second section of the survey aimed to assess the extent of the experience felt by the users during the experiment. This section also comprises 6 questions regarding the overall experience of the users of both groups i.e., the control group and the test group through selection and statement-type responses. The third and last section of the survey comprises 3 questions aimed at capturing statement responses to gauge the user opinion of the quality of interaction throughout the experiment. The complete survey questionnaire can be found in Table 1.

Last, the feedback from the users was transferred from the paper-based survey questionnaire to the Microsoft® Excel™ spreadsheet for further analysis. The data were analyzed using descriptive analysis to generate useful insight into the effectiveness of the techniques utilized and gauge the effectiveness of the technologically advanced IVR environment in facilitating the delivery of construction management education.

Table 1. Questionnaire

Subjective Measures	Questions
Characterization of Users	**Question 1:** Year of your Undergraduate study (Tick One) o *First Year* o *Second Year* o *Third Year* o *Final Year* **Question 2:** Did you take any construction management courses in your degree so far? (Selection Response) o *Yes* o *No* **Question 3:** Do you have any construction-related internships so far? (Selection Response) o *Yes* o *No* **Question 4:** Did you review the Gantt Chart/2D or experienced Virtual Reality? (Tick One) o *Gantt Chart/2D* o *Virtual Reality* **Question 5:** How familiar are you with Gantt Chart/Virtual Reality technique? (Selection Response) o *Very Familiar* o *Somehow Familiar* o *Not Familiar* **Question 6:** How familiar are you with Construction Planning/Sequencing? (Selection Response) o *Very Familiar* o *Somehow Familiar* o *Not Familiar*
The extent of Experience Felt	**Question 7:** How difficult was this experience for you? (Selection Response) o *Very Difficult* o *Somehow Difficult* o *Not Difficult* **Question 8:** Did you entirely complete the given task? (Selection Response) o *Yes* o *No* o *Couldn't review through this method* **Question 9:** Do you think that you have found all errors/ irregularities in the construction sequence? (Selection Response) o *Yes* o *No* o *Not Sure* **Question 10:** Do you think that you had understood the given task properly before starting this experiment? (Selection Response) o *Yes* o *No* o *Not Sure* **Question 11:** Do you think enough time was given to review the construction schedule in this experiment? (Selection Response) o *Yes* o *No* o *Not Sure* **Question 12:** Please respond to the following aspects of the tool/technique/method you have experienced (Selection Response): i. Information was clear with this method o *Strongly Agree* o *Agree* o *Neutral* o *Disagree*

	o *Strongly Disagree* ii. Information was easily understood with this method o *Strongly Agree* o *Agree* o *Neutral* o *Disagree* o *Strongly Disagree* iii. Not required to consult with the professor for clarifications o *Strongly Agree* o *Agree* o *Neutral* o *Disagree* o *Strongly Disagree* iv. The method was effective in presenting the construction sequencing information o *Strongly Agree* o *Agree* o *Neutral* o *Disagree* o *Strongly Disagree* v. Sequencing errors/irregularities were easier to locate o *Strongly Agree* o *Agree* o *Neutral* o *Disagree* o *Strongly Disagree*
User Opinion of the Quality of the Interaction	**Question 13:** What aspects were difficult for you to complete this task? (Statement Response) **Question 14:** What do you think could be done to make it easier for you to perform this task? (Statement Response) **Question 15:** Please specify all construction sequencing errors/irregularities found. (Statement Response)

3 Results and Discussion

3.1 Participant Characterization, Experience, and Quality of Interaction

To conduct this comparative study to test the effectiveness of IVR in teaching construction sequencing and planning as compared to traditional 2D teaching techniques, a total of 22 users participated and completed the survey questionnaire after the test. For users' educational year, more than 80% of the users were enrolled full-time in their fourth and final year of study at the Department of Architectural Engineering. There were 3 users currently enrolled full-time in their second year of study and only 1 user was enrolled full-time in the third year of the study. For users' construction management-related education, all the users are either enrolled in the construction management-related course/s or have already taken one of them in previous semesters. The Department of Architectural Engineering offers three construction management-related courses in its Bachelor of Architectural Engineering Degree Program i.e., ARCH 326 – Building Construction Methods and Equipment, ARCH 440 – Construction Project Management, and ARCH 450 – Construction Project Planning and Control. For users' construction-related exposure either through full-time jobs or internships, only 36% of the users, the same figures for the control group and the test group, had actual construction experience through summer internships.

Both, the control and the test, groups comprise 11 users each. For users' familiarity with the method tested, 72% of the users were '*somehow familiar*' with the method they are being tested on, 18% of users were ‘*not familiar*’ with the technique they were using and only 1 user stated a higher level of familiarity with the method in the test group. For the control group, 63% of the users stated that they were ‘*somehow familiar*’ with the method of identifying the construction sequence using a 2D set of drawings and the Gantt chart and the rest were unfamiliar with the method altogether. Furthermore, for their familiarity with construction scheduling and sequencing, 45% and 63% of the users, in the test group and the control group respectively, were ‘*somehow familiar*’ with construction scheduling and sequencing. A summary of responses on users' characterization is presented in Table 2.

Table 2. Summary of participant characterization

	Qualitative Responses (Out of 11 for VR and 11 for 2D)	
	VR	2D
Characterization Questions		
Educational Year		
o First Year	-	-
o Second Year	2	1
o Third Year	-	1
o Final Year	9	9
Construction Courses		
o Yes	11	11
o No	-	-
Internships		
o Yes	4	4
o No	7	7
Method Used	11	11
Familiarity with Method		
o Very Familiar	1	-
o Somehow Familiar	8	7
o Not Familiar	2	4
Familiarity with Sequencing		
o Very Familiar	6	-
o Somehow Familiar	5	7
o Not Familiar	-	4

Moreover, to gauge the quality of the user's interaction, the survey presented 5 selection response questions on the level of difficulty of the task, extent of its completion, opinion of the users on whether they had found all the errors, understanding of the task beforehand and opinion on whether they were given enough time to complete the given task. For the level of difficulty of the task, 55% of the users in the test group reported the task as ‘*not difficult*’ and the rest of them classified the task as ‘*somehow difficult*’. In contrast, 91% of the users in the control group found this task ‘*somehow difficult*’. Regarding their opinion about the completion of the given task, all of the users in the test group agreed that they successfully finished the given task. However, there was an equal difference of opinion about the completion of the given task in the control group, as 45% of the users stated that the given task wasn’t finished to its entirety and 1 user stated that it wasn’t possible to review through this method. Regarding the identification of all the errors in the given task, 63% of the users in the test group were confident about finding all the errors and irregularities in the construction sequence and only 45% said the same in the control group. All the users in the test group agreed that they clearly understood the task before starting the experiment and enough time was given to complete the test as well. However, in the control group, only 73% stated that they had understood the task beforehand and a similar percentage agreed on having enough time to finish the task at hand.

The users were also asked to provide their feedback on the following 5 aspects of the method used: 1) Information clarity 2) Information understanding 3) Professor's assistance 4) Methods' effectiveness and 5) Locating errors. The responses are discussed briefly as follows and also summarized in Table 3.

Information clarity: The users were asked whether the scheduling and sequencing information provided through the method being tested was clear enough. For the test group, 82% of users '*Strongly agreed*' that the information was clear enough and the rest of the users in the group '*Agreed*' as well. However, only 55% of the users in the control group either '*Strongly agreed*' or '*Agreed*' on the clarity of the information and 36% remained '*Neutral*'.

Information understanding: The users in both, test and control, groups were asked to state whether the information provided was easily understood. For the test group, 82% of the users '*Strongly agreed*' with the statement, and only 1 of the users remained '*Neutral*'. In contrast, only 45% '*Agreed*' with the statement while 27% and 18% of the users in the control group remained '*Neutral*' and '*Disagreed*' respectively.

Professor's assistance: During the experiments, the users were allowed to consult with their professor for any clarification and were also asked about it in the survey questionnaire as well. For the test group, 64% of the participants either '*Strongly agreed*' or '*Agreed*' with the fact that they didn't feel the need to consult the professor during the experiment and only 36% remained '*Neutral*'. On the contrary, 91% of the users in the control group either '*Disagreed*' or '*Strongly disagreed*' with this statement.

Method's effectiveness: The users were also asked whether they think that the given method was effective in presenting the construction sequencing information or not. 82% of the users from the test group '*Strongly agreed*' with the statement which shows the effectiveness of IVR in presenting the construction sequencing information to the users. However, only 55% of the users '*Agreed*' and 36% remained '*Neutral*' from the control group.

Locating errors: At the end of this section of the survey questionnaire, the users were asked to provide their opinion on the ease of finding errors and irregularities using the given method. For the test group, 73% of the users '*Strongly agreed*' and 18% 'Agreed' with the fact the errors and irregularities were easier to locate using IVR. However, 36% of the users in the control group remained '*Neutral*' and a similar percentage of the users either '*Disagreed*' or '*Strongly disagreed*' with the statement.

Table 3. Summary of participant's experience

	Qualitative Responses (Out of 11 for VR and 11 for 2D)	
Experience Questions	VR	2D
Level of Difficulty		
o Very Difficult	-	1
o Somehow Difficult	5	10
o Not Difficult	6	-
Completion of the Task		
o Yes	11	5
o No	-	5
o Couldn't Review	-	1
Finding all Errors		
o Yes	7	2
o No	-	3
o Not Sure	4	6

Understanding of the Task		
o Yes	11	8
o No	-	-
o Not Sure	-	3
Enough Time Given		
o Yes	11	7
o No	-	3
o Not Sure	-	1
Aspects of the Method Used		
i. Information Clarity		
o Strongly Agree	9	3
o Agree	2	3
o Neutral	-	4
o Disagree	-	1
o Strongly Disagree	-	-
ii. Information Understanding		
o Strongly Agree	9	1
o Agree	1	5
o Neutral	1	3
o Disagree	-	2
o Strongly Disagree	-	-
iii. Professor’s Assistance		
o Strongly Agree	4	-
o Agree	3	-
o Neutral	4	1
o Disagree	-	7
o Strongly Disagree	-	3
iv. Method’s Effectiveness		
o Strongly Agree	9	-
o Agree	1	6
o Neutral	1	4
o Disagree	-	1
o Strongly Disagree	-	-
v. Locating Errors		
o Strongly Agree	8	1
o Agree	2	2
o Neutral	1	4
o Disagree	-	1
o Strongly Disagree	-	3

For user opinion on the quality of interaction, two questions were asked and users were directed to provide a ‘statement response’ to the questions. For aspects that posed difficulty in the completion of the task, 55% of the users from the test group mentioned motion sickness and dizziness during their interaction. However, 63% of the users from the control group stated that the lack of enough knowledge of construction sequencing was the major hurdle in task completion. In their opinion on improving the similar experience, 45% of the users from the test group mentioned adequate training and practice in the VR environment beforehand. However, 82% of the users from the control group stated that prior adequate construction planning and sequencing knowledge as the key factor for an improved experience. Further detail on the user opinion on the quality of interaction as thematic responses is summarized in Table 4.

Table 4. User opinion on the quality of interaction

User opinions on the quality of interaction	Thematic Responses VR	2D
What aspects were difficult to complete this task?	Motion sickness and Dizziness (6/11) Lack of VR training (3/11) Error identification without enough knowledge of construction sequence (2/11)	Not enough knowledge of construction sequencing (7/11) Locating information from 2D documents (5/11) The number of activities was high (2/11)
What could be done to improve the experience?	Adequate VR training and practice (5/11) Adequate knowledge of construction sequencing (2/11) Better resolution and quieter environment (2/11)	Prior construction planning and sequencing knowledge (9/11) Site visits or actual construction experience (5/11) Easier/clearer schedule (2/11)

3.2 Errors/Irregularities Identification

While preparing the simplified construction baseline schedule and the IVR simulation, the researchers intentionally made 5 logical sequencing errors. An overview of the sequencing errors is as follows: 1) the height of the ground-floor columns was extended till the first-floor ceiling slab 2) ground floor stairs were being built before the ground-floor ceiling slab 3) the second-floor ceiling slab was being built before its beams 4) the lift well was being built from the ground up after the roof slab was poured and the structure finished 5) the second-floor walls were being built before its columns. All the users were expected to locate these intentional logical sequencing errors during the experiment. For error 1, 82% of the users from the test group successfully identified the error as compared to only 18% for the control group. For error 2, 45% of the users from the test group successfully identified the logical error and none from the control group could do the same. Similarly, the users in the test group were able to identify the following errors with a certain percentage of success, however, this statement wasn't true for the control group. This comparison presents the effectiveness of the IVR in identifying sequencing errors and irregularities as compared to a complicated construction baseline schedule. Figure 1. presents an overview of the task completion status of both groups.

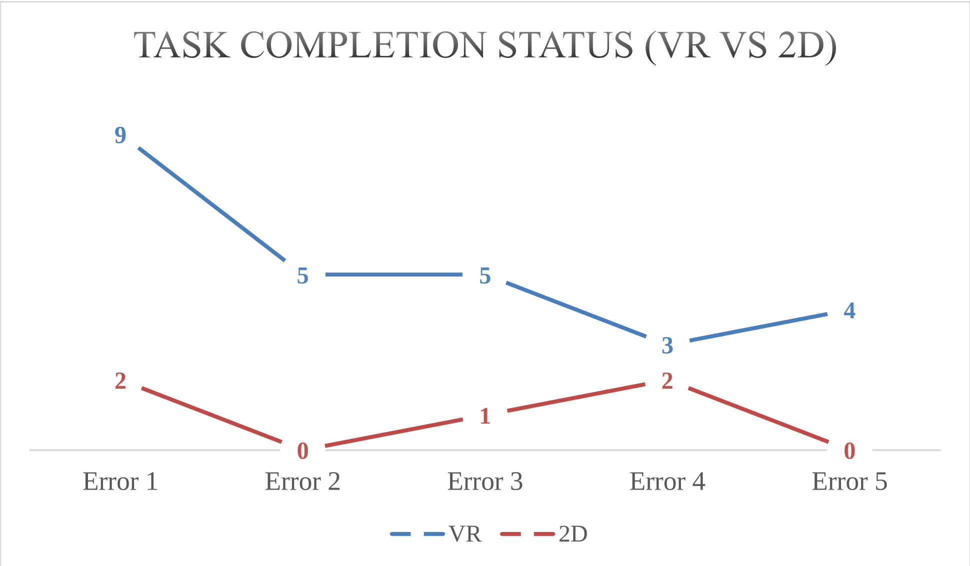

Figure 1. Task Completion Status

4 Conclusion

Ever since the advent of the IVR, researchers have explored its effectiveness in almost every domain of knowledge. Also, a plethora of research is available on the integration of the IVR into education and specifically the delivery of technical education in a classroom environment. However, this research study aimed at addressing a niche in the existing knowledge by integrating the IVR environment into the construction sequencing and planning content delivery. To test the effectiveness of the IVR-based construction sequence simulation against the traditional 2D documentation, this research study devised an experiment within the classroom of an undergraduate course i.e., construction project planning and control by randomly splitting the class into two groups i.e., control group (2D) and the test group (VR). Both groups were briefed about the test and asked to find the intentional logical errors in the construction baseline schedule of a low-rise apartment building. The results have indicated that the IVR simulation was indeed effective for users to identify the errors and irregularities within a construction schedule as compared to the traditional 2D documentation. The results from the survey questionnaire demonstrated that the information presented in the IVR was more clear, easier to understand, effective in presenting sequencing information, and facilitated in locating logical sequencing errors without the assistance of the professor. The users also seemed more confident in addressing various aspects of the interaction after the IVR simulation as compared to the 2D method where users seemed confused.

Despite the evidence of the IVR's effectiveness in delivering construction planning courses to students, some major concerns still limit the capabilities of this method. The major hurdle was the unfamiliarity of the users with the construction sequence. Also, the limited number of students and dismissing the effect of the number of construction management-related courses taken during their degree, exposure to the real construction environment through internships, and the extent of learning during their internships are a few demographic factors of the users that limit the generalizability of these findings. Furthermore, dizziness, motion sickness, and soreness of the eyes were also among the major factors limiting the ability of the users during the experiment. However, this is a common and well-established issue while experiencing IVR simulations. This situation can be averted by exposing the users to the IVR environment for a longer period and letting them get used to the technology through semester-wide training.

Future research will employ and experiment with diverse demographics by carefully selecting users with at least some field experience and an understanding of construction planning and sequencing. Usually, the graduate-level students in the department are working professionals and have been exposed to the real construction environment either through part-time or full-time employment. Also, experimenting with field personnel with first-hand experience in construction planning, monitoring, and control will help understand the effectiveness of the proposed system, and such learning will further help in improving the experience for undergraduate students.

5 Acknowledgment

The authors would like to extend their gratitude to students from the Department of Architectural Engineering at the United Arab Emirates University (UAEU) who participated in this research study. The authors would also like to acknowledge the research funding provided through Summer Undergraduate Research Experiences (SURE) Plus program by the UAEU's Research Office.

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CIB Doctoral School - AUBEA 2022

Community-focused Renewable Energy Transition with Virtual Power Plant in an Australian City – A Case Study

Chengyang Liu[1], Rebecca Yang[1*], and Kaige Wang[1]

[1]Solar Energy Application Lab, School of Property, Construction and Project Management, RMIT University, Melbourne, VIC 3000, AUSTRALIA

chengyang.liu2@rmit.edu.au; rebecca.yang@rmit.edu.au; kaige.wang@rmit.edu.au
* Corresponding author

Abstract:
As renewable energy becomes more competitive in terms of costs, benefits, and energy production, the transition to a renewable-powered economy is gaining traction around the world. With greater flexibility and economic potential through supplying renewable energy, participating in the electricity market, and providing electricity network services, renewable energy integrated Virtual Power Plants (VPPs) have the advantages of facilitating renewable transition, reducing impacts of distributed generators, and creating values for the prosumers and community. However, although gifted with abundant renewable resources and supported by state and commonwealth-level incentives, there are still multiple technical and economic uncertainties, such as the financial viability of the investment and the effectiveness of the renewables transition. In this paper, we conducted a case study in the City of Greater Bendigo to evaluate the challenges and opportunities of the community-focused renewable energy transition through establishing VPP with community-based renewable generators and storage systems. We formulated the VPP system with a reinforcement learning algorithm capable of making optimal decisions regarding energy supply, demand shift, and market trading. It was found that the proposed VPP system has great potential in improving the economic value and carbon emission reduction performance of the local renewable resources in the future: it is capable of reducing 50-70% of the case study city's carbon emission in 10 years, and reducing the electricity price from the current range of $ 0.15/kWh (off-peak) - $ 0.30/kWh (peak) as provided by Victorian Essential Services Committee to a much lower range of $ 0.05/kWh (off-peak) - $ 0.08/kWh (peak). Overall, this study proposed a comprehensive framework to investigate community-based VPP in a complex urban environment and validated the efficacy of the VPP in supporting the renewable transition for Australian communities.

Keywords:
Case study, Community-focused, Distributed renewable energy, Reinforcement learning, Virtual power plant

1 Introduction

Cities and their inhabitants consume more than 75% of global energy production and contribute 80% of glasshouse gas emissions (UN, 2012). According to the United Nations Department of Economic and Social Affairs (UN DESA), the global population has increased from 751 million in 1950 to 4.2 billion in 2018, with a projected increase to 7 billion by 2050 (UN, 2018). With rising population and energy consumption, it is critical to accelerate the energy transition and urban sustainable development.

There are numerous options to improving urban sustainability including active approaches such as introducing renewable energy alternatives and passive approaches such as demand shift, demand reduction, etc. Among these options, distributed renewable energy (DRE) such as solar photovoltaic (PV) is garnering increasing interest in both research and market. DRE can (1) reduce carbon emissions, (2) increase energy fairness, supply security, and independence, and (3) reduce dependency on energy infrastructure investment.

However, there are many challenges faced by DRE in urban area such as limited physical space for installation, reduced access to natural resource due to urban density, unstable output, impacts to the public electricity grid, etc. Therefore, a formidable energy management system is essential amid the growth of DRE in the urban environment.
As a novel energy management concept, the virtual power plants (VPPs) are gaining increasing research interests. VPP is a network of distributed generators in which these integrated elements can participate energy market as a single entity and own the function similar to a conventional power plant (CPP).

However, as an energy network working in complex and uncertain contexts, VPPs can be significantly influenced by urban temporal and spatial dynamics such as supply/demand conditions, demographic profiles, renewable energy resources, urban growth, population growth, etc. The implementation of such energy systems involves greater long-term economic and technical uncertainties.

Hence, this study aims to further explore the challenges and opportunities for end-users and local communities of using VPP's concept in an Australian city's context. The main research objectives of this study are:

(1) To establish a research framework to implement VPP concept in an Australian city.
(2) To model the VPP's performance for urban communities across an Australian city.
(3) To optimise VPP performance for urban communities across an Australian city.
(4) To evaluate the technoeconomic impacts of VPP and provide discussion and suggestion for future development and policymaking.

2 Literature Review

2.1 VPP's risks and benefits for prosumers and communities

VPP development and operation is a multi-party process involving service providers, consumers, prosumers, legislators, and local communities. However, the majority of the previously stated profit-enhancing or risk-reduction measures are primarily applicable to VPP systems or VPP operators (Yang et al., 2021). Although it is critical to ensure that VPPs perform optimally when participating in the electricity market, the success of VPPs is largely dependent on the participation and interaction of all stakeholders, as an electricity supply system that may involve substantial investment and significant impacts on urban development (Liu et al., 2021).

The previous studies in this domain mostly focus on investigating VPP's economic potential by optimising its operation strategies in the energy market. For example, (Tan et al., 2018; Zhang et al., 2019) provided the optimisation of VPP's profitability of participating energy market through frequency control ancillary services and energy trading. (Kong et al., 2019; Wang et al., 2020) investigated the optimisation of VPP system's operation cost and penalty due to system instability. While (Hadayeghparast et al., 2019; Shafiekhani et al., 2019) evaluated the VPP's cost and benefits through reducing greenhouse gas emission.

Although the previous research has developed comprehensive understanding of VPP's benefits as an entity, there is a lack of consideration for the benefits and risks for end-users and communities where the VPPs are based in. The participation of prosumers and the communities is one of the essential criteria in the implementation of VPPs (Wang et al., 2021), for its reliance on the cooperation and aggregation of distributed prosumers. However, in most of previous research, the end-users in VPP framework are considered as flexible loads (Wei et al., 2018; Naval and Yusta, 2021) or simply the source of revenue for the VPP entities.

2.2 Modelling and problem-solving techniques in VPP studies

As an energy system interacting with various demand patterns, generation patterns and energy market conditions, the modelling of VPP involves numerous amounts of uncertainties such as weather forecasting, demand forecasting, market price forecasting, etc (Yu et al., 2019). The two commonly adopted modelling methods are deterministic modelling, which create sophistic calculation model for renewable energy system, VPP control system, user demand and energy market (Rahimiyan and Baringo, 2016), and stochastic modelling, which represents VPP's components with probability models (Baringo and Baringo, 2017; Khorasany and Raoofat, 2017; Tan et al., 2018). In addition, some studies also use actual data records of generators' output or user demand instead of modelling them (Qiu et al., 2017; Wei et al., 2018).

In terms of problem-solving methods such as optimisation and control strategies, the commonly used approaches can be categorised as heuristic approach and mathematical approach. Mathematical approaches such as linear or nonlinear programming usually adopts regression methods to seek the global or local optimality within the VPP's operation constraints (Naval and Yusta, 2020). Although these mathematical optimisations are well-developed methodologies, they are under critiques in the application of VPP due to their vulnerability when dealing with uncertainties and the insensitivity to the global optimality (Yu et al., 2019; Naval and Yusta, 2021). The heuristic approach such as particle swam optimization, agent-based optimisation, machine learning based heuristic approaches have more flexibility when dealing with uncertainties and are easier to identify the global optimal (Qiu et al., 2017; Gao et al., 2018). However, pointed out in (Naval and Yusta, 2021), these methods may be ineffective for achieving local optimal. This is because, given a small population size, the optimisation algorithm typically treats significant contingency events, such as demand spikes and market price spikes, as outliers, even though these contingencies may be essential for enhancing the energy conservation and economic performance of the VPP.

Hence, a more robust and effective problem-solving and modelling approach should be introduced to provide optimised decision-making for VPP implementation. As a branch of machine-learning, reinforcement-learning (RL) is a potent tool for assisting decision-making in dynamic situations. RL approaches can provide robust optimisation for different scenarios (Al-Nima et al., 2021) in the application of energy network control and optimisation.

2.3 Summary of literature review

The literature research indicated that although prior VPP studies made substantial contributions in exploring the optimisation of VPP operation using different mathematical or heuristic techniques, most of these studies focused on the VPP's advantages and profitability for the VPP system or operator. The risks and benefits for end-users and local community are rarely discussed. Current VPP research problem-solving methods have reached their limits in addressing the mounting uncertainties and difficulties of urban VPP implementation. This research performed a case study in an Australian city using a unique RL-based VPP architecture to address these research gaps and limitations. The case study assessed VPP's carbon emission reduction, profitability, and end-user advantages.

3 Research Methodology

3.1 VPP implementation case study in an Australian city

To investigate the VPP's efficacy in supporting community-based renewable energy transition, this study conducts a case study in the urban area of the City of Greater Bendigo. The City of Greater Bendigo is located near the geographical centre of Victoria, Australia (2006), and is the third largest city in Victoria. The urban and rural area of Bendigo covers nearly 3000km^2 (2019) and is home to 111 thousand people. The City of Greater Bendigo has a strong commitment towards sustainable urban environment. According to an environment strategy report by the City Council of Bendigo, the city encourages the transition of sustainable urban and has a target to achieve 100% renewable energy goal in 20 years. However, it is unclear how the renewable systems can deliver the expected effects in carbon reduction and economic viability. In addition, most of the distributed PV and home battery systems have low visibility to the grid operator, which poses a challenge to the grids stability and brings more uncertainties for future planning on the electricity supply infrastructure.

In this research, we adopt statistical area level 1 (SA1) as the community unit for modelling and data analysis. The statistical area hierarchy is introduced in Australian Statistical Geography Standard (ASGS) (Australian Bureau of Statistics, 2011) to reflect the social geographic location of people and community. Among the statistical area hierarchy, SA1 is designed to maximise the geographic detail available for Census of Population and Housing data while maintaining confidentiality. This study covers a study area of 235 SA1s in the City of Greater Bendigo.

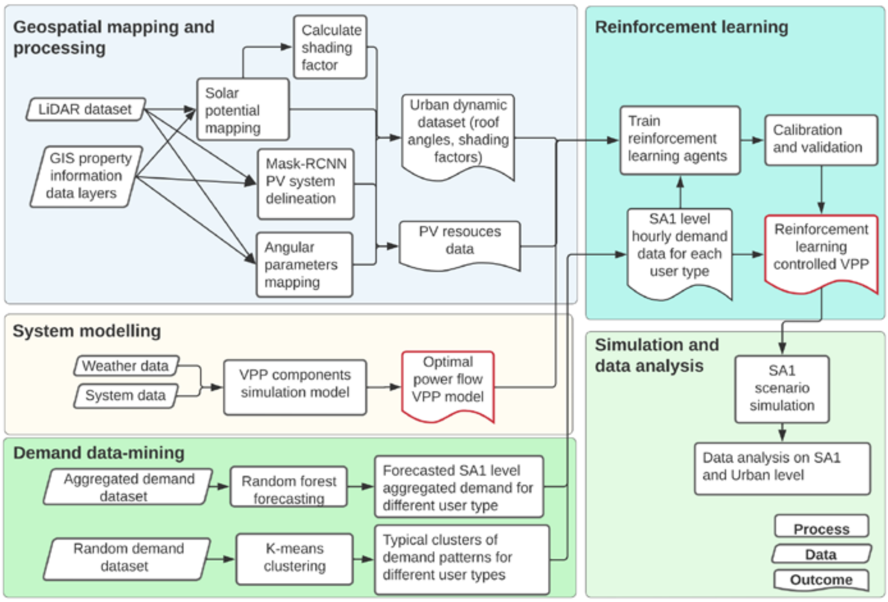

Figure 1. Summary of the research process

3.2 Data processing, assessment, and modelling

To conduct the case study, a research framework is designed to implement the VPP network in the City of Greater Bendigo (Figure 1). To provide comprehensive analyses of the VPP implementation with the local communities' urban environment conditions, supply-demand conditions, and socioeconomic and demographic profiles, this research employed multiple methods including geospatial information system (GIS) processing and analysis, system modelling, demand data-mining and reinforcement learning.

3.2.1 Geospatial mapping and processing

GIS is a powerful tool which facilitates a better understanding of urban environment dynamics and local resource distribution. In this part of the study, GIS data on the City of Greater Bendigo were collected, and GIS platforms (QGIS and ArcGIS) and processing tools were adopted to analyse the geographic data and map the urban environment and PV resources. In this study, the GIS data was collected from the Department of Environment, Land, Water and Planning (DELWP) of the Victoria State Government. The dataset includes the LiDAR data of Digital surface model (DSM), high resolution aerial image, and property footprint. The DSM data was used to create the case study city's roof angular profile including tilt and azimuth angle (Figure 2).

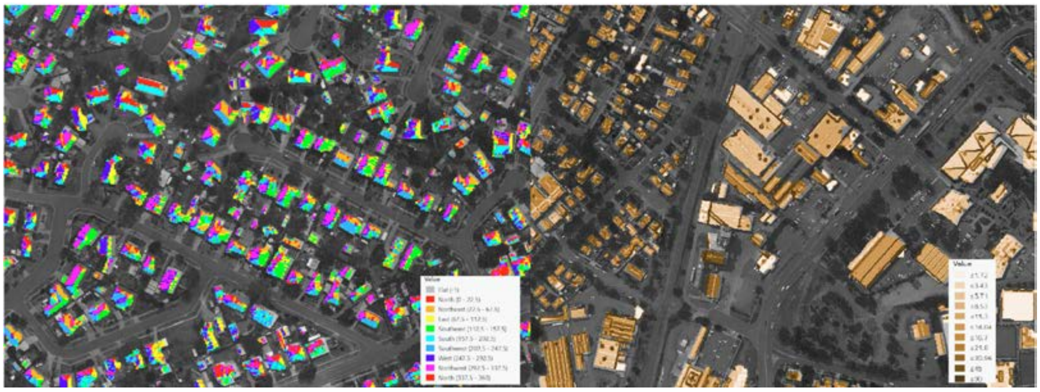

Figure 2. Geoprocessing outcomes of rooftop angular parameters (Left: Azimuth angle; Right: Tilt angle)

Furthermore, GIS-based approaches are used to identify both existing and potential solar PV resources in the case study city. With the high-resolution aerial image data and the Mask R-CNN (He et al., 2017) image recognition algorithm, the existing PV systems installed on Bendigo's rooftop are delineated. Based on the angular parameter and shading impact factor, the solar PV potential mapping of the rooftop PV in the case study area is created (Figure 3). The GIS processing outcome of PV delineation, azimuth angle, tilt angle and potential mapping is used in the following sections for PV modelling and simulation.

Figure 3. Rooftop solar irradiation potential raster

3.2.2 System modelling

The system modelling in this study comprises of the modelling of PV system, battery energy storage system (BESS), the control mechanism of the VPP and the energy market. The modelling is carried out using MATLAB and Simulink. To simulate the operation of the PV system, the following factors were taken into consideration: (1) Plane of array (POA) irradiance; (2) Solar position; (3) Losses caused by heat transfer; (4) Losses caused by the inverter, mismatch, wiring, shading, dust, etc. The model adopted the PVlib toolbox developed by Sandia National Lab (Holmgren et al., 2018). The modelling of a storage system mainly requires inputs of system specifications such as charge/discharge rate, maximum capacity and efficiency. The reference value for BESS is based on the specifications of the TESLA Powerwall (2022).

3.2.3 Demand data mining

Energy consumption data was provided by the case study city's local distribution network service provider: Powercor. The dataset included an aggregated customer type-based dataset for postal areas and 3000 de-identified samples with categories of different property purposes: residential, commercial, industrial, agricultural (coded as R, C, I and A, respectively). A data-mining approach integrating Random Forest (RF) and K-means Clustering is used to extract the features of the sample demand data and reconstruct the demand dataset for the four-user types in each SA1 cluster (Figure 4).

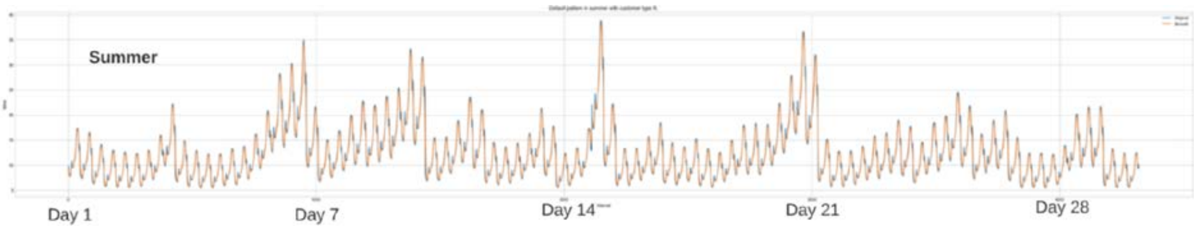

Figure 4. Sample reconstructed demand pattern for residential users in summer season

The reconstructed hourly demand pattern was then amplified to fit the aggregated SA1 electricity consumption in each SA1 for each user type. The outcome is the hourly interval demand data for each type of user in each SA1 of the City of Greater Bendigo.

3.2.4 Reinforcement learning VPP operation model

To operate the VPP under uncertainties and complexities in the urban environment and provide optimised control decision, this study applied an RL-based approach to model the VPP control system. The concept of RL is very similar to human behaviour patterns when we observe and learn about the world.

In this study, the RL controlled VPP system is capable of adjusting electricity trading and scheduling strategies based on the observation and forecast of the users' demand, national energy market (NEM)'s electricity price for wholesale and FCAS services, and the renewable energy systems' output. In total, four RL-agents were trained under the four demand patterns namely A, C, I and R. The RL agent applies the deep-deterministic policy gradient (DDPG) algorithm to construct its deep neural network through training iterations. The VPP system structure is modelled in Simulink with a MDP environment embedded (Figure 5). The RL system's objective function is to maximise the economic benefits and minimise the losses in the operation of a VPP by providing demand shifting and participating in the electricity market. The objective function can be formulated as following equation:

$$max\ CF = \sum_{t=1}^{T} p_{ge}(t) \times k_{RRP}(t) + abs(p_{FCASL/R}\ (t)) \times k_{FCASL/R}(t) \qquad \text{Equation 1}$$

where, CF is the total cashflow of all timesteps, $k_{RRP}(t)$ is the AEMO-recommended retail price used to estimate the cash flow for trading with the public grid, and $k_{FCASL/R}(t)$ is the AEMO FCAS market price used for estimating FCAS incomes.

With the objective function defined, the reward function for the RL system can then be formulated with the following three components: (1) the objective reward (R_{obj}), (2) the step reward (R_{move}) and (3) the finishing reward (R_{madeit}). The reward function for the RL system can be described as:

$$max\ R = \sum_{t=1}^{T}[R_{obj}(t) + R_{move}(t)] + R_{madeit} \qquad \text{Equation 2}$$

R_{obj} is modified from the objective function (Equation 2) to represent the actual cash flow of the VPP system.

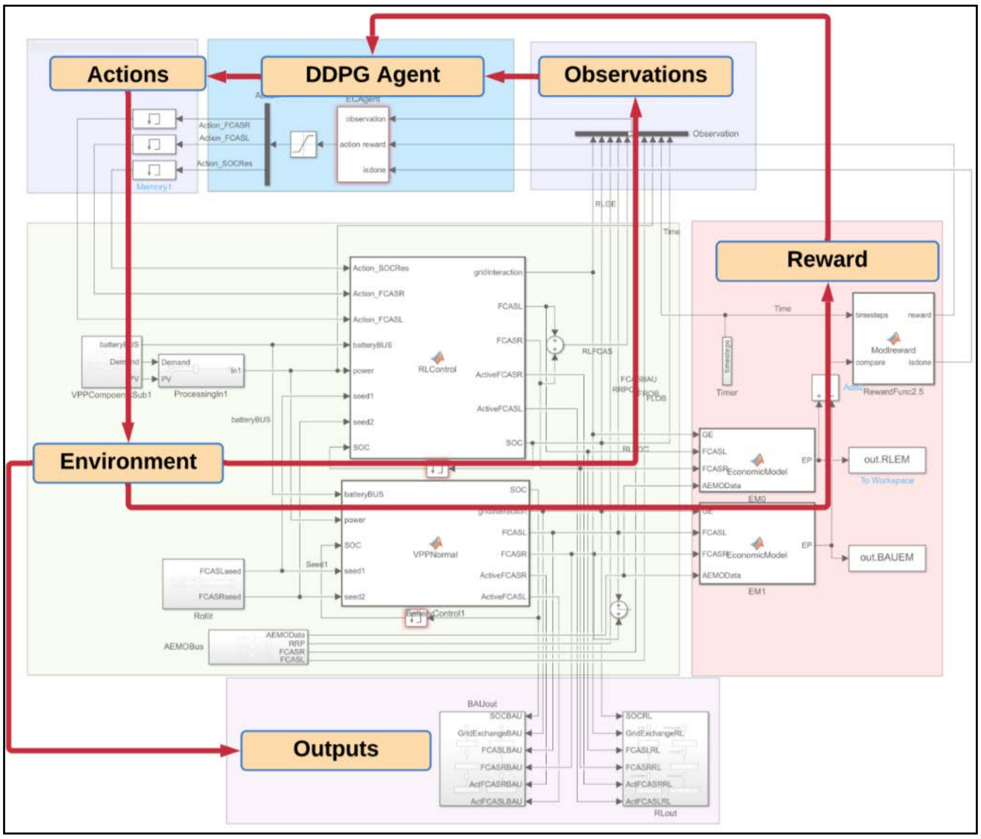

Figure 5. Simulink RL model built based on the MDP for VPP economic dispatch model

3.2.5 Multi-scenario simulation and analysis

The multiple scenario analysis of this study simulated and investigated the impacts of different VPP operation strategies under the different scenario cases. When generating scenario cases, this research considers the spatial and temporal dynamics of the urban environment in terms of the demand/supply changes, market changes, etc. Following aspects are considered in the scenario settings:

Scenario group A: Scenarios of potential PV coverage: Based on the PV system delieanation results, the PV coverage scenario will be established considering solar potential, rooftop orientation, the slope of the roof and the rooftops' financial viability for deploying PV systems. The scenarios are as follow (1) Base case with currently detected solar panels, (2) Medium coverage ratio scenario (25% of total available rooftop), (3) High coverage ratio scenario (50% of total available rooftop).

Scenario group B: Scenarios of electricity storage facilities: For scenario group B, three cases are introduced: (1) base case scenario without battery capacity, which affects the base case VPP operation scenario only, (2) battery capacity of 70% PV capacity, (3) battery capacity of 140% PV capacity and (4) battery capacity with 210% PV capacity.

Scenario group C: Scenarios for electricity demand growth: The demand growth scenario has three scenario cases: (1) Current demand, (2) 5 years demand growth, and (3) 10 years demand growth. Among the three scenario cases, the current demand is based on the demand data as introduced in Section 3.2.3. The cases 2 and 3 are the forecasted demand using the estimated demand growth rate recommended by Australian Department of Industry, Science, Energy and Resources (DISER) (2020). In the DISER's 2020 report, the recent growth rate for 2019-2020 is used to estimate the five years growth in the near future, while the DISER's estimated 10 years growth rate is used for the long-term demand growth.

4 Findings and Discussions

This section discusses the feasibility of a distributed renewable energy management system – VPP from the following aspects: (1) Carbon emission reduction, (2) Project economic performance, and (3) User electricity price reduction

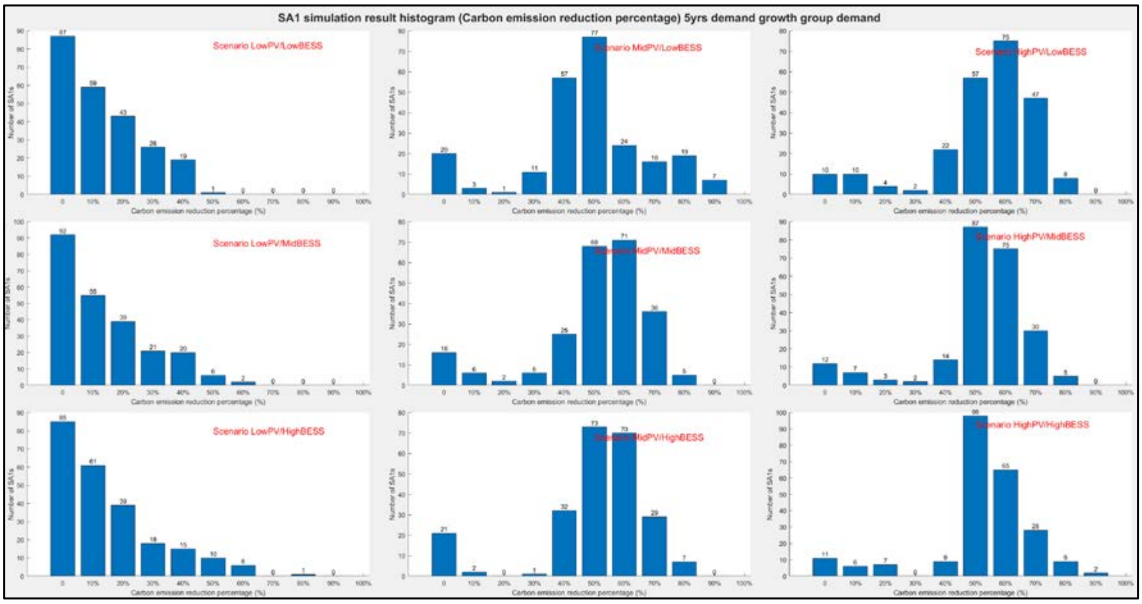

Figure 6. Histogram plots of SA1 simulation results for carbon emission reduction rate

4.1 Carbon emission reduction performance of VPPs

Figure 6 presents the histogram of the simulation results of carbon emission reduction (CO_{2-e}) with VPP implemented in each SA1. The emission reduction is calculated using Equation 3, where C_{e-VPP} is the emission of CO_2 with VPP implemented, $C_{e-Total}$ is the total CO_2 emission, and C_{e-R} is the emission reduction rate.

$$C_{e-R} = \left(1 - \frac{C_{e-VPP}}{C_{e-Total}}\right) \times 100\% \qquad \text{Equation 3}$$

The carbon emission reduction factor is calculated based on the emission factor for the carbon dioxide (CO_2) emission factor provided in (2020b) for electricity purchased from the grid. According to the report, in Victoria, Australia, the emission factor for CO_2 is 0.98 kg/kWh. As can be found in Figure 6, with low PV coverage levels, the vast majority of SA1s have carbon emission reduction rates lower than 10%, and the frequency of the 0-10% group increases while the demand growth scenario changes from current to future years. Increased PV coverage scenarios have a significant effect in increasing the rate of reduction of CO_2 emissions. It can also be noticed that within the same PV coverage scenario, increasing BESS capacity enlarge the group size of SA1s with higher carbon emission reduction rates.

4.2 Economic performance of VPPs measured by 25 years Net Present Value (NPV)

To measure the financial viability of investing in VPPs, this study calculated the VPP project's life cycle net present value (NPV) for each SA1. The NPV calculation considers a 25-year lifetime for PV and BESS systems. In the life cycle, the cost of the project includes (1) The cost of PV systems, (2) The cost of BESS systems, (3) The cost of construction, (4) The cost of maintenance and replacement, (5) The cost of electricity purchased from the grid. The income of the project includes (1) Income from selling electricity wholesale, and (2) income from participating FCAS services.

The NPV calculation is this research applied the following equation:

$$CF_{n=1} = \frac{\left(C_{PV} + C_{BESS} + C_{E\_purchase\_grid} + C_{Maintenance} + I_{wholesale} + I_{FCAS} + S_{E\_consumer}\right)}{(1+R)^{(n-1)}}$$

$$CF_n = \frac{\left(C_{E\_purchase\_grid} + C_{Maintenance} + I_{wholesale} + I_{FCAS} + S_{E\_consumer}\right)}{(1+R)^{(n-1)}}$$

$$NPV = \sum_{n=1}^{25} CF_n \qquad \text{Equation 4}$$

where, CF_n is the present value of annual cashflow at year n, C is the cost item, I is the income item, $S_{E\_consumer}$ is the saving in expenditure on electricity by offsetting users' demand and the R is the discount rate.

It is found the financial performance of VPP largely relies on the capacity of renewable generators and storage systems. When the capacity remains at current level, the forecasted net present value (NPV) for investing community-level VPP will be low: The simulation results on the 25 years project NPV indicates that with current PV coverage, most of SA1s have low NPV or negative NPV values and the lowest NPV is found at around -5 to -4 million AUD. In the current scenario, around 34-35% SA1s have positive NPV values. This indicates that the investment on VPP with current installed PV capacity will have a relatively low expected financial payback.

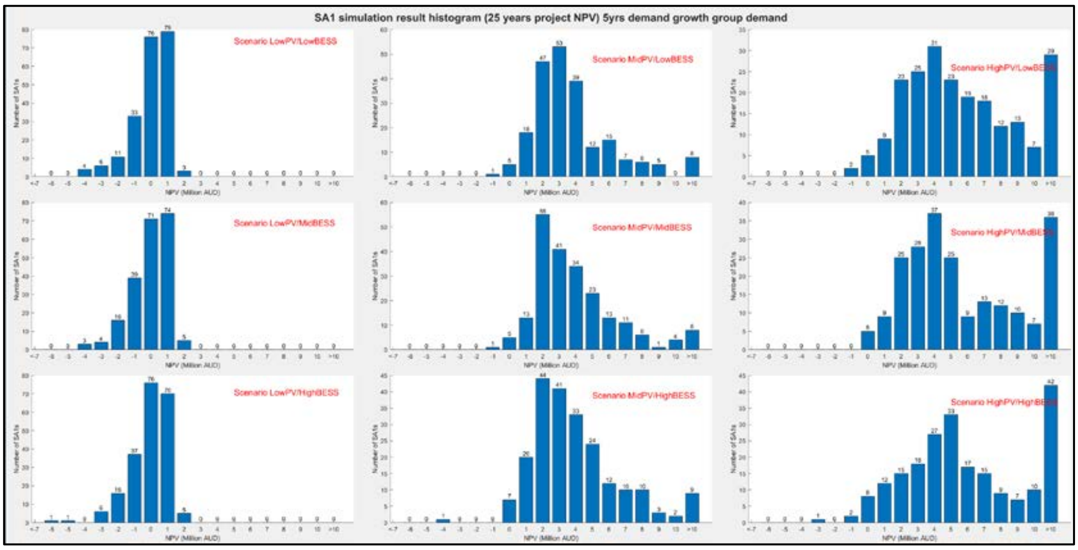

Figure 7. Histogram plots of SA1 simulation results for 25 years NPV

When the PV coverage increases to medium or high level, the NPV among SA1s shows a pattern of increasing, with over 88% of the SA1s populated above 1 million AUD in the 5 years scenario. The percentage grows up to above 90% of the SA1s have higher NPV than 1 million AUD in the 10 years scenario. Increasing PV capacity will have a positive impact on the VPP's NPV among the SA1s. However, the increase in BESS capacity can have a double-sided effect on the project NPV. For example, if an SA1 community already has a higher estimated profit (above 10 million AUD 25 years NPV), extra BESS capacity will be more likely to further increase the profits level. On the contrary, if an SA1 community has an estimated profit less than 1 million AUD, the extra BESS capacity that incur more initial cost and maintenance cost will have higher chance to reduce the exiting profit.

In summary, the economic payback and project value of the future VPP deployment largely rely on the capacity of PV and BESS system. Higher PV and BESS system capacity gives VPP greater capability in demand offset and energy trading. It can also be found that the high BESS capacity can sometimes reduce project economic feasibility, which may be due to the high capital cost and maintenance cost of the BESS system.

4.3 Economic benefits of VPP for communities and end-users

Based on the calculation of the NPV, this research also provides an estimation of the electricity retail price which can fully offset the cost of the VPP. The adjusted electricity was calculated using the ratio of the users' net demand after the demand offset action of VPP and the 25-year NPV in each SA1, as shown in the following equations:

$$CF'_{n=1} = \frac{\left(C_{PV} + C_{BESS} + C_{E\_purchase\_grid} + C_{Maintenance} + I_{wholesale} + I_{FCAS}\right)}{(1+R)^{(n-1)}}$$

$$CF'_{n} = \frac{\left(C_{E\_purchase\_grid} + C_{Maintenance} + I_{wholesale} + I_{FCAS}\right)}{(1+R)^{(n-1)}}$$

$$NPV' = \sum_{n=1}^{25} CF'_{n}$$

$$P_{adjusted} = \frac{\sum_{n=1}^{25} {(E_{Total} - E_{VPP\_User})}/{(1+R)^{(n-1)}}}{NPV'} \qquad \text{Equation 5}$$

where, E_{Total} is the total demand in each SA1 and E_{VPP_User} is the user demand offset by VPP.

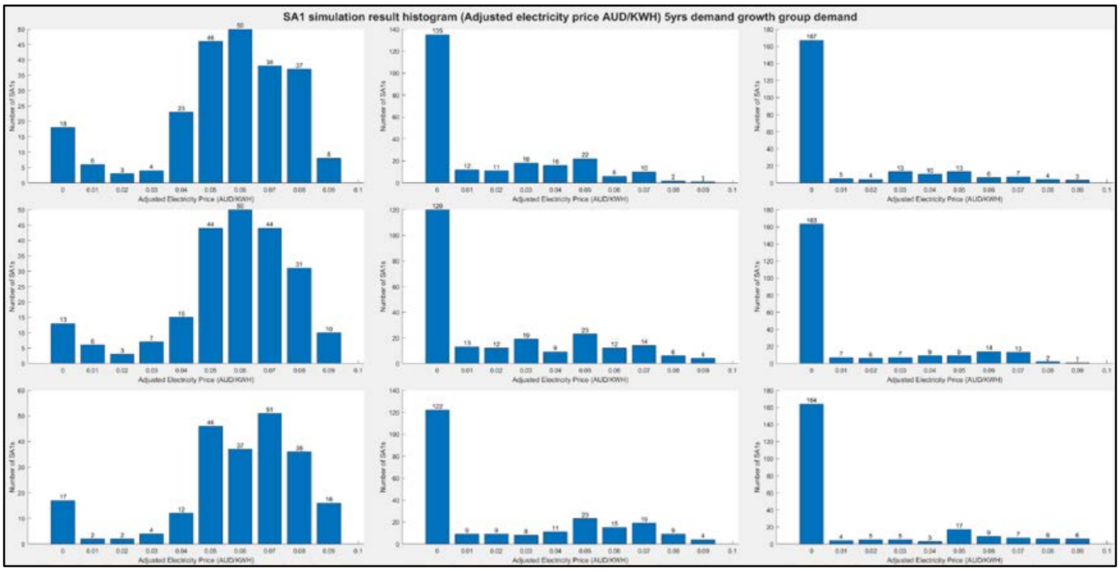

Figure 8. Histogram plots of SA1 simulation results for adjusted electricity price

The resulting histogram plots are shown in Figure 8. It can be found that VPP’s economic performance has strong impact on reducing the electricity cost for the local communities, even with the current PV installation capacity. Most of the SA1s with current PV capacity and low BESS capacity have reduced electricity price ranging from 0.05 to 0.08 AUD/kWh while over 50% of the SA1s have the electricity price of less than 0.01 AUD. This illustrates a significant reduction compared to the Default Offer electricity price (ranging from 0.1297 to 0.3091 AUD/kWh excluding the service charge) provided by the Essential Services Commission (ESC) of Victoria (2022b). This demonstrates that the VPP has significant capacity in reducing the users’ electricity expenditure with different demand profiles.

5 Conclusion and further research

The paper reports the results of a case study of an implementation of community focused VPPs system in an Australian city. To sum up, this research validates the VPPs benefits for end-users and the communities in terms of reducing carbon emission and reducing electricity cost. Still, the financial viability of VPP projects largely depends on the availability and capacity of the renewable energy generators and storage systems.

Due to low economic value and inadequate carbon emission reduction, VPP is not a viable investment choice at current PV penetration levels. However, PV and BESS development scenarios show that the VPP has enormous potential to assist the City's future renewable energy system and unleash the distributed system's benefits among communities. This study's economic analysis and conclusions may help future VPP operators assess the financial impact of upgrading system and infrastructure, such as assessing the margin for prosumer incentives or rebates. For end-users, VPPs have great capability in reducing the user’s expenditure on electricity in all the scenarios when the adjusted electricity price lower than the Default Offer as provided by the Victoria Essential Service Commission.

This research could not gather specific distribution network data, including voltage and frequency limits, due to information security concerns. This research has limitations in VPP technical analysis like voltage and frequency regulation. Future research should extend data collecting and analysis to determine VPP's impact on power quality for end-users and communities. The future research should additionally extend VPP modelling and functionality. Electrical engineering research might also involve voltage and frequency.

6 Acknowledgement

This research project reported here is supported by ‘Transitioning Bendigo’s energy economy - a feasibility study of renewable energy transition across an entire regional city [200928_58]’ funded by the Centre for New Energy Technologies (C4NET), the City of Greater Bendigo and RMIT University. The researchers acknowledge the data contributions and support of PowerCor, the Department of Environment, Land, Water and Planning (DELWP) of the Victorian Government, and CoGB’s local community members who have a great passion for and an exceptional vision of the transition to renewable energy.

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Dynamic Construction Scheduling and Resource Planning Based on Real-time Project Progress Monitoring

Kartika Nur Rahma Putri[1], Ziang Jiang[1], Xuesong Shen[1*], Khalegh Barati[1]

[1]School of Civil and Environmental Engineering, University of New South Wales (UNSW Sydney), Kensington, Sydney, NSW 2052, AUSTRALIA

k.putri@unsw.edu.au; ziang.jiang@unsw.edu.au; x.shen@unsw.edu.au; khalegh.barati@unsw.edu.au
* Corresponding author

Abstract:
Effective management of resources, such as materials, equipment, and workers, is critical to the success of a construction project. It requires adequate project monitoring to match resource needs with available resources to prevent idling. Currently, resource planning in construction projects usually relies on a static master schedule. At the same time, the change of schedule will interchangeably impact the change of material demands. Thus, accurate construction progress will be needed to ensure that the resources can be available on-site just in time. Nowadays construction progress tracking is typically performed manually. Previous studies have tried applying digital technologies such as laser scanners, image processing, and photogrammetry to capture the construction progress. However, the benefits of progress monitoring have not been widely used in dynamic project scheduling and resource planning. This paper aims to develop a framework for using the latest progress monitoring digital technologies to support accurate prediction about resources needed. To overcome this issue, construction progress monitoring was generated by comparing as-planned building information model (BIMs) with the as-built 3D point clouds taken by a laser scanner. The duration of the upcoming activities was predicted using past historical data on the team's productivity. The updated progress monitoring and prediction of activities will be used to estimate the resources needed for some weeks ahead. The results indicate that the proposed framework could effectively predict the resources needed to support construction site decision-making.

Keywords:
Construction, Dynamic scheduling, Progress monitoring, Resource management

1 Introduction

With around US$ 10.7 trillion spent on material and service delivery in 2020, the construction sector became one of the world's biggest industries (Oxford Economics, 2021). Around 50-60% of project costs were distributed for buying materials in a construction project (Kar and Jha, 2020). Failure in resources management such as material, equipment, and worker would lead to loss of profit, decreased service levels, impact the reputation, and a decline in the company's market share. Therefore, the ability to match the demand and supply of resources is a key to project success to ensure the completion of the project on schedule, on budget, safely, and satisfy the required specification (Simchi-Levi *et al.*, 2014).

The Architecture, Engineering & Construction (AEC) industry is considered one of the sectors that relatively experienced a slight change in the project execution process. In fact, over the last 50 years, labor productivity in the construction sector decreased by around 20%, while the non-farm business experienced a 153% increase (World Economic Forum, 2016). In the middle of rapid technological change, the construction industry has missed the opportunity to utilize digital tools that improve productivity, sustainability, and cost-efficiency (Heigermoser *et al.*, 2019). However, in recent years, heavy investment in digital technology is an indication that there is a potential transformation in the way of AEC industry executes its construction projects. With the rising of various new technologies, construction companies are increasing their awareness of applying the new approach to optimize a construction project (Chen *et al.*, 2021).

Building Information Modelling (BIM) and its integration with other technologies such as laser scanners, RGB cameras, Unmanned Aerial Vehicle (UAV), and some sensing technologies are becoming the most widely used technologies to make construction progress and resources tracking. However, the system focuses only on data capturing technology and offers time or cost reduction on digital monitoring compared with manual monitoring. In fact, the data of updated progress monitoring could further analyze to improve real-time prediction of resource needs and provide the project manager with a data-driven insight to support resource management. Despite the increasing research regarding digital technology, there are some gaps in the literature. There is a lack of research focusing on synchronizing real-time construction progress and material availability to provide an early warning system of resources needed for the project stakeholder.

This paper aims to develop a framework for using the latest progress monitoring digital technologies to support accurate information about resources needed. To overcome this issue, construction progress monitoring was generated by comparing an as-planned 3D point cloud with the as-built 3D point cloud taken by a laser scanner. The duration of the upcoming activities was predicted using past historical data of team's productivity. The updated progress monitoring and prediction of activities will be used to estimate the resources needed for some weeks ahead. The remainder of this paper is organized as follows. A literature review on the current digital technology in construction progress monitoring and resource tracking is discussed in Section 2. Then, a methodology section will focus on proposing a framework for resource planning based on real-time progress monitoring. A case study will be presented to verify the proposed method. Finally, the discussion and conclusion of the study will be reviewed.

2 Literature Review

To improve the productivity of a construction project, three main material management practices were to identify the long-lead materials, manage the procurement plans for materials, and materials delivery schedule (Gurmu, 2020). The latest digital technology to quantify progress monitoring and resources tracking in the construction project will be discussed in this section.

2.1 Construction Progress Monitoring

Based on Rao *et al.* (2022), technology adapted to provide a real-time 3D mapping of construction projects varying from laser scanners, RGB cameras, depth cameras, ground-penetrating radar, and sensor integration used as a mapping sensor. The sensor platform could be stationary, handheld, equipment-mounted, wearable, trolley, Unmanned Ground Vehicle (UGV), or Unmanned Aerial Vehicle (UAV). The difference between real-time 3D objects collected from the mapping tools (as-built) and the as-planned 3D design will be measured as construction progress. Previous research has been successfully calculate the progress monitoring by using Unmanned Aerial Vehicle (UAV) (Hamledari *et al.*, 2017), Light Detection and Ranging (LiDAR) (Puri and Turkan, 2020), or low-precision 3D scanning devices (Pučko *et al.*, 2018).

Construction progress monitoring is closely related to the construction schedule, usually known as 4D BIM modelling. To automatically process the construction progress into 4D BIM modeling, Hamledari *et al.* (2017) propose an automatic update of the construction schedule based on the Industry Foundation Classes (IFC) format using a UAV with an onboard camera. The system uses an image-based processing algorithm. The proposed method can modify the schedule relationship and hierarchy, update each building structure's progress percentage, color code the elements based on expected and actual progress, and update the finish dates and task duration. Meanwhile, Pučko *et al. (*2018) propose a new method where changes and as-built models are continuously updated during construction by using low-precision 3D scanning devices located in the worker's helmet within an hour. This system exploits the usage of the 3D point clouds method to identify the differences in the 3D model before it is matched with the schedule of the element (4D BIM). The comparison between 4D as-designed BIM and 4D as-built BIM provides schedule deviations.

Most previous research focuses only on technical issues to provide construction progress monitoring to illustrate the functionality of the proposed method. By using the latest technology, construction progress monitoring could be conducted automatically. However, further analysis to use the progress monitoring data are still rarely reviewed. The resources management area could benefit from real-time progress monitoring by using the data to dynamically change resource management.

2.2 Resource Tracking in Construction Project

In the material identification and measurement area, 3D points cloud and image processing are two techniques that are widely used nowadays. By assessing point cloud roughness, the state of the soil material could be identified. The volume and elevation changes are measured by differentiating the point clouds, resulting in automatic earthwork progress material and schedule updating (Lo *et al.*, 2022). Meanwhile, the volume of aggregate and sand stockpiles could be identified using deep learning-based point cloud segmentation (Kamari and Ham, 2021). For prefabrication materials such as steel plates, Kang *et al.* (2019). propose a Feasibility study of UAVs with embedded radio-frequency identification systems for construction materials detection on large-scale open sites.

3D point clouds combined with machine learning algorithms for equipment identification could identify backhoe loaders, bulldozers, dump trucks, excavators, and front loaders (Chen *et al.*, 2017). Crane lifting optimization and movement of the crane has successfully recognized by Structure from Motion (SfM) photogrammetry. Meanwhile, on worker identification, 3D point cloud and photogrammetry technology combined with a deep learning algorithm could detect the construction workers on-site (Son *et al.*, 2019) or off-site construction (Xiao *et al.*, 2021). Furthermore, detecting worker movement around the machinery could increase workplace safety (Son and Kim, 2021).

To improve resources availability, some sensing technology such as Ultra-Wide Band (UWB), Global positioning System (GPS), vision cameras, Radio Frequency Identification (RFID), Wireless Sensor Network (WSN), LiDAR was adopted in a construction project. For example, Teizer *et al. (*2008) propose a UWB technology to determine the real-time location of workers, materials, and equipment. Meanwhile, an RFID/WSN-based construction supply chain management is proposed to improve the information management framework and reduce 32% of the time necessary to complete the factory production into site delivery and installation (Shin *et al.*, 2011). Another RFID technology combined with BIM and a look-ahead plan was proposed by to improve supply chain coordination between stakeholders (Chen *et al.*, 2020).

Material, equipment, and worker automatic detection techniques are still growing in the construction industry. The application of resource detection and progress monitoring is mainly adopted to update the project schedule only. The resource management area could benefit from the automatic 3D and 4D updating technology. Information about schedule changes and earlier activity delays could save material holding costs. Therefore, by leveraging the information of real-time schedules distributed to all parties, the stakeholders in the construction project could gain more advantages in cost savings.

3 Research Methodology

A framework to manage construction resource management is proposed in this study, as illustrated in Figure 1. The methodology started by developing 3D and 4D BIM models as the baseline of the as-planned design. The 3D model was used to generate a virtual 3D point cloud. The as-built 3D point cloud data were acquired from the laser scanning procedure. Then, the construction progress was measured by comparing the ratio of as-planned and as-built 3D point clouds that could illustrate their geometric status. Based on the progress calculation, the schedule will be updated to generate a new schedule for the construction project. A prediction for upcoming activity duration will be calculated based on productivity analysis from historical data and workers-hour from the field. This updated schedule will generate a new material and equipment plan to assist the project manager in resource management.

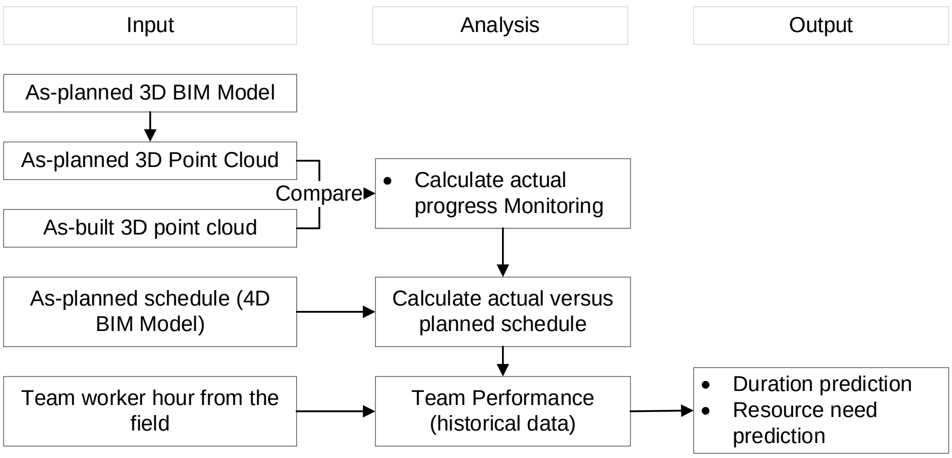

Figure 1. Research Framework.

4 Case Study

A traffic bridge constructed in New South Wales, Australia, was selected as a case project to check the reliability of the framework. The structure consists of 1,847 m^2 reinforced concrete for the piled bridge abutment walls, 84 prefabricated concretes for parapet barriers, and 264 m capping units. The Bridge is 99 meters long and consists of three spans constructed using prefabrication Bulb-T girders and cast-in-situ reinforced concrete deck slab. The 3D model and 3D point cloud of the Bridge are illustrated in Figure 2. The as-built laser scanning data were acquired from the surveying company. Since the scanning was conducted after the construction project was completed, some assumptions were used to describe the progress of the construction project. All the data used for scheduling, such as activity, duration, and historical team productivity, are artificial data for simulation only.

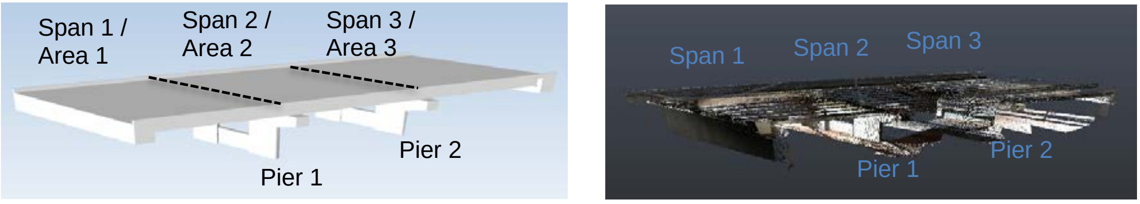

Figure 2. As-planned Bridge Model and 3D As-built Point Clouds.

4.1 Construction Progress Monitoring

The project scope comprises preparation work, pier construction, girder erection, slab, abutment, and parapet installation. The as-design 3D model was developed using Autocad Civil 3D. To model the schedule of the project, a 4D BIM model was built on Synchro pro software. Firstly, the list of activities in the project, such as equipment mobilization, material procurement, shop drawing preparation, steel installation, and concreting, were modeled in the BIM-based software. The duration, predecessor, successor, and cost of each item were inputted into the model. It is assumed that the project was planned for 58 working days, starting from 7 June 2022 until 25 August 2022. This date was set as the Baseline (BL) illustrated in Table 1.

To check the reliability of the proposed framework, two terrestrial laser scanning was utilized to produce a 3D point cloud of the Bridge's as-built model. The as-built and as-design models were compared using Cloudcompare software to calculate the construction progress. The detailed method for progress monitoring was based on (Jiang *et al.* (2022). The laser scanning procedure was conducted on 7 July 2022 as one of the weekly monitoring works. The laser scanning process results show that the as-built volume for pier 1 is 122.53 m^3 (45.3%).

Based on the baseline schedule, on 7 July 2022, the process of girder area 1 erection should have been started. However, some works, such as crawler crane mobilization, pier shop drawing, structural steel procurement, and steel installation, were delayed based on previous construction progress monitoring. Therefore, the actual start and finish dates differ from the baseline start and finish dates, as depicted in Table 1. The result of the laser scanner showed that the progress of concrete pouring for the pier was 121.53 m^3 or 45.3% of the total pier volume. This data becomes an input to the 4D model to update the schedule.

Table 1. Baseline Schedule, Actual Schedule (7 July 2022), and Predicted Schedule.

Task Name	BL Dur	BL Start	BL Finish	Actual Dur	Actual Start	Actual Finish	Predicted Start	Predicted Finish
Bridge	**58**	**7/06/22**	**25/08/22**	**0**	**7/06/22**			
Preparation Work	**3**	**13/06/22**	**15/06/22**	**5**	**20/06/2**	**24/06/22**		
Crawler crane mobilization	3	13/06/22	15/06/22	5	20/06/22	24/06/22		
Mobile crane mobilization	3	13/06/22	15/06/22	3	20/06/22	22/06/22		
Pier	**18**	**7/06/22**	**30/06/22**	**29**	**7/06/22**	**15/07/22**		
Material Procurement	9	7/06/22	17/06/22	16	7/06/222	28/06/22		
Pier Shop drawing	2	7/06/22	8/06/22	4	7/06/22	10/06/22		
Structural Steel	7	9/06/22	17/06/22	12	13/06/22	28/06/22		
Steel installation	8	20/06/22	29/06/22	12	29/06/22	14/07/22		

Task Name	BL Dur	BL Start	BL Finish	Actual Dur	Actual Start	Actual Finish	Predicted Start	Predicted Finish
Steel installation Pier 1	4	20/06/22	23/06/22	6	29/06/22	6/07/22		
Steel installation Pier 2	4	24/06/22	29/06/22	6	7/07/22	14/07/22		
Concreting	5	24/06/22	30/06/22	7	7/07/22	15/07/22		
Concreting Pier 1	1	24/06/22	24/06/22	2	7/07/22	8/07/22		
Concreting Pier 2	1	30/06/22	30/06/22	*2*			*15/07/22*	*18/07/22*
Girder	**40**	**9/06/22**	**3/08/22**	**40**				
Girder shop drawing	2	9/06/22	10/06/22	2	13/6/22	14/6/22		
Girder Precast material order	10	17/06/22	30/06/22	10			*4/7/22*	*15/7/22*
Girder erection area 1	7	06/07/22	14/07/22	7			*19/7/22*	*27/7/22*
Girder erection area 2	7	15/07/22	25/07/22	7			*28/7/22*	*5/8/22*
Girder erection area 3	7	26/07/22	03/08/22	7			*8/8/22*	*16/8/22*

By having the data of construction cost and progress, one can calculate the project's earned value. Planned Value (PV) is defined as a percentage of complete (planned) multiplied by the project budget. Earned Value (EV) is defined as a percentage of complete (actual) multiplied by the project budget. Meanwhile, Actual Cost (AC) is a percentage of complete (actual) multiplied by actual cost. Based on actual progress on 7th July 2022, the amount of Planned Value (PV) = 43.93%, Earned Value (EV) = 17.99% and Actual Cost (AC) = 18.27% as illustrated in Figure 3. Earned value shows a smaller amount than the planned value because the overall progress is delayed. After the schedule has been updated, the estimation of upcoming activities based on the precedence relationship of each activity can be calculated automatically in the 4D BIM software (displayed in italics and blue colour in Table 1).

The interface for the construction monitoring is illustrated in Figure 3. The schedule, Gantt chart, and earned value graph could show the progress. The 3D illustration of the planned model (left-bottom side) and actual model (right-bottom side) could better visualize the real progress.

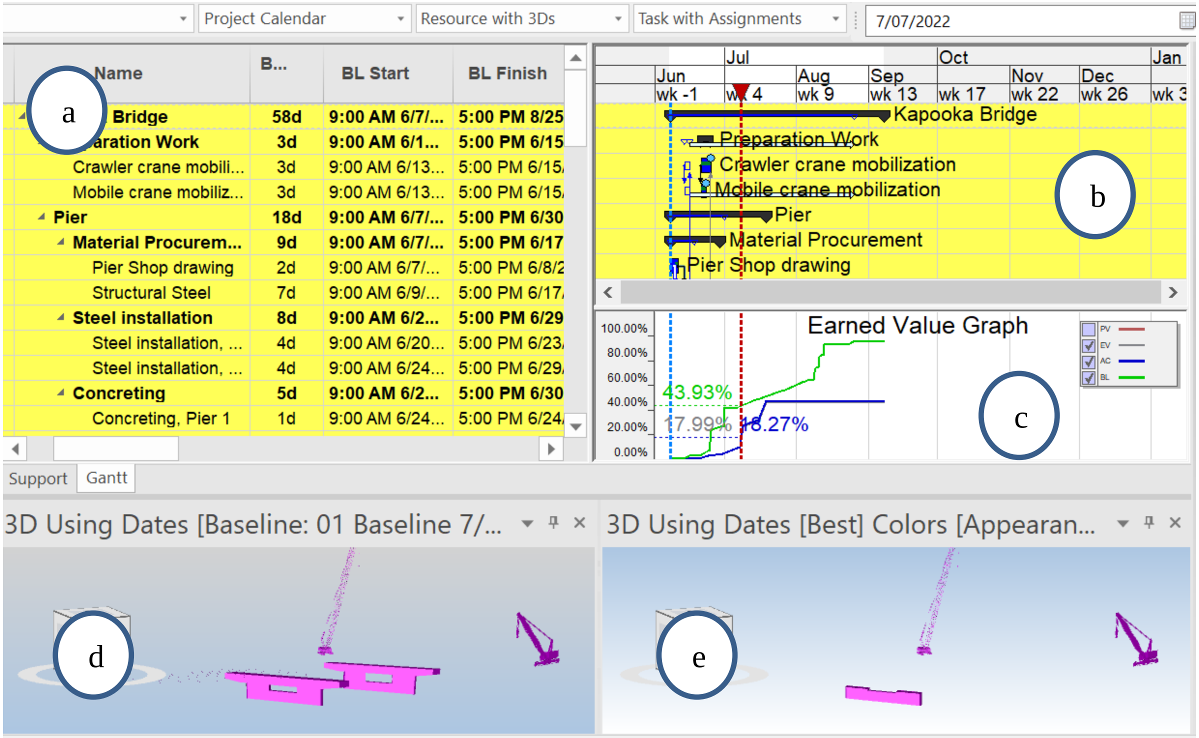

Figure 3. Interface for construction progress: (a) Schedule, (b) Gantt chart, (c) Earned Value Graph, (d) Planned 3D model, and (e) Actual progress 3D model.

4.2 Activity and Resources Forecasting

Currently, the forecasting for upcoming activities is mainly based on the planner's history and experience. The duration of the upcoming activities is still the same as the planned duration. Meanwhile, progress monitoring data can calculate the productivity of each team in the project. This data will be analysed to provide actual productivity of the project site and become the basis for predictive data analytics for the upcoming activities.

A team's productivity is influenced by factors such as team size, type of work, labour percentage, method, direct work, and support work (Khan, 2005). Different factors influencing construction productivity led to uncertainty in each activity's duration. Therefore, the duration of each project activity will be more suitable to be predicted as a probabilistic rather than deterministic variable. Inspired by Task Completion Risk (TCR) calculation by Lin and Golparvar-Fard (2021), this research proposes a schedule data analytics to predict productivity. The productivity of each team can be calculated based on actual works on the construction site for the same contractor. The volume of work was obtained from the BIM model, and the worker hours were obtained from the field. This data can be continuously updated to ensure real-world condition and provide better prediction. By having historical data about previous productivity of each team, the data can be plotted into distribution. The goodness of fit calculation will be conducted to find the best statistical distribution such as normal, exponential, poisson, etc. Using this distribution, the system can predict the upcoming productivity of activities and determine the duration of activity.

For example, from 30 observations ($n = 30$), the average productivity of concreting team (μ) was 150 m^3 per day with a standard deviation (σ) of 20 m^3. This data is assumed to be following a normal distribution. The productivity of concreting team with a confidence interval of 95% can be calculated using Equation 1. The value of z can be obtained from a cumulative standard normal distribution. This data will be used to calculate the Pier 2 concreting activity duration.

$$\text{Productivity} = \mu + z\,\frac{\sigma}{\sqrt{n}} \tag{1}$$

$$\text{Productivity} = 150\ \text{m}^3 \text{per day} + 1.65\ \frac{20\ \text{m}^3}{\sqrt{30}} = 156.025\ \text{m}^3\ \text{per day}$$

From the BIM calculation, the volume of concreting pier 2 is 267 m^3. Therefore, the duration of this activity can be calculated using Equation 2.

$$\text{Duration} = \frac{\text{Volume}}{\text{Productivity}} \tag{2}$$

$$\text{Duration} = \frac{267\ \text{m}^3}{156.025\ \text{m}^3} = 1.711\ \text{days}\ \approx 2\ \text{days}$$

The predicted duration of 2 days for concreting Pier 2 activity was inputted into the schedule to generate the schedule prediction (Table 1 in blue colour). If the system has enough historical data for each team, the productivity and duration can be calculated continuously to create a better forecast for an upcoming activity.

4.3 Resource Inventory Tracking

The construction site project can obtain equipment and bulk material information from the camera surveillance illustrated in Figure 4. Meanwhile, the prefabricated girder or concrete can be obtained from an RFID tag or information from the supplier. The site project could acquire the resources needed for three weeks by monitoring the construction progress. When resources required can be matched with inventory availability, the project site is expected to manage resources better.

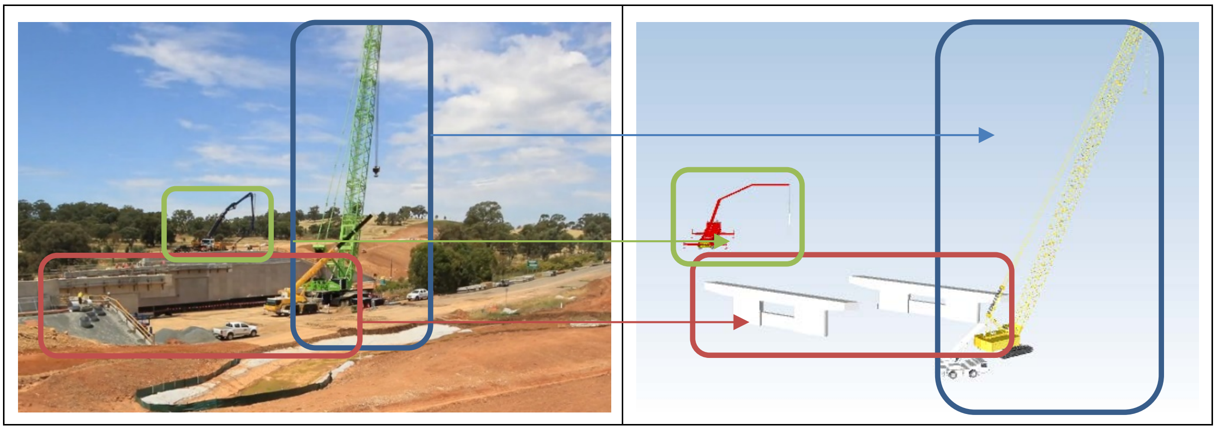

Figure 4. Comparison of a Site Photographs and As Built 4D Model on a Specified Day.

5 Findings and Discussion

The schedule change in this research was based on two data sets. The first is obtained from the actual progress based on laser scanning data, and the second is from the prediction based on the past productivity of the contractor. Resources needed for structural steel, concrete for Pier 1 and Pier 2 were different from the actual need because the construction progress was delayed. After the schedule has been updated, the resource need will change accordingly. In the case study, in the planned schedule, the girder material order should be started on 17 June 2022 (Table 2). However, due to the delayed schedule from the previous activity, the girder material order was changed to 4 July 2022 (Table 3).

Table 2. Resource Need Plan.

Resource Name	Vol.	Unit	6-10 June	13-17 June	20-24 June	27 June - 1 July
Crawler Crane Long Boom 150'	1	unit	1	1	1	1
Mobile Crane 120T 14m-20,5T	1	unit	1	1	1	1
Structural Steel	12.5	ton	4	9		
Concrete Pier 1	293	m3			293	
Concrete Pier 2	267	m3				267
Girder Drawing	1	unit	1			
Girder Material Order	33	unit		3	17	13

Table 3. Resource Need Updated (7 July 2022).

Resource Name	Vol.	Unit	6-10 June	13-17 June	20-24 June	27 June - 1 July	4-8 July	11-15 July
Crawler Crane Long Boom 150'	1	unit		1	1	1	1	1
Mobile Crane 120T 14m-20,5T	1	unit		1	1	1	1	1
Pier Drawing	1	unit	1					
Structural Steel	12.5	ton	5.21	5.21	2.08			
Concrete Pier 1	293	m^3				293		
Concrete Pier 2	267	m^3					267	
Girder Drawing	1	unit		1				
Girder Material Order	*33*	*unit*					*16*	*17*

Information provided by the updated schedule is essential to manage construction rescheduling and resource management. By sharing the real-time status of construction progress and prediction of upcoming activity, the contractor could better estimate the look-ahead planning, resource optimization, and storage evaluation. The lead time of each activity could assist the decision-making of the construction manager in prioritizing the critical activity and analyzing important resources to be procured. The information regarding updated resources demand is expected to be beneficial for reducing warehousing costs by ordering the material just in time. This information also can be used for the supplier to manage their production schedule based on priority to anticipate any potential production problems.

6 Conclusions and Future Research

This research proposed a framework to illustrate the dynamic changes of a construction schedule based on actual progress monitoring from laser scanning data. A practical example of forecasting the upcoming activity duration based on historical productivity data was presented. From the updated schedule, a prediction of resource needs is also generated to provide better information for resource management. Once the data can be acquired continuously, the prediction model could be improved and can provide reliable information for decision-making and support continuous improvement.

Effective data analytics for construction management is still lacking. Most previous research focuses more on schedule analysis using concepts such as look-ahead planning, just-in-time, and the last planner system. To obtain a full picture of the management, the implication of schedule change needs to be reflected in the resource planning and further in the entire supply chain of a construction project. Therefore, this research provides a step to synchronize the actual condition of the project with the resource management to increase project efficiency.

The limitation of this proposed framework is due to the unavailability of the actual project data (i.e., the as planned 4D BIM and worker productivity for each activity). Moreover, the example study was relatively simple as it only considered the progress monitoring for one pier girder and schedule change in a one-month time frame. The number of activities and its sequencing network in a real-world project will be greater, making the simulation more complex. Room for improvement can be conducted by changing the manual process of progress monitoring, updating the schedule, and predicting future resources to become automatic. In future research, resource demand prediction needs to be synchronized with the inventory. Moreover, the production status from the supplier can be integrated into the system for better collaboration between stakeholders. When working with many sources of data and systems, interoperability of different data into one platform becomes one issue that needs to be solved.

7 Acknowledgment

The authors are grateful to the Indonesian Education Scholarship Program from the Ministry of Education, Culture, Research, and Technology for funding this research. The laser scanning data provided by the Linke & Linke Surveys are greatly appreciated.

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Issues in Compliance with Low-Carbon Requirements in the Australian Residential Building Industry

Yi Lu[1*], Gayani Karunasena[2] and Chunlu Liu[3]

[123]School of Architecture and Built Environment, Deakin University,
Geelong VIC 3220, AUSTRALIA

[1]yi.lu@deakin.edu.au; [2]gayani.karunasena@deakin.edu.au; [3]chunlu.liu@deakin.edu.au
* Corresponding author

Abstract:
Low-carbon requirements have long been acknowledged as critical instruments to facilitate residential building industry's transition toward decarbonization in Australia. However, recent studies in the residential building sector have shown that compliance with low-carbon requirements is under-researched, which has led to a significant divergence between low-carbon requirements' intentions and actual performance. Therefore, based on the methodology of literature review, the paper aims to provide a comprehensive exploration of issues in compliance with low-carbon requirements within the Australian residential building industry. Through reviewing research works and policy documents, the paper firstly demonstrates the Australian developments in promoting low-carbon residential buildings, by summarizing key low-carbon requirements and their corresponding purposes. This highlights the significance of these requirements in spurring emission reduction from residential buildings. Subsequently, relying on regulatory studies concerning the National Construction Code (NCC) energy efficiency provisions, the paper reveals the wide presence of non/under-compliance challenges across every construction stage. It further indicates that such issues are largely attributed to major stakeholder groups including regulators (policymakers, building control officers), regulated building practitioners and occupants. Finally, the paper identifies research gaps and proposes future works in the areas of enhancing enforcement regimes, design of the energy simulation tool, raising occupants' awareness and investigating building practitioners' compliance behaviour. The paper implies the urgency to investigate the suboptimal compliance phenomena in the Australian residential building industry, as these issues have already impeded the achievement of the industry's low-carbon future. It also brings contributions via enlightening future research areas to address the issues.

Keywords:
building practitioner, compliance, energy efficiency, low-carbon, residential building industry

1 Introduction

Australia is one of the highest emitters per capita in the world (Ahmed et al., 2021). In 'Australia's Long-term Emissions Reduction Plan' released ahead of the United Nations Climate Change Conference (COP26) in 2021, the government's commitment to net-zero emissions by 2050 is reaffirmed (Commonwealth of Australia, 2021). For achieving this target, as stated in this whole-of-economy Plan, Australia's building sector will need to nearly achieve decarbonization by 2050 (p. 69). Along with the evolution of Australian climate change mitigation policy, residential building has always been highlighted as a critical and indispensable part of the strategy to reduce Australia's carbon emissions. Currently, residential buildings consume around 12% of total carbon emissions in Australia, 2% more than non-residential buildings' contribution (Commonwealth of Australia, 2022). Apart from the challenges of this existing carbon emissions profile, the significantly increased number of new dwellings alongside the growth of Australian population has imposed an even larger burden.

According to Urban Property Australia (2016), Australia is estimated to have 2,700,000 new homes by 2030.

Governments in Australia have issued a wide range of policies to drive the low-carbon transition in the residential building industry. However, notwithstanding the considerable efforts made via regulatory measures, the current residential building industry will be unlikely to deliver a low-carbon housing as targeted (Hurlimann et al., 2018; Doyon & Moore, 2020). A prevailing explanation is the difficulties in compliance with low-carbon building requirements (van der Heijden, 2016; Enker & Morrison, 2019). In Australia's National Energy Productivity Plan 2015-2030 which seeks to reduce carbon emissions (Council of Australian Governments (COAG) Energy Council, 2015), one of the measures (measure 32) is to improve compliance with building energy efficiency regulation. Furthermore, in a report that particularly investigates the Australian building regulation framework, Harrington and Toller (2017) stress that key elements of an optimal low-carbon policy setting for the built environment should constitute, among others, encouraging compliance and over-compliance with the regulation. Accordingly, for Australia to fulfil the 2050 net-zero carbon built environment commitment, the issues with compliance with low-carbon requirements must be addressed urgently (Bannister et al., 2018).

Nevertheless, recent study suggests that the compliance with low-carbon requirements within the residential building industry is still under-researched (Chen, 2021). Therefore, the current research seeks to comprehensively explore the issues in compliance with low-carbon requirements within the Australian residential building industry through the methodology of literature review.

2 Literature Review

Globally, some organizations and countries have issued a set of requirements which seek to accelerate residential housing's movement to decarbonization. For instance, in 2021, the European Commission has proposed a revision for its earlier version of Energy Performance of Buildings Directive (2018/844/EU). The proposal provides a trajectory for Europe to achieve a zero-emission and completely decarbonized building stock by 2050 (European Commission, 2022). In New Zealand, the central government also initiated 'Building for Climate Change programme', which sets operational and embodied carbon reduction targets for buildings (New Zealand Government, 2022). Other developed countries such as the USA, UK, Canada also established their corresponding regulatory framework aiming at low-carbon dwellings. Such initiatives underline the importance of regulatory measures within the residential sector in spurring carbon emission reduction internationally.

Parallel in Australia, building policies have also long been recognized as a critically important instrument to systematically facilitate the reduction of emissions from Australian residential buildings, especially if the industry is to transition to a lower-carbon future (Moore et al., 2019; Commonwealth of Australia, 2021; Li et al., 2022). On that account, many regulatory measures targeted at low-carbon residential buildings have been developed and implemented in Australia. A summary of the key policies and their corresponding low-carbon targets residential buildings is provided in Table 1.

Table 1. Australia's policies targeting low-carbon residential buildings
Source: Doyon and Moore (2020), ABCB (2022) and NatHERS (2022)

Policy	Year	Mandatory or voluntary	Low-carbon related target
National Construction Code (NCC)	1990 1st edition; 2022 is the latest edition	Only the minimum performance requirements are mandatory	Energy performance is set and linked to the NatHERS
Nationwide House Energy Rating Scheme (NatHERS)	Introduced in 1993; Revised in 2022	Mandatory	A stringency increased to 7-star in 2022, determined based on home's design, materials and climate zone
Trajectory for Low Energy Buildings	Issued in 2018; agreed in 2019	Voluntary	An outline of trajectory spanning from 2018-2027 towards the achievement of low energy (and carbon) ready buildings
Your Home Manual	2001 1st edition; currently 6th edition	Voluntary	Improved sustainability in a broad sense. No specific targets set
National Australian Built Environment Rating System - Home	Launched in 1998	Mandatory for all new buildings over 2000 m^2 and buildings that are up for lease and sale	Improved energy and water use. Specific targets are set based on building type, use and located climate zone
National Carbon Offset Standard for Buildings	2017	Voluntary	No specific targets set

Since the Australian Labor Party campaigned on legislating a net zero emissions target by 2050, with a 43% reduction by 2030 (Evans, 2022), the federal election of the Labor government in May 2022 offered a glimmer of hope that Australia may join actions to combat global warming more ambitiously (Pears, 2022). Nevertheless, though under the pressure of achieving the net-zero commitment by 2050, the overall manifestation the low-carbon policy developments in Australia greatly reflects a glacial speed of change rather than a radical transformation, which is also implied by Berry and Marker (2015) and Doyon and Moore (2020). Remarkably, it takes the national government more than a decade to increase the stringency level of minimum energy performance from 6 star in 2010 to 7 star in 2022, which lags well behind other developed countries' developments (Fuerst & Warren-Myers, 2018). Compared with the federal-level slow development, the state-level government seems to have a stronger will to expedite the low-carbon activity, with exploring multiple guidelines and program that go beyond the NCC requirements, similar to Harrington and Toller (2017)'s findings. However, most of these policies are not mandatory. At the municipality level, whilst still voluntary approach, the attempt to find a way around the federated system can also be observed. Under these circumstances, if the compliance status is continuously suboptimal, the effectiveness of the low-carbon regulation will be further negatively impacted (Meacham, 2016), and the 2050 net-zero target will probably not be achieved (Bannister et al., 2018).

3 Research Methodology

Compliance studies in the context of low-carbon buildings typically involves research areas concerning low-carbon building regulations (van der Heijden & De Jong, 2009), legal studies involving compliance theories (Becker, 1968) and behavioural science (Enker & Morrison, 2019). As per Snyder (2019), literature review is an excellent way to provide a comprehensive exploration of a certain issue of which the research work is disparate and interdisciplinary. The current research thus adopts a three-step systematic review methodology, including planning, conducting and reporting stages, which have been popularly leveraged in recent review studies (Cai & Choi, 2021; Srinivas et al., 2022).

In the first step of planning, the key activity is to identify keywords that result in a list of academic works regarding compliance with the low-carbon residential building requirements. As mentioned in section 1, studies in this domain are under-researched, the researcher manually investigated the titles, abstracts and keywords of relevant articles. Ultimately, ‘compliance’, ‘building regulatory compliance’, ‘low carbon’, ‘building regulation’ ‘energy efficiency’ are determined as the keywords for retrieving papers. In the second step, a search query was performed in Scopus and 136 articles were retrieved. Subsequently, inclusion and exclusion criteria were established to perform filtering process manually. By reading the titles and abstracts, papers on indoor air quality, urban planning and those not related to residential domain were excluded. Complementing the Scopus query, the researcher also tracked and inspected articles that were referenced in the filtered papers. Notably, 4 reports under the National Energy Efficient Buildings Project (NEEBP) were included, as the NEEBP specifically investigates compliance with the NCC energy efficiency provisions in Australia. In the final stage, 22 articles were selected for review. Based on keywords, objectives and findings, the reviewed articles are segregated into compliance issues relating to regulators (13), regulatees (10) and occupants (9)[1], with many works investigating more than one type of stakeholders. The articles which provide a general compliance status information that do not fall under any of the earlier categories, were classified as others (5). The literature retrieval and segregation process are summarized in Figure 1.

In order to analyse the influencing factors that impact compliance, the collected literature was analysed through method of code-based content analysis using NVivo 20. Content analysis is a research method which is used as subjective interpretation of the article content by systematic classification process of coding (Hsieh & Shannon, 2005). The multi-level coding 'factors from regulators', 'factors from regulatees' and 'factors from occupants' was used in analysis for identifying common themes separately under each of the key project phase, which is consistent with stakeholder group classification in the work of Pan and Ning (2015). Data processing in NVivo 20 was conducted following six steps (i) importing files; (ii) running word frequency query to get a list of keywords; (iii) generating nodes based on relevant keywords; (iv) conducting text search query for keywords; (v) visualizing; (vi) reporting. In this study, the articles were imported into the software and explored to identify keywords. Accordingly, under three main nodes (design stage, construction stage, operation stage), sub-nodes were identified, and coding structure was established. Subsequently, 'text search query' was performed by restricting the search to minimum three keywords. The coding structure was then visualised in Figure 2 and ready for analysis.

[1] In the current study, regulators refer to policy makers and building control officers, which include e.g., law makers, building surveyors, energy assessors. Regulatees refer to regulated building practitioners such as architect, builder, engineer etc. Occupants refer to occupiers and end-users of the residential dwelling.

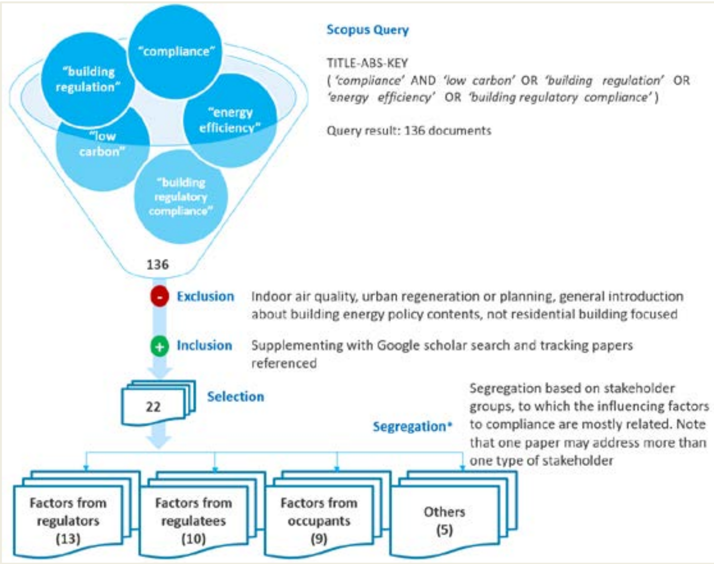

Figure 1. Flowchart of the literature retrieval and segregation process (*segregated papers may address more than one stakeholder)

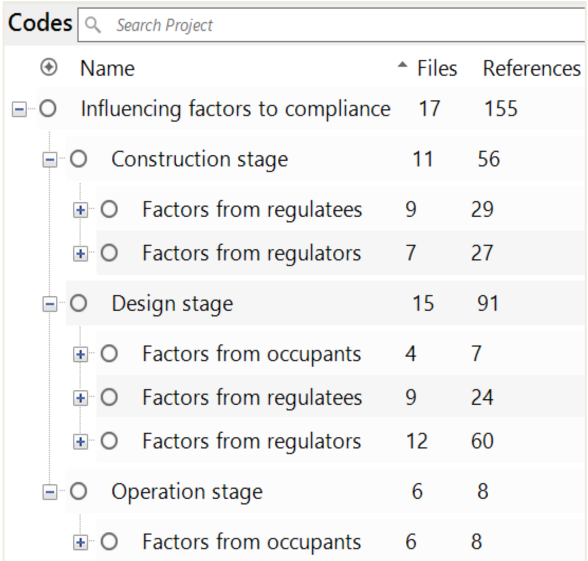

Figure 2. Overview of the coding structure

Key findings derived from data analysis are illustrated below.

4 Findings and Discussion

Most of the selected literature relates to the Australian building industry (54.5%), followed by UK (13.6%), the USA (9.1%), and other countries. In the following section 4.1, the issues prevailing in compliance are revealed, which focuses on the specific Australian residential building industry. Section 4.2 then specifies the contributing factors to compliance which draws predominantly from Australian studies, with supplementation from works in other countries.

4.1 Overview of Issues in Compliance

Low-carbon requirements in the residential building industry concern more than energy efficiency, however it is discovered that all the reviewed articles in Australian context pay their attention to the NCC energy efficiency provisions. This more narrowed focus is consistent with arguments from recent low-carbon building policy studies. For example, Li et al. (2022) state that energy efficiency provisions in the NCC are the most critical instrument to drive the low-carbon future in Australia's residential building industry. In the context of NCC energy efficiency provisions, compliance means complying with both the governing requirements of the NCC and the performance requirements. This infers that the compliance is relevant to not only the design phase (i.e., pre-building permit stage) but also the construction stage (i.e., post-permitting stage) (Miller et al., 2020). Several studies have highlighted that compliance issues exist systematically along the building project stages. Such research in Australia is typically represented by NEEBP commenced in 2012, which is led by the Government of South Australia's Department of State Development and is co-funded by all Australian states and territories through the Council of Australian Governments (COAG) Energy Council.

Under NEEBP, the study by Pitt & Sherry (2014) undertakes a national investigation of non-compliance with NCC energy efficiency provisions and argues that non-compliance exists in each jurisdiction, and covers all stages of a residential construction project. Though this report does not quantify the extent of compliance or non-compliance (Pitt & Sherry, 2014, p. vii), it indicates the wide-presence of non-compliance issues across the Australian residential building industry. Then, subsequent NEEBP studies examine possible solutions concerning the inspection process and building data management system to address the compliance issues. Other than the NEEBP research, Moore et al. (2019) and Jensen et al. (2020) have also provided empirical evidence on how the Australian residential building industry stands in terms of its NCC energy efficiency compliance level at the design and construction stages. Drawing substantially from the above findings, key points of issues in compliance in the Australian residential building industry are summarized in Figure 3. As indicated by Bannister et al. (2018) and Miller et al. (2020), these compliance issues are still present.

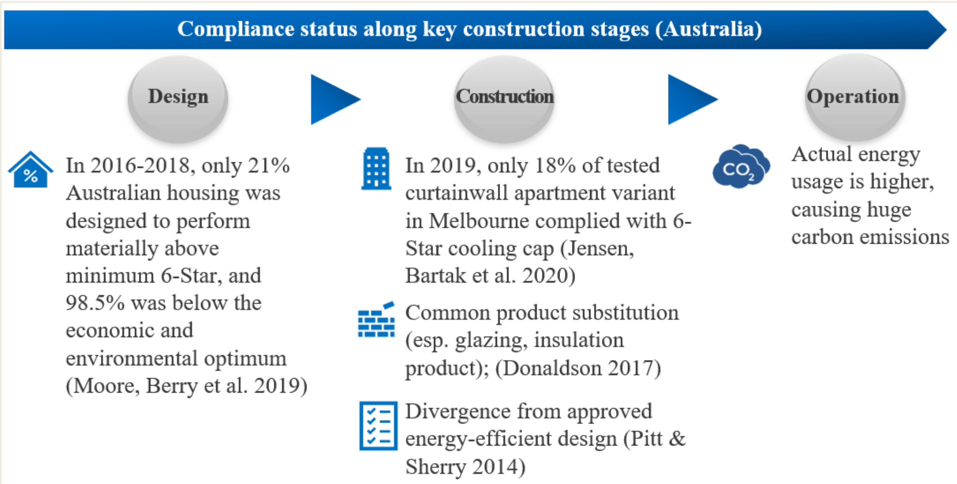

Figure 3. Issues in compliance with the NCC energy efficiency requirements

This high-level summary figure indicates that compliance with the NCC energy performance requirements is generally poor, and issues cover key aspects of the building project stages. In the design stage, most housing designed in Australia was designed only to meet minimum standard, without aiming for economic and environmental optimum. Such situation was described as '*mediocrity*' by Moore and Holdsworth (2019, p. 602), which reveals building industry stakeholders' hesitance to move beyond code minima. Moving to the construction stage, the recently tested compliance result by Jensen et al. (2020) reflects the severance of non-compliance, with only 18% of tested samples achieving minimum cooling cap. Additionally, substitution with low-efficiency building products and systems was commonly observed. Furthermore, projects were largely not delivered as per approved design documents. All the weaknesses presented above have negatively impacted the energy performance during the operation stage. They imply higher energy consumption and higher costs for building owners. Importantly, they imply higher emissions to society, and jeopardize the country's motion toward net-zero.

Therefore, it is necessary to investigate what contributes to these issues in compliance. A list of factors was recognized and described in subsequent section 4.2.

4.2 Influencing Factors to Compliance

Through reviewing a set of empirical studies in Australia and other countries, several contributing factors to compliance have been identified, which are sorted according to its relevance to key project stage. Detailed list of factors and corresponding referenced articles are presented in Table 2.

Table 2. Influencing factors to compliance with building energy requirements

Stage			Influencing factors to compliance	Stakeholder			Reference (* are studies conducted beyond the context of Australia)
Design	**Construct**	**Operation**		**Regulator**	**Regulatee**	**Occupant**	
✓			As-designed not as-built energy assessment	✓			[1],[2]
✓			Changes in code provisions	✓			[1],[3*],[4*]
✓			Divergent energy performance requirements set in the regulation cause confusion on levels of compliance needed and negatively affects the compliance with rules[2]	✓			[5]
✓			Emphasis level on energy efficiency issues by building control officers	✓			[1],[3*]
✓			Flawed energy assessment tool	✓			[1], [6*],[7*],[8*],[9],[10],[11]
✓			Inconsistent code interpretation in different states	✓			[1],[4*],[5],[9]
✓			Lack of accountability settings	✓			[1],[2],[4*],[5]
✓			Lack of mandatory disclosure of energy performance	✓			[1],[2]
✓			Lack of options to prove compliance	✓			[1]
✓			Sign-off culture among (private) surveyors and energy assessors	✓			[1]
✓			Skills insufficiency and lack of training for building control officers	✓			[1],[2],[3*],[10],[15]
✓			Unclarity in the regulation	✓			[1],[4*],[5]
✓			Under resourcing of inspectors within Local Government	✓			[1],[9]
✓			Gaming around different compliance pathways		✓		[11]
✓			Ignorant and apathetic attitude toward energy efficiency provisions		✓		[1],[12]
✓			Low compliance-related knowledge		✓		[1],[2],[3*],[4*],[14],[15]
✓			Moral duty to obedience		✓		[13*]
✓			Shopping-around culture among regulated building practitioners		✓		[1]
✓			Social norms to comply		✓		[12],[13*]
✓			Unbuildable design		✓		[1]
✓			Consumer lacking interest on energy-efficient design			✓	[1],[2],[12],[15]
	✓		As-designed not as-built energy assessment	✓			[1],[2]
	✓		Changes of code provisions	✓			[3*],[4*]
	✓		Lack of accountability settings	✓			[1],[2],[4*],[5]
	✓		Lack of mandatory inspection	✓			[1],[2],[9],[15]
	✓		Lack of performance testing of building products	✓			[1],[9],[15]
	✓		Builders' removal of energy-efficient features or designs		✓		[1],[10]
	✓		Ignorant and apathetic attitude toward energy efficiency provisions		✓		[1],[12]
	✓		Low compliance-related knowledge		✓		[1],[2],[3*],[4*],[13*],[14],[15]
	✓		Moral duty to obedience		✓		[13*]
	✓		Social norms to comply		✓		[12]
	✓		Substitution of high-efficiency version products		✓		[1],[15]
		✓	Occupant behaviour			✓	[1],[6*],[7*],[10],[16*],[17*]

List of referenced articles

1	Pitt & Sherry (2014)	7*	Ouf et al. (2019)	13*	May (2004) USA
2	Harrington and Toller (2017)	8*	Choi (2017)	14	NEEBP (2016)
3*	Pan and Garmston (2012)	9	Bannister et al. (2018)	15	Donaldson (2017)
4*	Nwadike and Wilkinson (2021)	10	Enker and Morrison (2020)	16*	Martinaitis et al. (2015)
5	Miller et al. (2020)	11	O'Leary et al. (2018)	17*	Gill et al. (2010)
6*	Carpino et al. (2020)	12	Enker and Morrison (2019)		

[2] In the NCC 2022, Class 1 dwellings will be required to achieve 7-stars NatHERS and the corresponding heating and cooling load limits. Class 2 dwellings will be required to achieve an average of 7 stars and minimum of 6 stars.

As per the coding structure in Figure 2, during design stage, 12 referenced articles ([1]-[11],[15]) discussed influencing factors that are generated from the regulators side. 9 works ([1]-[4],[11]-[15]) concerns factors from regulatees side, and 4 articles ([1],[2],[12],[15]) relate to factors from occupants. In the construction phase, 7 literature ([1]-[5],[9],[15]) relates to factors from regulators and 9 articles ([1]-[4],[10],[12]-[15]) to factors from regulatees. In the operation stage, 6 articles ([1],[6],[7],[10],[16],[17]) indicate factors from the occupants side.

Observing the overall building project cycle, following main findings can be elicited. First, the energy rating tool is identified as one of the most significant influencing factors. 7 of chosen literature indicates the flawed design of the energy assessment tools in that they do not reflect actual energy usage, or they generate varied simulation results even on a same building project, which could be potentially gamed by practitioners through switching to different tools to achieve a compliant result when the project is actually under-compliant (O'Leary et al., 2018). Second, knowledge level toward compliance with energy requirements is low for all stakeholder groups. Building control officers have insufficient skills to assess energy compliance, while building practitioners have not mastered energy-efficient techniques or knowledge regarding available compliance options that are offered in the NCC. Third, implementation and enforcement are also a paramount challenge. Among others, inconsistent implementation and interpretation of the NCC energy requirements among different states and territory, lack of mandatory inspection regime on energy efficiency feature especially during post-design stage, and inadequate tracking of building products and systems' information are all considered significant. Fourth, human behaviours relating to building occupants and residential building practitioners play a central role in contributing to the current compliance status. As the building end-users, occupants generally have low awareness of energy efficiency. Resultantly, the way they use the buildings has greatly undermined the energy-efficient design's value. From the building practitioners' side, many factors are manifested which include ignorant attitude toward low carbon and energy efficiency, social pressure from clients, and personal moral concerns.

5 Conclusion and Further Research

This research has conducted a review on the literature in order to explore main issues in compliance with low-carbon requirements within the residential building industry, with a focus in Australia, supplemented by relevant evidence in other countries. It is uncovered that countries worldwide have developed and implemented a series of policies, which are meant to be a powerful and preferred instrument for delivering improved building performance outcomes. However, analysis shows that the effectiveness of these requirements has been negated by problems with compliance issues along the construction stages. As key research findings, influencing factors to compliance can be attributed to all stakeholder groups based on a compound of technical, social and behavioural aspects. Considering the issues discovered in the selected literature, a set of gaps warranting further research is discovered.

The first future research area relates to the enforcement regimes from the regulators side, which is deemed as a serious challenge in the Australian low-carbon residential building industry (Bannister et al., 2018). Special focus can be put on the quality assurance mechanism which facilitates the implementation, tracking and verification of compliance with the NCC energy efficiency requirements.

Furthermore, there is an urgent need to develop an energy rating tool that can better reflect better true occupants' practices upon various residential building types (Ouf et al., 2019)

In addition, future studies should draw notions from behavioural economics to enhance building occupants' awareness of the benefits of energy efficiency (Enker & Morrison, 2020).

The fourth area is to investigate practitioners' compliance behaviour. It is implied by Pan and Ning (2015) and Enker and Morrison (2019) that there is insufficient research on understanding on why practitioners perform such compliance behaviour as they respond to these low-carbon requirements, and under what situations will their behaviour be triggered to change (Pan & Ning, 2015; Enker & Morrison, 2019). This overlook in the research works has caused significant divergence between low-carbon requirements' intentions and actual compliance behaviour (Pan & Ning, 2015). It is important to understand why practitioners perform such compliance behaviour as they respond to these low-carbon requirements, and under what situations will their behaviour be triggered to change.

6 Acknowledgement

The authors thank Mr Stephen Kip (Board member of the Australian Building Codes Board) in providing insights on the current research topic with his depth of knowledge and experience in the area of Australian building regulations.

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A Review of Using Augmented Reality to Improve Construction Productivity

Zhidong Xu[1]*, Mostafa Babaeian Jelodar[1], Zhenan Feng[1], and Brian HW Guo[2]

[1]School of Built Environment, Massey University, NEW ZEALAND
[2]Department of Civil & Natural Resources Engineering, University of Canterbury, NEW ZEALAND

zxu1@massey.ac.nz; m.b.jelodar@massey.ac.nz; z.feng1@massey.ac.nz; brian.guo@canterbury.ac.nz
* Corresponding author

Abstract:
Low productivity has been a long-term issue in the construction sector. Human-made errors, lack of experience, and poor management are the common factors that cause low productivity. Low productivity can result in significant delays and economic losses to construction projects. Researchers have introduced innovative approaches to improve construction productivity, such as Augmented Reality (AR). Previous studies focused on state-of-art AR applications in different construction domains. There is little literature review studying AR applications in construction activities from the technical aspect and impact on productivity. This paper reviews AR technologies in the planning, design, and construction phases of construction projects and studies the leverage of AR technologies in improving construction productivity. This paper classifies AR applications by features that facilitated construction activities and improved productivity factors. This paper demonstrates the capability of AR to improve construction productivity.

Keywords:
Augmented reality, Construction industry, Literature review, Productivity

1 Introduction

Poor productivity has always been a critical problem in the construction industry (Woetzel et al., 2017). Innovation is urgently needed to overcome this issue. Over the last decade, the rapid development of Information and Communication Technology (ICT) has accelerated the arrival of the Fourth Industrial Revolution (Industry 4.0) with cyber-physical systems being the essential features (Lasi et al., 2014). One of the emerging technologies to facilitate cyber-physical systems is Augmented Reality (AR). AR is a technology that superimposes virtual objects into the real world, which enables interaction with virtual objects and enhances users' perception of reality. AR applications have been widely used for the assembly and maintenance in the manufacturing industry (Egger and Masood, 2020). . Although the construction industry is behind other industry, such as healthcare and retail adopting AR solutions, more studies have focused on utilising technology in the construction industry (Noghabaei et al., 2020). AR could be a useful tool to facilitate information flow and exchange for construction activities. Nassereddine et al. (2020) reviewed 23 AR use cases in the construction industry and found that AR can enhance decision-making, improve collaboration and communication, improve productivity, and reduce rework. Rankohi and Waugh (2013) reviewed AR applications in architecture, engineering, construction and facility management disciplines. The result showed that previous studies were highly interested in monitoring project progress through superimposing the as-planned and as-built status. Wang, et al. (2013) reviewed hundreds of journal articles on AR applications in built environments published between 2005 and 2011.

They classified AR applications according to their concept, implementation, evaluation, and industrial adoption. The result showed that most studies were still in the evaluation layer and no study was in the industrial adoption layers. Li et al. (2018) studied several AR prototypes for construction safety management. They found that safety inspection and hazard identification were the major domains applied to AR. Hajirasouli, et al. (2022) reviewed AR applications in the design and construction phases and illustrated AR's benefits. They demonstrated that AR might reduce cognitive workload and data overload in heavy machine operation and assembly tasks. Moreover, Xu and Moreu (2021) reviewed AR applications in civil infrastructure construction and found that underground utilities, structure health detection and discrepancy check were the main research areas. The literature demonstrates that AR applications are becoming popular in the construction industry. AR has different forms, features, and capabilities to assist in construction activities. However, the technical details of AR for different types of construction activities remain unclear. More importantly, there is little evidence on whether AR applications can improve productivity in the construction industry. This study aims to bridge the gap by conducting a literature review. Three research questions were raised: (1) What construction activities have been investigated with AR applications? (2) How can AR applications be utilised in those construction activities? (3) How can AR applications impact the productivity of those construction activities? By answering the research questions, this study classifies AR applications based on their features and use cases (i.e., construction activities). This study reveals the impact of AR applications on the productivity of construction activities.

2 Methodologies

This study follows the literature review method proposed by Khan et al. (2003). Scopus and Web of Science were used as the databases. Both journal articles and conference papers were considered in this literature review. The first part of the search keywords is: "augmented reality" OR "mixed reality" OR AR. We included mixed reality because there is a mixed used of mixed reality and augmented reality in the literature since mixed reality shares a similar meaning to augmented reality. In many cases, mixed reality is the superset of virtual reality and augmented reality (Azuma, 1997). The second part of the search keywords is: "construction industry" OR AEC OR "civil engineering". In order to obtain the maximum coverage of the literature about AR and construction, we did not use any further keywords (e.g., productivity) to narrow down the search. An operator, AND, was used to combine search keywords. The search fields were set to titles, abstracts, and keywords. The search was conducted in November 2021. There were 345 results returned from Scopus and 624 from Web of Science.

The Preferred Reporting Items for Systematic Literature Reviews and Meta-Analyses (PRISMA) approach was used to filter the search results (Page et al., 2021), as shown in Figure 1. Firstly, 127 duplicates were removed. Secondly, articles were removed if they met the following exclusion criteria: (1) The article has no relation to augmented reality. (2) The article does not propose an AR-based prototype. (3) The proposed prototype is not designed to assist construction activities. For instance, articles focused on education or training were removed.

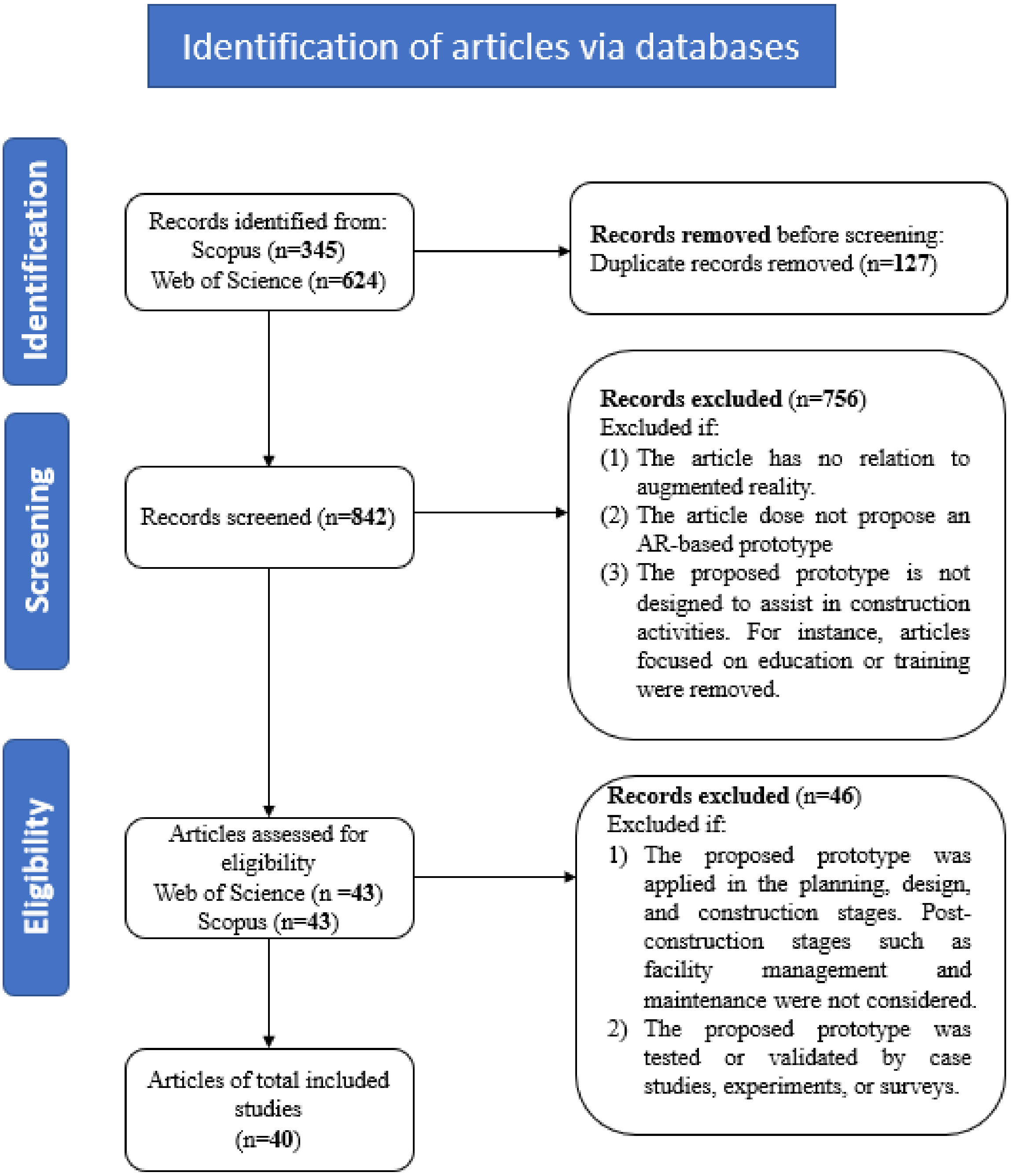

Figure 1. PRISMA methodology flowchart

In this step, 756 articles were excluded, with 43 remaining from Scoups and 43 from Web of Science. Lastly, we read the full text of the remaining 86 articles and applied the following inclusion criteria: (1) The proposed prototype was applied in the planning, design, and construction stages. Post-construction stages such as facility management and maintenance were not considered. (2) The proposed prototype was tested or validated by case studies, experiments, or surveys.

As a result, 40 articles remained, consisting of the eligible papers for this literature review. The eligible articles contain 30 journal articles and ten conference papers published between 2007 and 2022 (Figure 2).

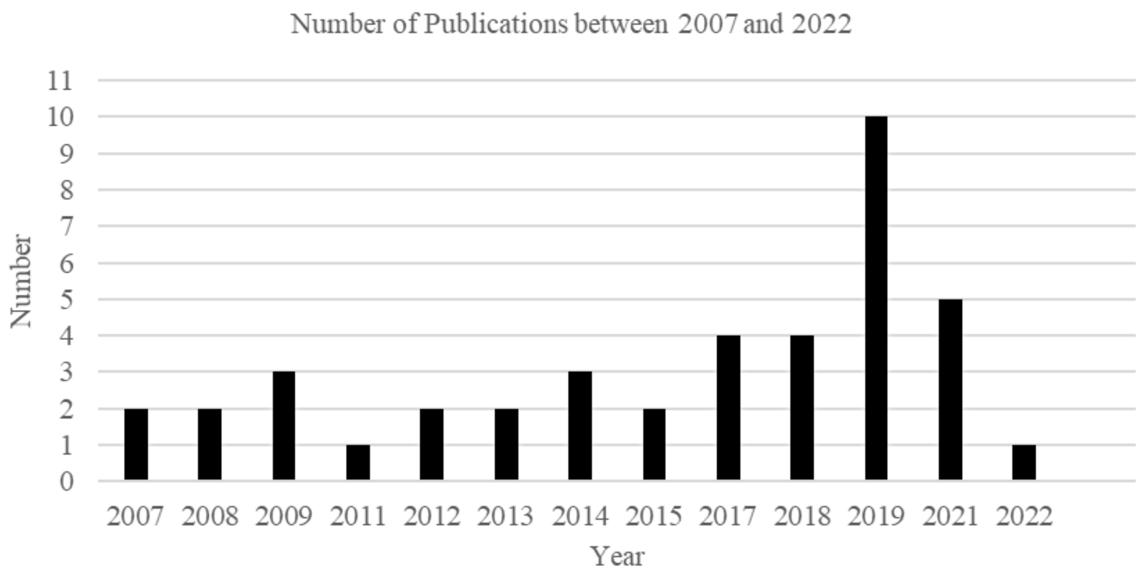

Figure 2. Number of publications from 2007 to 2022

3 Results

Based on the eligible articles, this study analyses the features, displays, processes, and tracking methods of AR prototypes (Figure 4). The width of the node represents the number of articles. Then, this study investigates the impacts of AR applications on the productivity of construction activities by studying the experiment in each article.

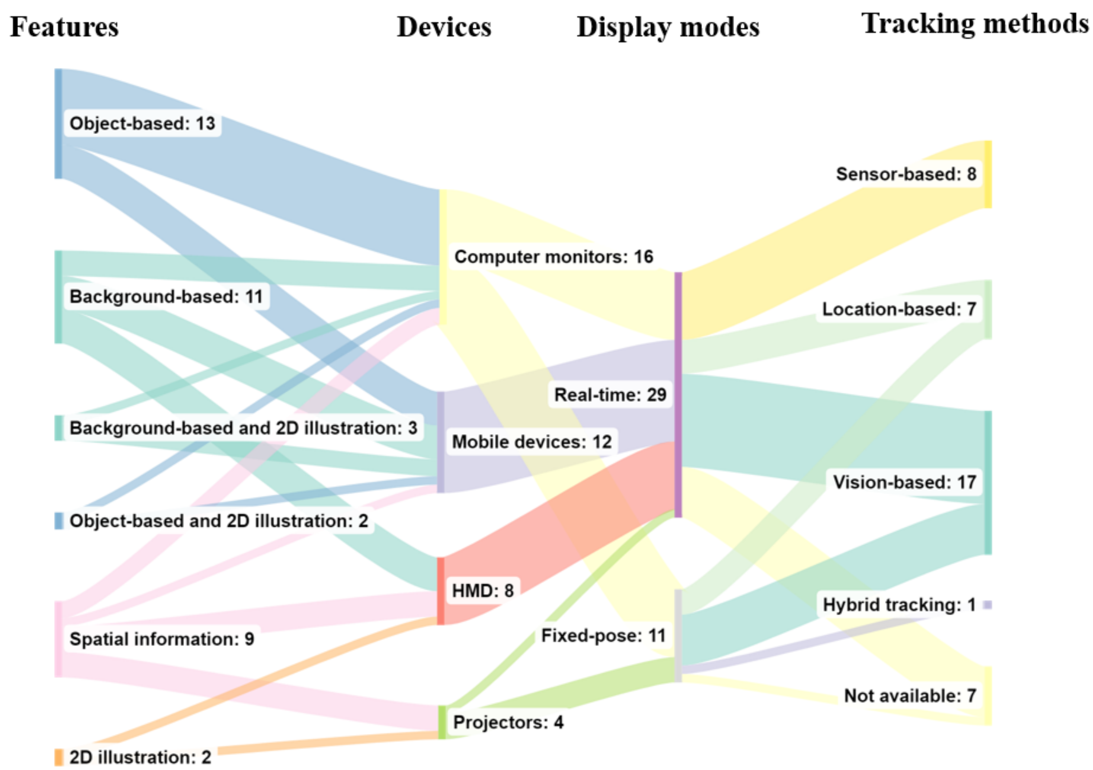

Figure 3. The connection between AR functions, display modes, and tracking methods

3.1 Features

This study identifies four major features of AR from the eligible articles: background-based, object-based, spatial information, and 2D illustration. The background-based feature means that real-world images or videos are used as the background of virtual content. The virtual content do not have real-time interaction with the real world. For instance, designers can stand around a table and visualise a 3D model on top of a 2D drawing via smartphones (Garbett et al., 2021). One advantage of using background-based AR is that users can perform physical measurements and interaction with virtual models in the real world. For instance, users can review the maintainability issues in their design by viewing a virtual model and checking if the facilities are reachable by their hand (Khalek et al., 2019). Users can use their arms to reach out and gauge the distance between themselves and virtual objects. Also, users can review virtual models while carrying out other works in the real world (Hui and Ieee, 2015, Sangiorgio et al., 2021). In some cases, a real-world image provides an intuitive feeling for users to interact with virtual models. According to this review, 14 of 40 articles propose AR prototypes based on this feature. The most popular construction activities facilitated by this feature include construction site transport simulation (Chen and Huang, 2013, Behzadan and Kamat, 2008), and heavy equipment operation simulation (Wang et al., 2022, Kim et al., 2012, Hammad et al., 2009).

The object-based feature means that virtual objects are overlaid or superimposed onto real-world objects. Benefiting from this, users can inspect the misalignment of constructed building components against design models by overlaying virtual models onto real-world objects (Mirshokraei et al., 2019, Georgel et al., 2007, Kumar et al., 2019, Shin and Dunston, 2009). Zhou et al. (2017) proposed an AR prototype based on this feature to check the displacement of adjacent tunnel segments. This prototype casts a geometric shape over tunnel segments, which requires a highly accurate tracking method. In addition to site inspection, this feature enables construction progress monitoring. Users can superimpose as-planned building models onto as-built buildings in the real world (Mani et al., 2009, Golparvar-Fard et al., 2011, Jiao et al., 2013). Moreover, this feature allows real-time interaction. For instance, AR-based interactive design permits users to annotate the virtual models superimposed onto the building components and support site documentation (Zollmann et al., 2014, Kim et al., 2018). Costa et al. (2017) introduced an AR prototype to facilitate design processes, where users can add virtual building components to a physical architectural model. A spatial relationship between virtual building components and physical models is established, which provides an intuitive understanding to designers (Carozza et al., 2014). In this review, 15 of 40 articles propose prototypes based on the object-based feature. The most popular use case of this feature includes site progress management (Zollmann et al., 2014, Meza et al., 2014, Mani et al., 2009, Jiao et al., 2013)and discrepancy inspection (Mirshokraei et al., 2019, Georgel et al., 2007, Shin and Dunston, 2009, Zhou et al., 2017, Kumar et al., 2019).

Regarding spatial information, this review identifies two types of information: directions and positions. Kim et al. (2017) used an AR device to display directional information, which points out the direction of hazards. A directional sign informs users where a potential risk could come from, therefore, enhancing safety awareness. Positioning means that AR applications can tell users where an object should be placed in the real world. DaValle and Azhar (2018) used AR to superimpose electrical conduits and plumbing pipes onto wall frames. Benefiting from this, workers can know the precise positions on site to install the conduits and pipes. Similarly, Degani et al. (2019) proposed an AR application to project an interior plan drawing onto the relevant floor. Therefore, users can intuitively tell the room's layout. In addition to indicating positions in the real world, AR can also show the spatial relationship within virtual objects. This can assist in assembly tasks because AR applications can demonstrate assembly processes by assembling virtual objects (Kontovourkis et al., 2019, Bhatt et al., 2017, Hou et al., 2015). In this review, 9 of 40 articles show AR prototypes featured spatial information. The most popular construction activities supported by this feature are assembly (Bhatt et al., 2017, Degani et al., 2019, Kwiatek et al., 2019, Kontovourkis et al., 2019, Hou et al., 2015).

It is also popular to use AR for 2D illustration (e.g., images or text) so the users can directly access information within their sight. Yeh et al. (2012) proposed an AR prototype to project 2D drawings onto plain surfaces so that inspectors can easily view drawings anytime on site. Similarly, Dai et al. (2021) proposed an AR-based communication method for safety inspectors. Safety inspectors can access safety manuals through AR devices on site. Also, Kim et al. (2018) used an AR application to display construction schedules when as-planned models are aligned to as-built site images. In this review, 7 of 40 articles demonstrate AR prototypes designed to deliver 2D illustrations. This function usually collaborates with the background-based (Garbett et al., 2021)or object-based (Mirshokraei et al., 2019) feature to enhance the interaction of the prototypes.

3.2 Displays

This review classifies the display devices of AR into four categories: head-mounted displays (HMDs), computer monitors, projectors, and mobile devices (e.g., smartphones and tablets). Eight articles choose HMDs as the display device of their prototypes. All HMDs mentioned in these articles are Microsoft HoloLens. Users can use their hands to assemble building components (Kontovourkis et al., 2019) or operate heavy equipment virtually via a controller (Kim et al., 2012) while wearing HMDs. Thanks to the wireless solution provided by Microsoft HoloLens, users can move freely (DaValle and Azhar, 2018). Sixteen articles use a computer monitor to view virtual content. One primary reason for using computers as an AR platform is that computers provide better computing performance when dealing with a high volume of data. For instance, Kumar et al. (2019) introduced a registration method based on point clouds. Therefore, a high-spec computer was necessary for the AR platform. Twelve articles introduce smartphones or tablets as the platform to deliver AR applications. Zollmann et al. (2014) argued that mobile devices such as smartphones are more suitable for outdoor activities. Lastly, four articles introduce projection-based AR applications. Projectors were used to project 2D illustrations onto walls or floors.

In addition to different types of display devices, this review also identifies two types of display modes: fixed-pose and real-time displays. Fixed-pose displays mean that the registration of virtual content is static and retrospective, which relies on images or videos captured by fixed-pose cameras as the background of virtual content. Virtual content can be updated when a camera captures a new image or video. In contrast, the registration process of real-time displays is dynamic, and tracking and registration take place synchronously in real time. Prototypes that used HoloLens or mobile devices are all real-time displays. Three of four projection-based prototypes are fixed-pose displays. The other one is real-time because a depth sensor was equipped with a projector (Degani et al., 2019). Most prototypes using computer monitors are fixed-pose displays. Only two articles proposed prototypes based on real-time displays with computer monitors. The porotypes can live stream videos to monitors and superimpose virtual content to videos (Kumar et al., 2019, Shin and Dunston, 2009).

3.3 Tracking methods

This review discovers four tracking methods: sensor-based, vision-based, location-based, and hybrid. Sensor-based tracking techniques track the user’s movement or position through magnetic, inertia and odometer sensors. Also, two or more sensors can be combined to track objects, which is called sensor fusion (Zhou et al., 2008). Vision-based tracking techniques use real-world images and calculate the camera pose through computer vision. There are two types of vision-based tracking techniques: marker-based and markerless-based. In addition, location-based tracking obtains a user’s location via the Global Navigation Satellite System (GNSS) or users defining their locations. Lastly, Hybrid tracking techniques combine sensing technologies with computer vision methods (Zhou et al., 2008). For example, the gyroscope can measure the rotation of the camera pose, and the measurement result can be used to enhance the accuracy of the computer vision technique and accelerate the processing time.

Eight prototypes are sensor-based AR. LiDAR is the most common technique in this case. Only one prototype utilised RFID for tracking due to the demand for accuracy (Schweigkofler et al., 2018). Moreover, this prototype was designed for indoor use. Therefore, RFID is more suitable. Seventeen prototypes used vision-based tracking. Ten prototypes use markers to estimate camera pose, while the rest are markerless. Markerless tracking requires computer vision techniques. For instance, Mani et al. (2009) used scale-invariant feature transform (SIFT) to detect and match the key points from site photographs and then used structure from motion (SfM) to estimate camera pose.

Seven prototypes used location-based tracking. GPS was used to track a user's location. Meanwhile, the built-in gyroscope of AR devices tells the orientation of a user's view (Fenais et al., 2019, Behzadan and Kamat, 2008). Another type of location-based tracking utilises the position viewpoint (Tavares et al., 2019). If the viewpoint is a fixed-pose camera, the spatial relations between the camera and real-world objects can be calculated via coordinates. Also, if a user uses a mobile device, their standing position can be incorporated into AR by inputting their coordinates (Yeh et al., 2012, Wang et al., 2022).

One article proposed a hybrid method for tracking (Zhang et al., 2021). The authors used simultaneous localisation and mapping (SLAM) to track the orientation of a user’s view and GPS to locate the user’s position (Zhang et al., 2021). Seven articles did not describe their tracking methods.

3.4 Impacts on productivity

This section discusses the construction activities supported by AR applications and their impacts on productivity. Eight types of construction activities supported by AR applications have been discovered (Table 1). AR applications are mostly investigated in two construction activities: progress management and design review. These two activities do not rely on the precise alignment of virtual and real objects since current AR technologies may not provide precise registration and positions. Positioning and layout tasks require an extremely precise overlay of virtual objects. Therefore, it could be the reason that few studies have focused on them. Eleven articles demonstrated experiments to test the impact on construction productivity. These experiments tested three construction activities: progress management, discrepancy check and. These experiments measured labour time, cognitive load, and accuracy to study the impact of AR applications on productivity.

Table 1. Number of articles on classified construction activities

Construction activity	Description	Number of articles
Progress management*	The as-planed model is superimposed over the as-built building.	9
Design review	AR provide an intuitive understanding and collaborative platforms for designers to review their design.	9
Discrepancy check*	AR replaces the traditional error measurement method by overlaying the model to the correct position.	6
Planning simulation	Users simulate the construction process in the real world before starting construction.	6
Assembly*	AR supports the pipes and structural components assembly tasks.	5
Hazard notice	The potential Hazzard source is highlighted, enhancing workers' awareness of the hazard.	3
Positioning	AR facility structural components fabrication by displaying the welding place on the component.	1
Layout	AR presents the layout by projecting the 2D drawing on the floor or wall.	1
* The impacts of AR applications on productivity have been investigated		

Experiments of assembly tasks were usually designed to measure the time taken to accomplish an assembly task. Kwiatek et al. (2019) found that AR can reduce the time for workers with low experience to understand design information. The test result showed that the application reduced the time required to absorb design information by 50%. Furthermore, the assembly facilitated by AR is more accurate than conventional 2D drawings. Hou et al. (2015) tested the cognitive load of workers carrying assembly tasks. They conducted questionnaires for each participant and found that AR can significantly reduce the mental load. Shouman et al. (2021) analysed the impact of AR on enhancing interpretation and collaboration in the design phase based on the result of a survey. Compared to the conventional 2D sketching approach, AR-based design had a significant impact on design interpretation. Sangiorgio et al. (2021) conducted an experiment showing that AR can reduce the decision-making process time and improve efficiency at the design stage. The authors compared the AR-based decision-making approach with the Analytic Hierarchy Process approach and discovered that the AR approach reduced the time by 77% when deciding the panel material. Shin and Dunston (2009) designed an experiment to test the accuracy of anchor bolt offset measurement and measure inspection time. The result showed that utilising AR can shorten the setup and work time by 85% compared to a conventional method using a high-precision survey instrument. However, accuracy was slightly lower than conventional methods. The rest of the 29 articles did not investigate the impact of AR on construction productivity. They showed experiments to only test the performance of their prototypes.

4 Conclusion

This literature review studies AR applications in the construction industry. It reviews 40 articles that cover AR applications in the plan, design and construction phases. All proposed prototypes are analysed based on AR features and applied construction activities. This review reveals the technical details of these AR applications. This review demonstrates different AR features and analyses the use cases for different construction activities. The result shows that positioning and layout tasks are barely studied. Moreover, most proposed prototypes assist the assembly task by delivering step-by-step instructions. Few prototypes identify the assembly components' position in the real world. However, installation works on the construction site require the worker to place the assembly components in the specified position. More research in AR to assist the assembly task should consider showing the components' position in the real world.

Most proposed AR prototypes use vision-based tracking techniques. Hybrid tracking techniques can provide more robust tracking than vision-based tracking. Therefore, further research could adopt hybrid tracking techniques, such as integrating computer vision and sensors to develop prototypes.

This review investigates the impact of AR on the productivity of construction activities. Factors such as time, accuracy and cognitive load have been measured in experiments. To achieve the full industrial adoption of AR and utilise AR to improve productivity, more efforts are required to explore the impact on human factors such as mobility and safety issues. For example, the virtual content may block their vision to the extent that they cannot notice potential risks on the construction site. Besides, it is recommended that more studies should be conducted to assess productivity factors systematically in a single construction task.

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A Method for Establishing an Infrastructure of Play within the Houses of Apartment Buildings

Dalia Bukhamsin
School of Architecture & Built Environment, The University of Newcastle University Dr. Callaghan, NSW 2308, AUSTRALIA

daliajafara.bukhamsin@uon.edu.au
* Corresponding author

Abstract:
An urban environment requires various forms of infrastructure to sustain living within its boundaries. The main purpose of such infrastructure is to connect residential areas to the city and its environment. For those who live in apartment buildings, many of these infrastructures provide the core services that enable many houses to exist above the ground and within one building. Some of the challenges with apartment buildings are inflexible and inadaptable. One of the interventions adopted in response to these challenges is the creation of PLAY-driven. PLAY is the relationship between understanding spatial qualities and spatial design when planning houses. The study aimed to evaluate the techniques and systems that create PLAY within a house. Specific objectives included; To evaluate the extent to which PLAY exists within apartment houses and determining whether it is a desirable characteristic; To design furniture and fixtures for apartment houses that enable a greater capacity for PLAY; and To analyse how the design of future apartment houses can incorporate PLAY. Regarding methodology, the study adopted a literature review and a case study, which involved analysing the Honeysuckle HQ apartment complex project, an apartment in Newcastle, Australia. The study outcomes indicated that adjacency could be exploited to enhance apartments' functionality. The study further emphasises the need for enhanced structural and functional features, including ventilation, connectivity, and outdoor space. Most importantly, the study found that architects must ensure that their apartment's designs can be aligned with the individual needs of occupants.

Keywords:
Adaptability, Architecture, Infrastructure, Living patterns, PLAY.

1 Introduction

An urban environment requires various forms of infrastructure to sustain living within its boundaries. The main purpose of such infrastructure is to connect residential areas to the city and its environment (Boverket, 2016). The past decade witnessed increased urbanisation, which further translated into increased city population density. Subsequently, the affected cities globally experienced challenges, including insufficient housing for the growing population, inflexibility, and inadaptability (Hulchanski, 2021). It further meant reduced government's ability to invest inhabitant-centered projects to the detriment of urban dwellers globally. One of the interventions adopted in response to these challenges is the creation of PLAY-driven buildings. According to Taipale (2012), PLAY is the relationship between understanding spatial qualities and spatial design when planning houses. Therefore, the purpose of this study was to analyze the organisation of spaces within houses by focusing on the extent to which they exhibit PLAY. The rationale was that given the changing trends in housing demands, it is essential to determine the functional characteristics of PLAY that are adaptable to lifestyle changes and ageing (Hulchanski, 2021). The thesis sought to analyse and resolve challenges between apartment building occupants and their changing preferences in their lifetime. Another essential contribution of the study was that it sought to identify new approaches in architectural practice concerning apartment houses. The goal was achieved by analysing the current apartment houses' organisational, spatial boundary conditions, and living patterns and determining their capacities for PLAY. In this regard, the study identified methods for analysing an apartment house's capacity for PLAY.

The first step in the analysis involved examining the organisation of the houses' spaces, their boundary conditions, and the extent to which they exhibit PLAY. The second step involved this analysis while reviewing precedents and literature on PLAY within house living. Finally, the analysis further reviewed the houses' potential to develop better capacity for PLAY through design. Ultimately, the study explored houses' potential to be transformed into solutions that comply with PLAY-based design.

Apartment houses are commonly characterised by one open facet to the outside, while all other sides are bound by walls, adjoining houses, and corridors. According to Magdziak (2019), the partitions and offerings of an apartment are difficult to restructure or redesign, given the structural interdependence among the units in a block. Such constructions, nonetheless, make cities more compact, which explains their accelerated mushrooming globally. In their study, Hulchanski (2021) argue that most densely populated countries have more than 50% of their populations residing in apartments. The rationale is that with a higher population in the cities, the demand factor hikes property prices beyond the reach of most city dwellers. Subsequently, apartments become a fallback plan given their comparatively affordable rents or mortgage.

Examples of such countries include Germany, Switzerland, and Italy. In the Australian context, the unprecedented growth in urbanisation has led to similar results, with land and property prices rising. Boverket (2016), for instance, argues that in 2018, the Australian population grew to 25 million, a factor that informed hiked property prices and altered the choice of housing. A similar observation is evident in Saunders et al. (2022) study, which observed that compared to 1991, the demand for housing in Australian urban areas increased by 78%. With the rapidly shifting demographic trends, one can only speculate the impacts such would have on the current housing in Australia.

Shifting demographic patterns imply that apartment houses designed a decade or two ago can no longer accommodate the needs and standards of their users. For instance, in their study Szafraniec (2017) observed that most people who preferred living in apartments were single or couples without children. Recent years have; however, witnessed families residing in apartments. For example, 50,000 families with children in Australia lived in apartments in 2011, which increased by 50% in 2016, when 79,000 families lived in houses. As a result, there is a need to ensure that they are extensively renovated or demolished to give room for relevant houses (Slaughter, 2001). However, several factors could hinder such changes from being actualised. The first among these include time and resource constraints, alongside the number of wastes likely to be produced. For instance, the construction industry is estimated to be responsible for between 30% and 40% of the global waste produced (Taipale, 2012).

Consequently, this research aimed to evaluate the techniques and systems that create PLAY within a house. Houses should meet their occupants' complementary and competing needs and be able to accommodate ongoing changing needs. According to Brown and Katz (2009), such can be achieved through adopting structural aspects that are marketable and inexpensive. PLAY identifies various elements of a structure that can be optimised in a building's architecture to accommodate different lifestyles and ways of living. In this regard, the residents of such houses will experience better outcomes (Fisher-Gewirtman, 2017; Nazmy & Kim, 2018; Schneiderman, 2018). The justification is that PLAY design combines spatial qualities, built environment, and contemporary practices to create structures that meet the greatest outcomes for users and relevant stakeholders. Subsequently, the specific objectives of the study included evaluating the extent to which PLAY exists within apartment houses and determining whether it is a desirable characteristic; in designing furniture and fixtures for apartment houses that enable a greater capacity for PLAY, and analysing how the design of future apartment houses can incorporate PLAY.

2 Literature Review

2.1 The Context of PLAY

One of the challenges currently experienced with housing in Australia is that structure is yet to meet the occupants' expectations and preferences. The conflict can be attributed to a lack of PLAY in the houses, which is evident in the domestic layout (Menzies et al., 2016). Pricing remains the most significant influence in the choice of apartments in Australia, with a bigger apartment implying a more expensive house (Saunders et al., 2022). More people currently reside in the apartments due to reduced travel distances, experiences, and recreation. Weetman (2019) further observes that individuals and families prefer apartments as they imply reduced costs in caring for lawns, reduced mortgages, and time-consuming home upkeep. Millennials are the most attracted to the apartments, given their preference for a new community-based multi-family way of living consistent with such living spaces. Nonetheless, such preferences change as they advance in age, a factor that emphasises a need to ensure that apartments are flexible living areas.

One of the factors that necessitate the need for adaptable housing is that more individuals today understand the functionality that residences ought to provide. Weetman (2019) remarks that such knowledge has necessitated attempts by investors to attempt making internal changes to existing apartments. One evident aspect of these attempts involves investing the least resources possible without rebuilding. According to Gusheh et al. (2021), the most common intervention today involves creating adaptable housing for people with disability. Such improvements are sometimes even undertaken by tenants considering that it is cheaper than finding or moving to a new apartment.

2.2 Localising the Case Study

The analysis was focused on Newcastle, given that almost 32% of its population resides in apartment houses. The city is also the seventh-largest in Australia and is experiencing dynamic development. Just like any other city in Australia, its housing market is expensive. Another factor in choosing this location is that it is currently experiencing intense investment in construction, with most of these buildings earmarked for residential purposes. In this regard, the city's faster growth and development are likely. Therefore, Newcastle was further considered since it still has areas that can be developed. Additionally, the city has the typical living conditions and resource and infrastructure availability that reflects Australia. Subsequently, it is a representative sample of Australia.

The case study focused on analysing the floor space of the existing apartment houses, especially within emerging and newly constructed apartment complexes. The PLAY framework analysed the floors' core components, including structural, functional, and cultural functions. Specifically, the study focused on the Honeysuckle HQ apartment complex project and its floor plans (Szafraniec, 2017). The apartment presents a new prototype of an apartment complex, which can be analysed to determine whether developers and contractors consider the changing needs of modern consumers, environmental changes, technological advancements, and the transformation of the housing market. The study further focused on other floor plans developed in the past five years to observe whether there had been substantial changes that reflect emerging needs in living spaces. The changes in economic structure have the most significant impacts on the desired floor spaces. For instance, with Australia becoming a service and knowledge-based economy, more jobs are centered in the cities, including Melbourne and Sydney. In addition, the change in economic structure implies a change in people's social preferences. For instance, more people would want to stay near their work locations but are unlikely to afford the housing costs (Saunders et al., 2022). As a result, affordable houses are often located away from the cities in the suburbs or away from their location of work or services.

Nonetheless, houses located near business hubs are known to enjoy are connected to the best job opportunities, best schooling facilities, best shopping malls, best parks and gardens, and best sporting and cultural facilities. Subsequently, there is a higher demand for houses. Szafraniec (2017) further weighs into this discussion by observing that in contemporary family units, both parents are working. As a result, they desire to live closer to their workplaces to spend more time with their families instead of spending long hours in transport. Another factor is that parents have become busier; thus, maintaining a big house becomes challenging. As a result, they prefer socialising through eating out, attending concerts, and participating in cultural activities. Such are attainable for those living in apartments near cities, thus their popularity in Australia. Another concern is that recent years have witnessed the shrinking of the average house in Australia. While the average size of an Australian house was 128.8 square meters in 2018, it was over 140 square meters in 2010, over 130 square meters in 2012 and 2015.

2.3 COVID-19 and Adaptable Housing

The housing industry was one of the most affected industries in Australia following the outbreak of COVID-19 in 2019(ABS,2022). The rationale was the industry relies on immigrants and international students, who were restricted by travel limitations at the time (Uribe, 2020). After the pandemic, more families have registered their desire to expand their homes. The rationale is to make their houses more adaptable to the different living scenarios.

2.4 Emerging Need to Change a House

2.4.1 Change in Life Events

Previous research indicates that 87% of Australians live in cities, and most reside in houses, not apartments. Nonetheless, 29% of those residing in apartments are between 25 and 34 years (ABS, 2016). The average age for those who live in houses, each male and female occupant, is 33 years. A further comparison indicates that women live longer in houses than their male counterparts. One of the likely contributing factors is that the female gender has a higher life expectancy than the males. Additionally, 48% of families occupied one single dwelling regardless of the members' age differences. In this regard, individuals resided in houses that were expected to meet the differing needs of a 20-year-old as well as a 60-year-old.

2.4.2 Design Issues in Infrastructure

It is extremely difficult to design a house where a person can stay throughout their lifetime. According to Lawson (2019), this is attributed to the fact that one's needs are likely to change drastically as one spends time in the facility. At the same time, it is difficult for one to change houses in accordance with their needs constantly. Inflexible and inadaptable apartments further worsen such challenges. Nonetheless, there have emerged mechanisms through which apartment buildings can be flexibly designed. AHURI (20209) proposes that pillar-based structures can help mitigate the inflexibility often experienced with apartments. Pillar-based structures can accommodate wall redesigns to accommodate new needs. The design changes can further accommodate the inclusion of Play areas and still not disturb other dwellers who would want their privacy maintained. Further, there are people whom additional facilities, including gardens, schools, and other facilities, might not attract due to demographic differences and increased rent or price.

2.4.3 *Child-Blind Houses*

Contemporary house designs are inflexible to change, especially when a family intends to increase in size or when couples get old and intend to downsize when their children become independent and start living independently. Subsequently, the introduction of an adaptable housing design is likely to help mitigate these challenges.

More families residing in cities such as Newcastle implies that designers should identify innovative ways through which will houses can accommodate the needs of residents for longer or for a lifetime. While 25% of Newcastle's house dwellers have children, those without cannot be ignored as they probably intend to have children at some point in their lives. One most conspicuous needs for children is play, which might be unattainable with the current space and design. Children need space, which has been shrinking in recent designs. Subsequently, questions arise on whether the house designs can integrate play areas on the rooftops, bus stops, nearby public gardens, and bus stops.

2.5 Spatial Qualities

2.5.1 The *Layout*

In design, a general layout implies a house whose rooms are not assigned a particular function. Instead, they can be used for various purposes without physically redesigning the space. In this regard, the rooms are interchangeable, which implies a house that can serve a variety of demands. In most instances, such houses' rooms are in square shapes. Various proposals have been made about the ideal size of such rooms, with Nylander (2007) proposing that their dimensions should measure 4x4 meters, as is the norm with the vernacular cottage in Sweden, or a 3.6-metre dimension akin to contemporary Swedish SBN 1985.

The building frame allows the user to subdivide it according to their desires and intended uses (Tila, 2004; Tila, 2021). Understanding the floor plan indicates that the rooms are not assigned a particular function and that different functions are occurring within the space. As a result, the user has the choice to organise the space to adapt to different living patterns. In this regard, families have the latitude to add a room when there is a need and to contact the space when they no longer need the added space.

2.5.2 Adaptability

A flexible layout is characterised by an architecture that allows for physical modifications through movable or demountable walls or fixtures such as cabinets. The aspect of adaptability makes it easy to configure the number of rooms and their sizes. In most incidences, the adaptable design scheme is usually an open space (Schneider & Till, 2007). Such innovation is traceable to Dutch architects in the 1930s, who thought that there were outstanding situations for the habitation process, each in principle and practice (Eldonk & Fassbinder, 1990). One project that helped tackle the difficulty of adaptable floor plans and the habitation manner was the Woningenkomplex Vroesenlaan. Van den Broek designed the floor plan in 1934.

Adaptability is usually considered a basic quality that progressively empowers homeowners to progressively differentiate their use of their multi-family private structures. In this regard, it enables homeowners to effectively react to the family’s changing requirements for space, especially when children grow into adults and leave home (Bostadsstyrelsen, 1976). One convergence among architects and homeowners is that a home’s capacity to allow for improvements to house space through spacing or partitioning is both a sensible and legitimate requirement. The rationale is that it allows families to remain in a similar house even as its needs and composition change. Such changes arise from the fact that while small families can change to become bigger with the birth of children, they can decrease once more following the growth of the young ones and their subsequent exit as adults. Bostadsstyrelsen (1976) opines that if a family unit stays in one home all through this time, such adaptations can help transform the dwelling by changing living patterns.

2.5.3 Open Empty Space

As indicated, flexible houses are also characterised by movable walls. Such plans are commonly referred to as "open plans." Adopting this architectural design means minimal fixed aspects of the building with more changeable elements. According to Alkhansari (2018), such houses adapt to the range of occupant demands based on the situation. One of the most popular concepts in this regard is Domino, a concept that Le Corbusier developed. The most significant aspect of the concept was that an open plan is best achieved by constructing a space to its basic elements of making it a space.

The plan starts with the structure but stops before it fully fits out. As a result, the open plan spaces can be fitted to adapt to the changing living patterns of its occupants. Another example of a building that adopts this design is the 45-storey Tower of David, designed by Venezuelan architect Enrique Gómez in Caracas. The house demonstrates its open-plan system by allowing over 750 families to inhabit and adapt their spaces based on their varying needs. Nonetheless, researchers continue to emphasise the need to develop open spaces adaptable to several functionality scenarios, including housing and office needs ((Edlund & Fouganthine, 2014).

A previous study on the Honeysuckle Project at 147-153 Hunter Street, Newcastle, NSW 2300, demonstrates the ingenuity of the designer's mind and the flexible and adaptable approach (Honeysuckle HQ, 2022). The spaces have been divided into specific fixtures, which have separate functions. The fixtures include a sleep fixture, live/eat fixture, work/study fixture, closet fixture, and storage fixture, among other fixtures. In addition, the fixtures can be adapted to the needs of the house's occupants as they can change shape to meet specific functions and desires of the users.

The project's designers argue that applying different scenarios and partitions helps ensure the facility is zoned and created in a perfect size for each individual's specific need. Each scenario is further fitted with a corresponding fixture, which adapts to the specific needs of the individual in the corresponding moment. It is possible to separate each functional space and scenario through zoning, adapt it to individuals' needs, and create unlimited possibilities in terms of design and use.

2.6 Research Gap

Modern trends are characterised by inadequate interest in the role of the fixtures as an essential element to be introduced during the design process. In this regard, the trends do not focus on add-ons after the completion of the design process. Instead, there is an emphasis on functional object or device that drives mobility in PLAY houses. Such objects include movable walls, cabinets, foldable furniture, and mechanical fixtures. All these objects play a role in the changes to the way people live in a house by supporting different living patterns.

2.7 Theoretical Framework

In architecture, Play is defined as direct interaction with the environment, one's personal knowledge in the same environment, and knowledge-building. Subsequently, architects ensure that their work implies Play with architectural forms and creating new forms, designs, solutions, and options for both buildings and infrastructure. In so doing, they must ensure that they adhere to established rules within Play. For instance, Play expects architects and designers to develop spaces while considering the likely achievement and shortcomings of their actions. Another essential aspect of Play is that it enables professionals to adjust to the living spaces to the conditions offered by the external environment. In this regard, it is right to argue that Play is a metaphor in architecture, which helps ensure that professionals apply their creativity to develop projects that conform to the time, conditions, occupants' needs, and availability of technologies. There exists various examples of Play in architecture. Some of these include the integration of an object with multiple functions, and transformational ideas. Another significant importance of PLAY is that it helps solve common problems witnessed in building and construction industry alongside resource availability challenges that might arise. PLAY further refers to an infrastructure that can accommodate different lifestyles and conditions given the changes that arise in users' lifetime. PLAY framework can further be used when developing living spaces, commercial spaces, or mixed-use spaces while considering users' demands, resource availability, external pressures, space availability, and the rapidly changing construction needs. Most importantly, it is essential to remark that PLAY framework encapsulates three classifications of characteristics. The three include structural, functional and cultural categories. Under structural characteristics, the main considerations include adjacency, polyvalence, and modularity. The functional characteristics are adaptability of area distribution, convertibility of functions, non-fixed furniture, multi-functionality, and adaptability. Lastly, cultural characteristics include privacy and personalisation.

3 Research Methodology

The methodology implied the implementation of several approaches, including a literature review and a case study approach to analyse the Newcastle property. The case study was anchored on Mee et al. (2019). The rationale was that the study identified the concept of livability within apartment homes in Newcastle, New South Wales, Australia. The methodology further involved inspecting the houses to assess their internal structure while considering the external space. The research further took into consideration the non-load-bearing walls, rooms, cabinets, and benches. The researcher further sought to discuss the furniture layouts and design. According to Mee et al. (2019), PLAY relates to the unit's boundaries and spaces inside and outside of that boundary to understand that the space on the other side of the entrance differs from the space adjacent to the toilet or the kitchen. Such aspects as the possibility of putting the unfixed furniture so that the appearance could be modified and arranged in more intuitive and spontaneous ways which adapted to future changes.

Further, a data generalisation was used to analyse the adaptation problems of existing housing units. Through studying the design schemes of residential apartments in recent years, it was concluded that design forms that cannot be well adapted to the needs and changes of residents could not be well adapted to the interior space and housing.

4 Findings and Discussion

A look into new house apartments in Newcastle reveals that they were developed in the past five years. Some of the properties analysed had outdoor spaces, including patios and gardens, which proved more essential for the analysis. The figures of floor plans below were selected to represent one-bedroom houses:

Figure 1. Floor Plan 1 (King Street, Newcastle) (Chapman Property, 2022)

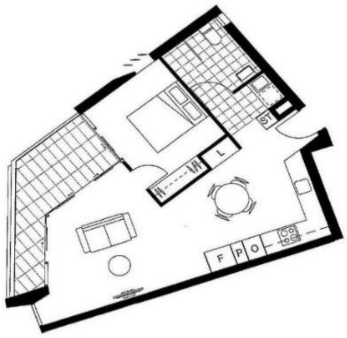

Figure 2. Floor Plan 2 (Verve Residence, Newcastle) (Walkom, 2022)

Figure 1 is a property's floor plan on 302/470 King Street, Newcastle. The houses are for either rent or sale and measure up to 69 m² (Chapman Property, 2022). The features include a bedroom, bathroom, living room, and a courtyard (patio). The house's design also includes a washstand and a potential laundry room. One observable trend in the house is that the kitchen and living room are not divided by a wall partition. Another unique aspect of the bedroom is that it lacks windows. Nonetheless, it has a very spacious courtyard compared to the house. Figure 2, on the other hand, is a depiction of another property up for sale or rent on 464/4870

King Street Verve Residence, New Castle (Walkom, 2022). The house's size is 66 m². Similarly, the house has a bedroom, a bathroom, and a small patio. The kitchen lacks any windows, which also applies to the living room. The living room, however, has a door that leads to the patio. The adjacency of the spaces can be attributed to the functional and structural aspects of the living spaces. For instance, in the first plan, the house has a bathroom next to the washstand. According to Aida et al. (2020), the approach is a hygienic and functional way of locating the rooms. The second-floor plan has one wet area next to the bedroom, as is the case with the first-floor plan. In incidences where dry and wet areas are separated in a plan, the design is simplified and space control enhanced, thus allowing for adjustments.

Another aspect of adjacency is evident in the first-floor plan's kitchen and living room locations. The kitchen is a distance from the living room and near a window. The most likely justification is that the temperatures in the kitchen are likely to be high and inform discomfort within the living room (Ma et al., 2015). Although the kitchen is opposite the windows, the design was not critical, considering that a verandah surrounds the house. Nonetheless, it is imperative to note that location is likely to be a limitation in planning. For instance, an increase in temperature would imply an increasing effect on the thermal sustainability of the house (Ma et al., 2015).

For example, the increase in temperature in the kitchen over the summer in Newcastle could inform occupants' decision to increase their use of AC. It is, however, evident that the kitchen area in Floor Plan two fails to comply with adjacency standards. For instance, it lacks any window near the kitchen. Additionally, the living room lacks windows that open except for the doors. Subsequently, an increased kitchen temperature will likely result in overheating (Ma et al., 2015). The rationale is that doors' and windows' locations regulate temperatures inside the house. In this regard, the kitchen's location near the window and the absence of doors or walls separating it from the living room indicates that the first plan's designers intended to decrease the temperatures inside the house by locating the kitchen away from it the wet areas. The house further benefited from retaining safety by ensuring that the electric gadgets were away from accidental contact with water.

According to Ledent et al. (2020), polyvalence concerns the structural features of living space. Further, it focuses on the possibility of adjusting these features and categorising them according to the owners' needs. Technically, it is evident that in the first-floor plan, the kitchen can be separated by a wall and door if the space is transformed. The purpose of such improvement could be to enhance the safety of young children.

However, the changes are likely to compromise space visually and physically. However, the second-floor plan is inflexible, given that it is impossible to separate the kitchen from the living room because it lacks a window. As indicated, polyvalent spaces enhance functionality for the occupants of a building, given that the base structure allows them to use or change the structure. From the analysis of the two floors, it is evident that both are highly functional, as they have a shared living room and kitchen. Nonetheless, it would not be easy to customise the second-floor plan space. In this regard, Floor plan two does not comply with PLAY.

Another essential aspect of PLAY analysed in this review is the multi-functionality of space and non-fixed furniture. In Floor plan 1, there is a fixed wardrobe, which limits the possibility of moving the bed or changing the room's layout (Magdziak, 2019). The kitchen furniture is equally fixed, while occupants have the latitude to use non-fixed furniture. Floor plan two equally has fixed furniture in the kitchen and the living room. The only convertible spaces for the two-floor plans include the living rooms, which can be converted into bedrooms whenever the occupants desire (Magdziak, 2019).

Lastly, space in PLAY's context is supposed to be adaptable to change by locating furniture or layout differently (Magdziak, 2019). It is evident that the two floors whose plans are discussed are moderately adaptable. Floor plan 1 is more adaptable, with the potential to divide the living room into two zones. For instance, a table and a chair can be placed in the living room to transform it into a home office and leisure space. Floor plan 2 is, however, inflexible because it cannot be easily maneuvered given the location, so the bedroom and the patio.

5 Conclusion and Further Research.

The analysis of the Honeysuckle Floor plans indicates that wet areas are effectively positioned in only three (2, 4, and 6). However, the rest of the floor plans lack similar professionalism concerning wet areas' location. For instance, plans 5 and 8 have their wet zones across the entire house. The wet zone in model 1 can equally be very uncomfortable for the occupiers, given that part of it is adjacent to outer space, a factor that could inform leaks. Plan 9 has comparatively many wet zones, given its small space. Another important observation is that not all flats in Floor plans 1-8 meet the demands of PLAY-based design. Nonetheless, all the floor plans have evident differences, with plans 5, 7, and 9 occupants being able to join two rooms or a room and a kitchen.

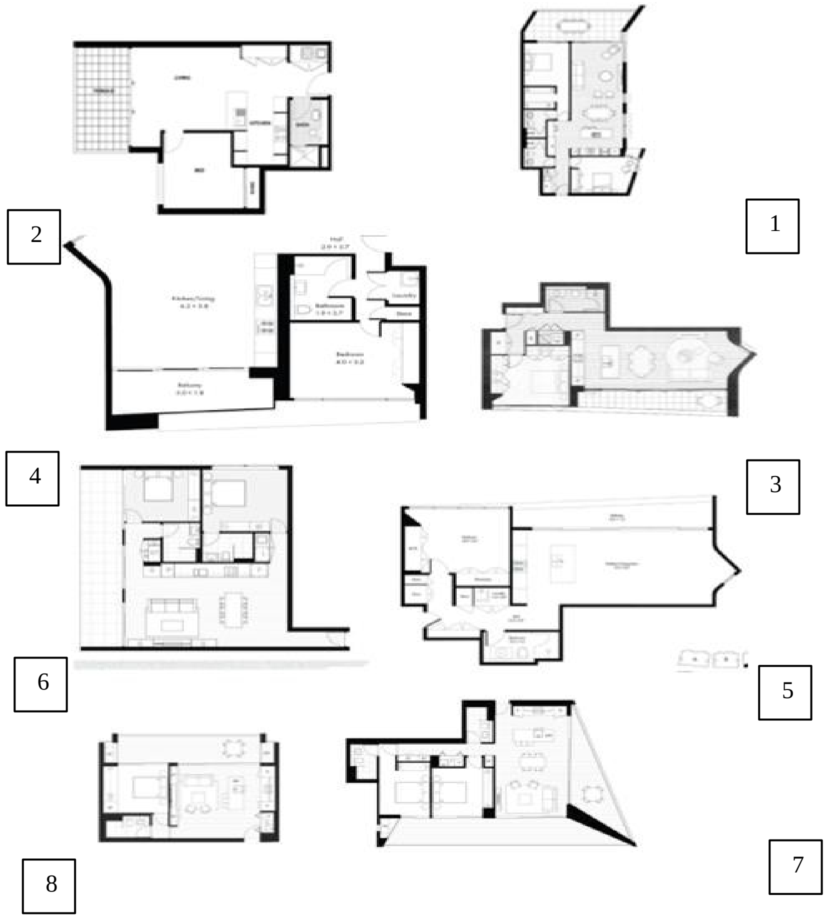

Figure 3. Honeysuckle Floor Plans 0-8 (Domain, 2022)

The plan further exploited adjacency to enhance the house's functionality and structural features. For all the floor plans except plan 8, the zoning conducted ensured effective locations of wet zones and outdoor space. For instance, there were floor plans that constructed the wet zones together, as evident in floor plans 1 and 3. Additionally, floor plans 1 and 3 ensured that a kitchen and bathrooms were located in the corners of the rooms, a design intervention that granted more space to the occupants. The remaining six plans did not provide similar levels of efficacy with regard to adjacency. For instance, scrutiny of plan 5 shows that it attempted to implement a new design by constructing a bathroom in the middle of the room. Although the design is not an effective zoning intervention; it is more flexible in terms of changes that occupants might want to implement.

Adaptability focuses on structural and functional features, including ventilation, connectivity, and outdoor space. All the floor plans on the building have outdoor spaces. Plans 1, 2, 7 and 8 all have more outdoor spaces. In plan 8, it is evident that the occupants' outdoor spaces are from both bedrooms and the kitchen. In this regard, there is enhanced connectivity around the house. A similar approach is evident in Plan 7, where occupants can access outdoor space from the kitchen and a bedroom. A similar plan is adopted in Plan 2. Nonetheless, Plan 1 lacks access to fresh air, considering that it lacks windows or access to the terrace, which implies that it does not meet PLAY's basic planning rules.

Technically, it is evident that all the plans are convertible, given that they can be aligned to the individual needs of occupants. For instance, the living rooms can be separated to create a separate office space. Alternatively, the spaces could be adjusted to meet the individual occupant's needs by integrating convertible furniture, which can apply to all spaces within Honeysuckle. Nonetheless, factors such as multi-functionality and adaptability of the plans are limited in all cases. Perhaps Plans 3, 5, 6 and 8 are the only units whose multi-functionality can be proven. The plans have more spaces, are favourably located, and are constructed within the building in a more adaptable manner.

Given this study's outcome, it is evident that there is an increasing demand for various urban infrastructures to sustain a living. Such infrastructures' main role is to connect residential areas to the city and its environment. For those residing in apartment buildings, such infrastructure offers core services that sustain the buildings in their current state. Nonetheless, the apartments are often inflexible and inadaptable. The rationale is that they fail to reflect the changing needs of their occupiers. Subsequently, PLAY needs to be adopted, which is a reliable framework in architecture and planning. As indicated, it guarantees the inclusion of spatial qualities and spatial design in house plans. While fewer apartments featured the aspects of PLAY, some of those constructed in recent years in Australia meet its stipulated characteristics. Such buildings ensure that furniture and fixtures for apartments are more movable, thus guaranteeing homeowners the latitude to enhance their spaces' functionality. Similar design aspects are also expected to characterise the actual buildings too. For instance, as demonstrated in this study, there is a growing demand for more open spaces that home users can manipulate to satisfy their needs whenever necessary. Such functionality answers the initial question of whether apartments can be designed for a lifetime. An analysis of the Honeysuckle HQ apartment complex project highlights and incorporates some of these functionality features in its plan as demonstrated. The principle of adjacency, for instance, is commonly exploited, as indicated in the findings. Equally, there is an emphasis on other structural features, including ventilation, connectivity, and outdoor spaces. In this regard, architects should consistently ensure that they design apartments that meet the individual needs of occupants. Future studies in this realm should focus on whether similar design enhancements can be employed in residential buildings other than apartments. Equally, there should be greater emphasis on multipurpose buildings, especially those used for residential and commercial purposes. Subsequently, the construction industry will witness an upsurge in more responsive buildings. The resultant adaptability further implies reduced costs and time frames involved in construction projects. The approach further implies a reduction in waste generation caused by demolitions and renovations. As a result, the construction industry will have contributed effectively to sustainable development devoid of environmental harms as envisaged in Sustainable Development Goal 12.

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Optimal BIM and LCA Integration Approach for Embodied Environmental Impact Assessment in Early Building Design

Yijun Zhou[1], Vivian WY Tam[1 *] and Khoa N. Le[1]

[1]School of Engineering, Design & Built Environment, Western Sydney University, Locked Bag 1797 Penrith NSW 2751, AUSTRALIA

19896117@student.westernsydney.edu.au; v.tam@westernsydney.edu.au; k.le@westernsydney.edu.au
* Corresponding author

Abstract:
Embodied environmental impacts of buildings refer to the resource consumption and environmental consequences produced in manufacturing, construction, and end-of-life stages of buildings. They are responsible for a large proportion of the total building environmental impacts. Embodied environmental impacts of buildings highly depend on the design decisions made in early design stages. Thus, it is considered important to examine the embodied environmental impacts in the early design practice for reducing the environmental impacts from building sector. Five BIM and LCA integration approaches have been developed to assess the environmental impacts of buildings. Appropriate choice of BIM-LCA integration approaches was proven to decrease time for assessment, improve accuracy of assessment results, and reduce the complexity of calculation processes in environmental impact assessment. However, the optimal BIM-LCA integration approaches for assessing the embodied environmental impacts in early design practice remains unclear. To address the issues, this research explores five BIM-LCA integration approaches to figure out the optimal one for assessing embodied impacts in early design by using non-structural fuzzy decision-making method. The results reveal that the approach of "using visual programming languages" is the optimal BIM-LCA integration approach for assessing environmental impacts in the early design stages, while the approach of "exporting BOQ into dedicated LCA tool" seems to be the least effective. The outcome of this research assists LCA practitioners in understanding the applicability of various BIM-LCA integration approaches and selecting the optimal BIM-LCA integration approaches in early design. Moreover, this research further promotes the applications of BIM-LCA integration approaches during the early design process of buildings.

Keywords:
Building information modelling, life cycle assessment, building design

1 Introduction

Building sector is responsible for about 37% of the global energy use and carbon emissions (IEA, 2021). Environmental impacts (e.g., use of resources and environmental consequences of release) of buildings are produced over their life cycle including raw material production, manufacturing, construction, use and end-of-life stages. Environmental impacts produced in product, construction, maintenance, repair, and replacement, and end-of-life phases are defined as embodied environmental impacts. Buildings' embodied impacts are a significant contributor to the life-cycle environmental impacts of buildings, and the contribution can approach the magnitude due to operational impacts in low- or near-zero energy buildings (Basbagill et al., 2013; Cavalliere et al., 2019).

A building consists of six components, namely foundation, wall/columns, floor, staircase, roof, doors and windows (Cang et al., 2020). The six major components are the main physical entities of early design. Interestingly, nearly 70% of the embodied environmental impacts of buildings are determined by decisions made in early design stages (Basbagill et al., 2013; Liu et al., 2015;

Wang et al., 2020). Therefore, making an environmental preferred building design in early design stages has great potential to reduce environmental impacts of buildings. In this case, the environmental impacts of early design solutions must be known for achieving environmentally friendly buildings.

Life cycle assessment (LCA) is a powerful tool for quantifying environmental impacts throughout a product's life cycle (The International Standards Organisation, 2006). This tool is widely used in building sector for assessing environmental impacts of buildings (Cavalliere et al., 2019; Jalaei & Jrade, 2013; Lee et al., 2015). On the other hand, building information modelling (BIM) digitally represents the physical and functional characteristics of a facility and related information of the building project (National Institute of Building Sciences, 2007). Adopting BIM technology in the embodied environmental impact assessment of a building can improve the assessment quality because BIM models provide essential information about life cycle inventory of a building, such as material specifications and quantity take-offs (Ajayi et al., 2015; Soust-Verdaguer et al., 2017). Consequently, five types of BIM and LCA integration approaches have been developed over the past decade (Wastiels & Decuypere, 2019). They are Type 1) exporting bill of quantities (BOQ) into Excel; Type 2) exporting BOQ into dedicated LCA tool; Type 3) adopting LCA plugin for BIM-software; Type 4) using visual programming languages; and Type 5) including LCA information in BIM objects. Type 1) approach refers to extracting the BOQ of building components from BIM model into Excel and calculating the embodied impacts of building components through multiplying their BOQ by corresponding embodied impact factors in Excel. In Type 2) approach, the BOQ of building components are extracted from BIM models and input into LCA tools (such as Gabi and SimaPro) for assessing the embodied impacts. When using Type 3) approach, the embodied impacts of a building can be automatically calculated the BIM environment as long as BIM objects are mapped to corresponding building components and materials in LCA plugin for BIM software. Type 4) approach requires to link building components to corresponding embodied environmental impact factors in visual programming environment (such as Dynamo). The embodied impacts can be obtained automatically through multiplying BOQ by embodied impacts in BIM environment. Type 5) approach defines the physic and thermal properties of building components in BIM model. Then the life span, density and embodied impact factors of building components are included in BIM objects through industry foundation classes schema. The embodied impacts of a building can be calculated in the BIM-based environment.

However, the assessment results on the same building project in early design stages by different BIM and LCA integration approaches can be different (Santos et al., 2020; Stadel et al., 2011). For instance, the software Athena is less effective to assess the environmental impacts when building information is not available in early design stage, while Tally is helpful to make quick environmental impact assessment with limited information (Najjar et al., 2017). Inappropriate BIM-LCA integration approaches has been proven to result in increased time for assessment, misleading assessment results, and over-complex calculation processes in embodied environmental impact assessment (Bueno & Fabricio, 2018). Therefore, a critical issue in assessing the embodied environmental impacts of buildings at early design stage is to select the most appropriate BIM-LCA integration approaches in order to ensure the effectiveness and efficiency of assessment processes and results.

Researchers have recognized the significance of appropriate BIM-LCA integration approaches in assessing the embodied impacts of buildings in early design practice. The applicability of various BIM-LCA integration approaches has been investigated through three types of research. The first type of these studies focused on examining the performance of an individual BIM-LCA integration approach on embodied impact assessment in early design stage (Najjar et al., 2017; Santos et al., 2019). The second type of study attempted to compare the performance of various BIM-LCA integration approaches using the indicators related to the assessment processes of building environmental impacts. For example, a comparison concerning time for assessment has been conducted between the two integration methods, namely Tally and "exporting Bill of quantities (BOQ) into Excel", and it has been found that Tally tends to provide quick feedback (Schultz et al., 2016). The third type of research has centred on finding out the optimal approaches by comparing the environmental impact outcomes of a particular case in its early design stage using various BIM-LCA integration approaches (Bueno & Fabricio, 2018). Despite useful, however, these studies failed to figure out the optimal BIM-LCA integration approaches for embodied impact assessment at early design stage due to three limitations: 1) the applicability of only few BIM-LCA integration approaches' were investigated; 2) several significant indicators linked to the performance of BIM-LCA integration approaches, such as automation degree and complexity, are neglected; 3) the optimal approaches determined by comparing the assessment results of a particular case cannot be generalized to other assessment scenarios because the calculation rules (such as the system boundary, life cycle inventory, and default replace frequency of building materials) set in each study case are different (Bueno & Fabricio, 2018). Consequently, it is imperative to adopt a scientific and general way for finding out the optimal BIM-LCA integration approaches for building environmental impact assessment at early design stages.

2 Research Methodology

To fulfill the research aim, this research adopts non-structural fuzzy decision-making (NSFDM) method to assess the performance of various BIM-LCA integration approaches and to assist in selecting the optimal BIM-LCA integration approaches. There are two reasons for employing NSFDM method in this study. First, this method is appropriate for making a choice from several alternatives and providing a comparison of the considered options (Chen, 1996; Zhu & Hu, 2011). Moreover, NSFDM method is considered robust and effective by launching automatic consistency checking and utilizing only 1, 0.5, and 0 to describe the scale of importance (Zhou et al., 2014). Therefore, this research selects optimal BIM-LCA integration approaches in early design practice by referring to the NSFDM method. There are five steps for selecting the optimal BIM-LCA integration approaches for environmental impact assessment: 1) collecting indicators for measuring the performance of various BIM-LCA integration approaches, 2) creating pair-wise comparison matrix for comparing the performance between the five BIM-LCA integration approaches, 3) calculating the assessment masks for each BIM-LCA integration approach, 4) judging the difference between BIM-LCA integration approaches by assessment marks, and 5) calculating the weight of each BIM-LCA integration approach and final evaluation results. A detailed description of these steps is discussed in the following section.

<u>Step 1: Collecting indicators for measuring the performance of various BIM-LCA integration approaches</u>

The first step is to collect the indicators which the performance of each BIM-LCA integration approach on embodied impact assessment in early design stages. Having examined previous related studies in the field of BIM and LCA integration (Tam et al., 2022), this research adopts five indicators namely, indicator 1) the qualities of the BIM model and LCA data for assessing environmental impacts, indicator 2) the time needed for assessing environmental impacts, indicator 3) automatization degree of BIM-LCA integration approaches, indicator 4) the complexity of operation for assessing environmental impacts, and indicator 5) the level of required skill for applying BIM-LCA integration approaches.

Step 2 Creating pair-wise comparison matrix for comparing the performance between the five BIM-LCA integration approaches

The second step is to create the pair-wise comparison matrix for comparing the performance between the five BIM-LCA integration approaches in referring to each performance indicator. Expert opinions are applied to judge the priority of BIM-LCA integration approaches against each indicator. To provide sufficient and effective experts' opinion, experts who have rich knowledge about BIM-LCA integration approaches and have used at least three types of approaches for assessing the environmental impacts were invited. 9 experts participated in the semi-structure interviews as 3 to 10 experts are recommended for making judgement (Seyis, 2020). Questions designed for comparison in referring to each indicator were shown as follows: Q1: How long does it take to conduct embodied environmental impacts assessment (including LCI data collection, the link of BIM information with LCA data, and calculation processes) by using each BIM-LCA integration approach? Q2: How much information of building objects will be lost during the processes of inputting BIM materials' information into LCA tools for environmental impact assessment by each BIM-LCA integration approach? Q3: How to update the embodied environmental impacts when the building is modified (e.g., the change of the building orientation, building shape, or the specifications of some building components) when it comes to using each BIM-LCA integration approach? Q4: How many tools are used to integrate BIM and LCA for embodied environmental impact assessment in each BIM-LCA integration approach? Q5: What skills or knowledge the practitioners should command to evaluate the embodied environmental impacts in referring to each BIM-LCA integration approach? The interviews were conducted online due to the restrictions of pandemic situation. After receiving expert opinions on the performance of each BIM-LCA integration approach in referring to each indicator, the comparison matrixes can be formulated based on the three rules (Chen, 1996): (1) the assessment marks is 0 if the performance of one BIM-LCA integration approach on a certain indicator is inferior to the other; (2) the assessment marks is 0.5 if both BIM-LCA integration approaches perform equally well on the indicator; and (3) the assessment marks is 1 if the performance of one BIM-LCA integration approach on the indicator is superior to the other.

Step 3 Calculating the assessment masks for each BIM-LCA integration approach

Based on the formulated matrix, the assessment marks of each BIM-LCA approach are determined by summing the values in each row. After then, the BIM-LCA integration approaches are rearranged in descending order by the total assessment marks. BIM-LCA integration approach with higher assessment marks is considered better in referring to a specific performance indicator.

Step 4: Judging the difference between BIM-LCA integration approaches by assessment marks

On the basis of the order of BIM-LCA integration approaches formed in Step 3, according to fuzzy theory, the semantic score of each BIM-LCA integration approach can be calculated by adopting equation (1) and the priority scores can be calculated by adopting equation (2):

$$ia_{1j} = 0.475 + 0.025iR_{j,}\ 1 \le iR_j \le 21 \quad (1)$$

$$ir_j = \frac{1 - ia_{1j}}{ia_{1j}}, 0.5 \le ia_{1j} \le 1 \quad (2)$$

Where ia_{ij} denotes Semantic score, iR_j denotes the rank order of BIM-LCA integration approaches, and ir_j denotes priority score.

Accordingly, the semantic scores and priority scores of each BIM-LCA integration approach in referring to a specific performance indicator can be determined.

Step 5 Calculating the weight of each BIM-LCA integration approach and final evaluation results

Having obtained the priority score of each BIM-LCA integration approach with respect to each performance indicator, the weight (r_{ij}) of each BIM-LCA integration approach in referring to each indicator can be calculated by normalization of the priority scores. Accordingly, the set of weights of five BIM-LCA integration approaches in referring to each performance indicator can be developed.

Subsequently, since the priority order of each performance indicator (w_j) varies in early design stages, the priority of each indicator will be determined by repeating step 2 to step 4. The judgement of the priority of each performance indicator is also made by experts' opinions according to the features and goals of impact assessment in early design stages. Then, the weights A(i) of the i^{th} BIM-LCA integration approach for embodied impact assessment in early design practice can be calculated by equation (3):

$$A(i) = \sum_{j=1}^{n} r_{ij} \times \omega_j \quad (3)$$

Where n is the number of performance indicators. The final priority order between the five BIM-LCA integration approaches can be obtained by referring to the overall weight of each BIM-LCA integration approach in descending order.

3 Research Results

Having adopted the procedures described in section 2, the assessment comparison matrixes are created. Then, the semantic scores and priority scores are calculated by applying the formula (1) and (2). Afterward, the weights are developed from the normalization of the priority scores. The results of the performance of each BIM-LCA integration approach in referring to each indicator are presented in Table 1.

Table 1. Comparison matrix, priority score, and weight of each BIM-LCA integration approach under each indicator

Indicator	Approach	Type 1	Type 2	Type 3	Type 4	Type 5	Horizontal sum	Semantic score ia_{1j}	Priority scoreir_j	Weight r_{ij}
Data quality (Indicator1)	Type 1	0.5	1	1	0	0	2.5	0.5526	0.8096	0.2159
	Type 2	0	0.5	0	0	0	0.5	0.7368	0.3572	0.0953
	Type 3	0	1	0.5	0	0	1.5	0.6316	0.5833	0.1555
	Type 4	1	1	1	0.5	0.5	4	0.5	1	0.2667
	Type 5	1	1	1	0.5	0.5	4	0.5	1	0.2667

Timing (Indicator 2)	Type 1	0.5	0	0	0	1	1.5	0.7083	0.4118	0.1322
	Type 2	1	0.5	0	0	1	2.5	0.604	0.6556	0.2105
	Type 3	1	1	0.5	1	1	4.5	0.5	1.0000	0.3210
	Type 4	1	1	0	0.5	1	3.5	0.5833	0.7144	0.2293
	Type 5	0	0	0	0	0.5	0.5	0.75	0.3333	0.1070
Automatization degree (Indicator 3)	Type 1	0.5	0	0	0	0	0.5	0.775	0.2903	0.0967
	Type 2	1	0.5	0	0	0	1.5	0.725	0.3793	0.1263
	Type 3	1	1	0.5	0	0.5	3	0.6	0.6667	0.2220
	Type 4	1	1	1	0.5	1	4.5	0.5	1.0000	0.3330
	Type 5	1	1	0.5	0	0.5	3	0.6	0.6667	0.2220
Complexity (Indicator 4)	Type 1	0.5	1	0	0	0	1.5	0.6429	0.5555	0.1607
	Type 2	0	0.5	0	0	0	0.5	0.7143	0.4000	0.1157
	Type 3	1	1	0.5	1	1	4.5	0.5	1.0000	0.2894
	Type 4	1	1	0	0.5	0.5	3	0.5714	0.7501	0.2171
	Type 5	1	1	0	0.5	0.5	3	0.5714	0.7501	0.2171
Level of required skill (Indicator 5)	Type 1	0.5	1	1	1	1	4.5	0.5	1	0.3737
	Type 2	0	0.5	0.5	1	1	3	0.625	0.6	0.2242
	Type 3	0	0.5	0.5	1	1	3	0.625	0.6	0.2242
	Type 4	0	0	0	0.5	1	1.5	0.75	0.333	0.1244
	Type 5	0	0	0	0	0.5	0.5	0.875	0.143	0.0535

Comparison results on data quality (Indicator1)

According to the horizontal sum in Table 1, in referring to indicator 1, the five BIM-LCA integration approaches can be rearranged as {Type 4=Type 5, Type 1, Type 3, Type 2} in descending order. In other words, the methods of Type 4 and Type 5 perform better than the other three types of BIM-LCA integration approaches in referring to the indicator 1, while Type 2 is the worst.

Comparison results on execution time (Indicator 2)

As shown in Table 1, in referring to indicator 2, time consumed by Type 3 is the least. Type 4 needs less time than other approaches except for Type 3. The time needed by Type 2 is less than by Type 1, while Type 5 requires the longest time for the assessment of environmental impacts.

Comparison results on automation degree (Indicator 3)

In referring to indicator 3, as shown in Table 1, the automation degree in applying Type 4 is the highest. Type 3 and Type 5 have similar automation degrees, and they are higher than Type 1 and Type 2. The automation degree in applying Type 1 is the lowest.

Comparison results on the complexity of operation and understanding (Indicator 4)

In referring to indicator 4, it can be observed from Table 1 that the operation of Type 3 is the easiest, while Type 2 is the most complex. The operation of Type 4 and Type 5 have similar complexity degrees, which are less complex than the operation of Type 1.

Comparison results on required skills (Indicator 5)

In referring to indicator 5, as shown in Table 1, Type 1 requires the lowest level of skill from users, while Type 5 requires the highest skill level. The levels of required skills for users in applying Type 2 and Type 3 are similar, and they are lower than Type 4.

After obtaining the priority order of each BIM-LCA integration approach in referring to each indicator, the priority order of each indicator for the embodied impact assessment at early design stages is achieved by referring to step 5. The results of the priority of each indicator in early design stage are presented in Table 2.

Table 2. Comparison matrix, priority score, and weight of performance indicators

Indicator	Indicator 1	Indicator 2	Indicator 3	Indicator 4	Indicator 5	Sum of row	Semantic score ia_{1j}	Priority score ir_j	Weight ω_j
Indicator 1	0.5	1	0	1	1	3.5	0.5625	0.7778	0.2887
Indicator 2	0	0.5	0	1	1	2.5	0.6875	0.4545	0.1687
Indicator 3	1	1	0.5	1	1	4.5	0.5	1.0000	0.3712
Indicator 4	0	0	0	0.5	0.5	1	0.8125	0.2308	0.0857
Indicator 5	0	0	0	0.5	0.5	1	0.8125	0.2308	0.0857

It can be seen in Table 2 that indicator 3 (automation degree of BIM-LCA integration approaches) is the most important indicator, while indicator 2 (time needed for assessing environmental impacts) is the least important factor when measuring the performance of BIM-LCA integration approaches on embodied environmental impacts in early design stage.

According to the weights (r_{ij}) of each BIM-LCA integration approach in referring to each performance indicator and the weights (ω_j) of each performance indicator in early design practice, the overall weight and priority order of each BIM-LCA integration approach for each scenario can be obtained by applying the formula (3). The results are presented in Table 3.

Table 3. Overall weight and priority order of each BIM-LCA integration approach in early design stage

Priority order	BIM-LCA integration approaches	Overall weight (percentage)
1	Type 4	0.2686 (26.86%)
2	Type 3	0.2255 (22.55%)
3	Type 5	0.2006 (20.06%)
4	Type 1	0.1663 (16.63%)
5	Type 2	0.139 (13.9%)

According to Table 3, the optimal BIM-LCA integration approach for evaluating environmental impacts in early design stages is Type4 (using visual programming languages) with the weight of 26.86%. Type 3 (adopting LCA plugin for BIM-software) is in the second ranking and its weight is about 22%. Type 5 (including LCA information in BIM objects) is less effective than Type 4 and Type 3 but seems more effective than Type 1(exporting BOQ into Excel) and Type 2 (exporting BOQ into dedicated LCA tool). However, Type 2 seems the least effective approach for assessing the embodied impact in early design stages.

4 Discussion and Conclusion

This research has revealed the optimal BIM-LCA integration approach for assessing the embodied environmental impact in early building design stages. One unanticipated finding is that Type 4 (using visual programming languages for environmental impact assessment) is the optimal BIM-LCA integration approach. The findings slightly differ from a previous study (Najjar et al., 2017), which argued that Type 3 is a more effective approach for environmental impact assessment in the early design stages. A possible explanation for this might be that the previous research only considers a single indicator of “the time needed for assessment”. If only "time needed for assessment" is considered in this research, the results are consistent with the results of previous research (Najjar et al., 2017).

Concerning the reasons for the optimal BIM-LCA integration approach in early design stage, they are presented as follows: It can be seen in Table 2 that indicator 3 (automation degree of BIM-LCA integration approaches) is the most important indicator for environmental impact assessment in early design practice. In referring to this indicator, Type 4 enables to automatically extract BOQ and LCA data, exchange the data between BIM and tools, and export assessment results (Kiamili et al., 2020), which is superior to other integration approaches that need manual assistance to input data, exchange data, or export assessment results (Soust-Verdaguer et al., 2017). Moreover, the link created between BIM materials’ data and LCA data in the approach of Type 4 is dynamic, allowing to quickly provide the assessment results of different design solutions. Therefore, Type 4 is the optimal BIM-LCA integration approach in the early design stages.

It should be noted, however, that the calculation results in Section 3 are based on the general purposes set in early design stage for environmental impact assessment. The weighting values may be adjusted in practice by the users according to the priorities they define between the performance indicators in referring to their specific circumstances in early design stages. Nevertheless, the procedures described in section 2 can be adopted in other circumstances as well. The outcome of this research can help better understanding the performance of different BIM-LCA integration approaches and provide LCA practitioners with a way to select the optimal BIM-LCA integration approach for LCA implementation in early design stage. Theoretically, this research provides an important reference to understand the evolution of the application of BIM-LCA integration approaches in environmental impact assessment by examining the applicability of various BIM-LCA integration approaches for early design practice.

Nevertheless, the priority setting between different performance indicators in using different BIM-LCA integration approaches is based on experts’ experience. A further comparison between different BIM-LCA integration approaches by using additional quantitative data is recommended in future research. Moreover, the way is intended specifically for BIM-LCA integration approaches that assess embodied environmental impacts. Approaches for operational impacts assessment are not the focus of this paper. A further comparison between different BIM-LCA integration approaches for operational impacts is recommend in future research.

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Identifying the Validity of Success Indicators in the 'Build Back Better' Approach

Francis Hubbard[1*] and Regan Potangaroa[1]

[1]School of Built Environment, Massey University, Albany campus, Auckland 0632, NEW ZEALAND

f.hubbard.nz@gmail.com; R.Potangaroa@massey.ac.nz

*Corresponding Author

Abstract:

'Build Back Better' is an ethics-based approach in humanitarian-led post disaster recovery yet, the 'Global Humanitarian Overview' (GHO) published in 2022 called attention to ever-increasing number of internally displaced people following disasters. This suggests that despite humanitarian delegates consistently reporting on success, outcomes of their deployments are not resulting in long term sustainable solutions. It has been well established that in knowing the indicators of success (or the components of a successful indicator), the probability of relief efforts continuing to be effective after humanitarian assistance ends increases expediently. Therefore based in the findings of the GHO, 'Build Back Better' indicators are either not sufficient suggesting the need for new indicators to be uncovered or, current indicators are sufficient but are not being used to guide activities to achieving outputs in a BBB approach. This papers aim is to explores these statements by first clarifying and introducing 'Build Back Better', its principles, and intended application. Secondly, highlight the impacts of a poorly executed 'Build Back Better' approach by exploring implications of the 'No-Build-Zone' policies in the Philippines following typhoon Haiyan in 2013, and analyse the most recently identified indicators of success from the latest 'Build Back Better' framework using hierarchical structural programming. This papers findings identify a new way to prioritise the existing indicators and suggest a better way to interpret and action the 'Build Back Better' framework for long term sustainable solutions.

Keywords:
Build Back Better, Humanitarian, Indicators, Post-Disaster, Theory vs Practise

1 Introduction

Previous research has equally promoted and criticised the term 'Build Back Better'. Praising its ability to quickly convey the appropriate optimistic tone while at the same time, chastising its often poorly defined concepts and its inability to easily transfer into practical application. A fact that continues to be proven through various case studies. Yet, because of its popularity and an endorsement by the United Nations, 'Build Back Better' will persist through both the colloquial and formal terminology of disaster reconstruction for many years to come. Thus, there is a pressing need to continue researching 'Build Back Better' and its long-term sustainability. 'Build Back Better' is used by many organizations in their respective grey literature including; policy, reports, guides, and plans for recovery. additionally, a great deal of research has been done on the theory of its application and indictors. Yet, rather than clarifying this has led to confusion on how 'Build Back Better' ought to be acted on. To untangle and simplify 'Build Back Better' for this paper its evolution is best explored chronologically providing necessary context for the case study and subsequent analysis.

2 Literature Review

2.1 2002: Beginning with Monday

The article that first poised ‘building back better’ by Jacquelyn Monday talks of an evolutionary shift in the approach used for mitigating impacts of future natural hazards. This would be accomplished by using a framework that links the reduction of vulnerabilities (using existing disaster risk reduction strategies) to environmental sustainability and social resiliency (Monday, 2002). Monday writes of this framework as a;

“…holistic recovery that takes advantage of the opportunity disaster brings … [and to] *…rebuild in a better way, instead of succumbing to the natural desire to put things back the way they were as soon as possible.”*

The framework is based on six sustainability focused principles and follows a 10-step process for ‘Local Holistic Recovery’. Which considered all aspects of improvement to a community rather than a singular focused outlook. Proffering that the wide and varied systems of a community; social, economic, environmental, physical, and so on are in harmonious balance and therefore must all have equal consideration for a successful, sustainable recovery.

Despite the level of acknowledgment this article receives as being the first documented use of ‘building back better’ in an academic publication, it is rarely noted that Monday was writing for localized disasters in North America, a wealthy region which has many existing well-resourced post-disaster systems of recovery (Neeraj, 2022; Mannakkara, Wilkinson, & Francis, 2014). In fact, it is Monday’s suggestion that the BBB framework be the next evolutionary step in already well instituted disaster programs at the community, county, and state levels relying on these existing systems being well resourced to be able to enforce the BBB approach (Noy, Ferrarini, & Park, 2019). Furthermore, writing for localised disasters such as regional earthquakes and flooding prompted Monday to state that this evolutionary holistic approach must be one that is context specific, apricating that every community has a unique balance of its various systems that causes different social, economic, and environmental needs and concern to be addressed (Mannakkara, Wilkinson, & Francis, 2014). From this BBB can be defined as, achieving the betterment of a local community in all aspects by seizing opportunities for improvement made possible by the impacts of a disaster. Achieved by using a defined framework based on six sustainability focused principles in a ten-step process supported by existing systems (Monday, 2002). This definition of BBB did not persist for long although the alluring alterative phrase became popular among post disaster partitioners key elements such as the principles and process of implementation where overlooked.

2.2 2006: Clinton’s influence.

Given the terms colloquial popularity among organisations and practitioners assisting in the response of the 2004 Indian Ocean Earthquake. It is not surprising the term BBB was unofficially legitimised with the publication of ‘Lessons Learned from Tsunami Recovery, Key Propositions for Building Back Better’ (Kennedy et al., 2008; Maly, 2017; Mannakkara et al., 2018; Fernandez & Ahmed, 2019; Vahanvati & Rafliana, 2019; Neeraj et al., 2021). The report was authored by Special Envoy of the United Nations Secretary General, William (Bill) Clinton. The report is an initial observation and recommendation on the international response to the disaster (Clinton, 2006). Researched in 2005 and published in 2006, Clinton set out ten key propositions to BBB. This report is widely attribute to the rise in influence and popularity of the term. (Khasalamwa, 2019; Neeraj, 2022; et al.) Yet remarkably, the use of the words only appears in the body of the report twice, both time in ‘Proposition Two’. Here Clinton writes of disasters as an opportunity to shift inequitable development patterns that occur in poorer nations. Patterns that inherently cause those living in extreme poverty to be the most vulnerable to disasters (Sorensen, Vedeld, & Haug, 2006; Brown, et al., 2008; Ahmed, 2017). This report officially linked BBB to overseas development assistance (ODA), writing;

"… financial resources, international focus, and openness to political and policy reform that often characterize a post-crisis period should allow us to build back better and break out of inequitable development patterns in a sustained way." (Clinton, 2006)

Although not referenced, the specific language of using a disaster as an opportunity suggest some level of inspiration from Mondays 2002 paper (or other papers influenced by it). The propositions consideration of social, economic, governance and other aspects of recovery hint at a holistic approach, although the exact term is not mentioned. Reasonable comparisons to Mondays BBB stop there. For example, no process for action is suggested. This is because while Monday writes to improve existing systems in a wealthy and stable region, Clinton's report seeks to establish guidance for an unprecedented circumstance in areas with recognized weaker governance and with less resources at their disposal. Thus, the tone and aim of the report is quite different as its purposes is to support a better and faster transition from internationally supported relief to recovery, helping communities towards a path to development (Clinton, 2006; Maly, 2017). Nonetheless, the report is often considered as genesis of BBB concepts hence its popularity in acidemia and influence in international aid development literature (Neeraj, 2022; Fernandez & Ahmed, 2019; Mannakkara et al., 2018; Khasalamwa, 2019; Vahanvati, 2019)

2.3 2007: Hyogo Framework for Action & Twiggs Guidance Note.

At the time Clintons propositions where being researched, similar concepts were being endorsed by the United Nation (UN) through the development of the Hyogo Framework for Action (HFA). 168 Governments adopted this ten-year strategy, embracing the first global blueprint for 'Disaster Risk Reduction' (DRR) which provided a detailed work plan for governments, IGOs and INGOs various sectors and actors to refer too. The HFA five priorities were

1. Ensuring that DRR is a national and local priority with a strong institutional basis for implementation
2. Identify, assess and monitor disaster risks and enhance early warning
3. Use knowledge, innovation and education to build a culture of safety and resilience at all levels
4. Reduce the underlying risk factors
5. Strengthen disaster preparedness for effective response at all levels (UNDRR, 2007)

In 2007, John Twigg authored 'Characteristics of a Disaster Resilient Community, A Guidance Note' which was commissioned by six agencies[1] who were in support of the promotion of the HFA but had realised in two years of practise that there was no way to monitor success at the community level (Twigg, 2007). The guidance notes aimed to solve this issue by simplifying the HFA into thematic categories that needed to be addressed. The thematic categories are; 'Governance', 'Knowledge and Education', 'Risk Management and Vulnerability Reduction', 'Risk Assessment' and 'Disaster Preparedness and Response'. These categories where further broken down into output and outcome-based indictors called 'Characteristics'. Across the five

[1] ActionAid, Christian Aid, Plan UK, Practical Action and Tearfund together with the British Red Cross/ IFRC

categories, 136 unique indicators (or 'Characteristics') were identified. Significantly Twigg noted that not all of these were of equal importance but without a universally agreed priority or hierarchy the implementation of these indicators would be at the discretion of the delegates to used based on the context of the situation. This work highlighted the relevance of Monday's theory (and supported Clinton propositions) that DRR and 'better' requires a co-ordinated and comprehensive approach in which progress in one area needs to be match by comparable progress in others. In other words, a holistic method is required. (Twigg, 2007; Zhou, et al., 2014).

2.4 2014: Initial BBB framework.

As the popularity of BBB grew, more organisations incorporated various elements of these themes and indicators into their guidelines. However, it seems that many continued to define BBB by its narrowest characterisation, seeing the term as physically restoring infrastructure with very loose concepts of what 'better' and betterment meant for the beneficiaries in other aspects. This often manifested in a singular focus outlook which not only neglected social and economic recovery but highlighted a poor understanding of the importance of community involvement (Schilderman, 2010; Mannakkara et al., 2018). In 2014, Researcher, Sandeeka Mannakkara developed a BBB framework in response to the confusion of practitioners choosing which BBB guideline to follow (Mannakkara, 2014). The framework identified categories and principles most acted on (or ought to be acted on) by an analysis of seven key standards. The standards analysed were;

1. Key Propositions for Building Back Better (Clinton, 2006)
2. Principles for settlement and shelter' (UNDRO, 1982)
3. Post-Tsunami Recovery and Reconstruction Strategy and Build Back Better Guiding Principles, Sri Lanka (GoSl, 2005)
4. Rebuilding for a more sustainable future, VBRRA, Australia (VBBRA, 2009; VBBRA, 2011)
5. Bam's Reconstruction Charter, BRSSPA, Iran (Omidvar et al., 2010)
6. Recovery and Reconstruction Framework, VBRRA, Australia (VBBRA 2009; VBBRA, 2011)
7. Recovery Strategy, CERA, New Zealand (CERA, 2013)

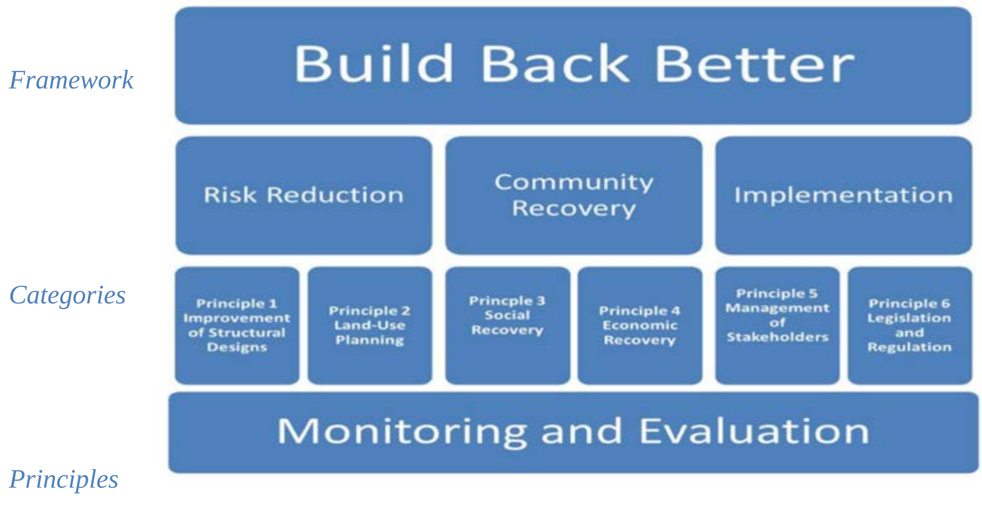

Figure 1: BBB Framework, edited for clarity by author.
Source: Mannakkara (2014)

As each unique concept of post disaster recovery was identified it was listed and then marked for the times it occurred across the set of documents. If a concept was repeated across all or most of the documents, it suggested that concept contributed greatly to achieving a successful recovery of BBB. Key concepts were grouped into broad categories with core principles noted below. The resulting BBB framework is Figure 1. The Framework, its Categories (Risk Reduction, Community Recovery and Implementation) and six principles are designed as a starting point to develop strategies of recovery with an overarching component of 'Monitoring and Evaluation' as the foundation of the principles. The inclusions of relevant indicators for this model are not addressed until 2018 with a revised framework which was first published in 2016 (Mannakkara, et al., 2018)

2.5 Case study: The 'No-Build-Zone', Philippines, 2014.

It was in this context, with established BBB frameworks, principles and indictors identified that ought to have guided and supported key decisions of the recovery following Super Typhoon Haiyan in the Philippines. Unfortunately what occurred was a quagmire, most significantly with the implementation of no-build-zones (NBZ). Used extensively in Indonesia and Samoa following the Indian Ocean Earthquake in 2004, the Philippines government applied a similar approach in 2014. The 'Department of Environment and Natural Resources' (DENR) enforced a NBZ of up to forty metres along the coastlines of eastern Samar and Leyte, two of the worst hit areas. The declaration was based on protocols outlined in Article 51 of the 'Philippine Water Code', as a presidential decree (Offical Gazette, 1976). The intention was to apply DRR measures and move those located in these areas to reduce the impacts of future disasters. However, there were numerous problems with this strategy. Firstly, the impact of the storm was felt on average 200 metres inland which highlights the destructive power of storm waves combined with storm surges and, as Haiyan occurred at a time of low tide, that distance could have extended by a further twenty percent. Therefore, the standardised 40-metre zone would not secure people's safety. In the city of Tacloban, where a four to seven metre surge was experienced, damage extended up to 500 metres inland at the northern and downtown parts of the city and this increased to upwards of two kilometres in low-lying, swampy areas south of the downtown. Thus, what was being touted as a DRR measure would achieved very little (Kinghorn, 2018; Santos, 2014; Mikami, et al., 2016).

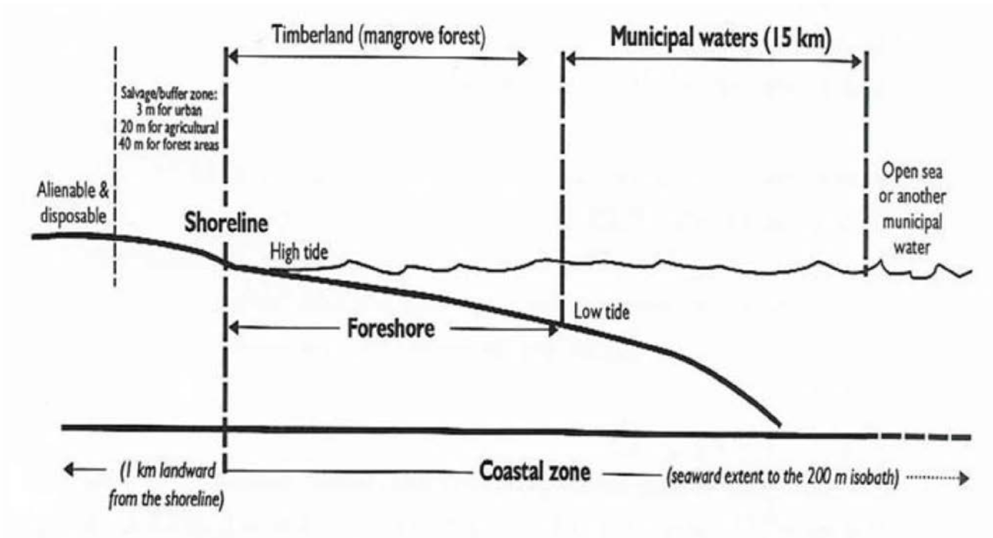

Figure 2. A diagrammatic representation of the foreshore area and other features in the coastal zone
Source: Land Management Bureau (1998)

The second problem was that these zones were the location of many informal settlements, a common issue for the Philippines. Two years prior to the impact of the typhoon in 2012, it was reported that 2.2 million Filipinos, or 5.4 percent of the total urban population, lived in informal settlements existing on the edge of many coastal municipalities where over sixty percent of the population reside. These settlements typically occupied contested zones, particularly the zone from the high tide to the low tide mark which belongs to neither state nor private ownership which led to those in systemic poverty to 'chose' to occupy these spaces (see Figure 2, foreshore). In addition to the opportunity the lack of land titles and ownership afforded, these areas gave those living there good access to the sea which was an invaluable resource of work and employment (DENR-USAID & EcoGov, 2004; USAID, 2017).

The third problem was that the NBZ was applied selectively, a consequence that was reportedly dependent on which political party the area had voted for in the last election. Areas that were known supporters of the current government faced less impacts from enforced relocations in comparison to others causing controversy, confusion and greatly impacting the quality of response form many aid agencies that had arrived in country to help (Atienza, et al., 2016; Basilio, 2014; Santos, 2014). These problems and the contested nature of these zones where most evident than in the city of Tacloban. Evident in the minutes of the meeting between the 'Tacloban Shelter Hub' and the 'Tacloban City' on June 3rd, 2014 (Seven months after Haiyan) which read as follows: (Board, 2018)

1. The City of Tacloban communicated their decision that no temporary shelter assistance should be provided in high-risk areas (NBZ). This overrode earlier consent for humanitarian agencies to assist.
2. And that any assistance had to be only in temporary relocation sites in Tacloban North. These were out of town, away from the sea and distant to the NBZ where affected families were originally.
3. Shelter Cluster partners countered with the need to address gaps in temporary relocation areas, such as accessibility, size of housing units, safety and security issues, access to basic services (WASH, electricity, education, health etc.); and access to sustainable livelihoods.

There had not been any discussion with aid agencies nor engagement with affect communities and moreover, the desire of the city mayor was to redevelop the area for tourism and hotel construction. Thus, aid agencies were blocked from assisting the most vulnerable, the most impacted, who had their lives in the NBZ. It raises the question if Twigg's indicators of the UNs priorities for DRR, were sufficient and if they were, why are the not being used to guide activities to achieving outputs in a BBB approach?

3 Research Methodology

Researchers Mannakkara and Wilkinson released an updated version of the BBB framework in 2016 (Figure 4). This version includes two additional principles, 'Early Warning and Disaster Risk Reduction Education' and 'Monitoring and Evaluation' which was an overarching component in the previous version of the framework but is now considered a principle unto itself, categorise under 'Effective Implementation'. This updated version reflects more recent finding from research, primarily by case studies which included all disaster types and locations to make the framework intentional broad. The updated version also reflect updated United Nation priorities for action, specifically the Sendai Framework which superseded the HFA in 2015 (Malay, 2017; Mannakkara et al., 2018; Vahanvati, 2019; Neeraj, et al., 2021; Cheek &

Chmutina, 2021) A publication on the practical applications of the framework in 2018 included a suite of 87 indictors. Indictors were grouped by common components within each principle and had the same aim as Twigg's 136 'characteristics', to simplify and measure success of the frameworks impact and guide a more successful recovery. A comparison between the two sets shows that there is significant overlap and Twigg's thematic categories of the HFA align closely to Mannakkara & Wilkinson's framework. Repetitive discovery of similar indicators suggest that it is not the indictors that are insufficient but in how they are being prioritised in their implementation. This would be improved with a universally agreed hierarchy.

	Methodology	Source		Outputs
1	• Literature review	• Initial database and web-based search for sources	• Selection of relevant sources used for this paper refined to 34	• Clarifying BBB • Clarification of BBB framework principles • Clarification of Intended application of BBB framework
2	• Case study	• 'No Build Zone' Typhoon Haiyan Philippines		• Reflection of practical application of BBB
3	• Hierarchical analysis	• 'Build Back Better Framework', Mannakkara and Wilkinson (2016)		• Prioritising of BBB framework principles and indicators

Figure 3: Research Methodology Flow Chart
Source: Created by authors

Figure 4: BBB Framework, edited for clarity by author.
Source: Mannakkara & Wilkinson (2016)

A method to achieve this is through hierarchical structural programming of the 87 indictors identified in the framework. These indictors where selected above Twigg's as they represent the latest and most up to date indicators of success in a BBB framework. Hierarchical structural programming is accomplished by first arranging the indictors in a matrix to identify which indictor links to which. An indictor may link to any number of other indictors and the connection is considered to go both ways.

Indictors can link across all components, principles and categories allowing the holistic nature of the approach is preserved. The links are then run through a hierarchical software which produces an organizational structure that groups the indictors into sets based on their connectedness reflecting levels of importance. This is visually represented in a tree structure, with a parental node (most connected indictor) at the top and then branches below to other grouped indictors. Several groups which are similar in theme are called a cluster. These cluster then can be named based on the common trend of the indictors contained within them. The result is a prioritised map of the indictors no longer defined by principles or categories yet preserving the frameworks holistic approach (Alexander & Manheim, 1962; Lutz, 2001; Nakada, et al., 2004).

Figure 5 shows the tree that was produced by the hierarchical programming. The numbers in the groups refer to the indictors set out in the 2018 publication '*Resilient Post-Disaster Recovery Through Building Back Better'* which were extracted and appropriately numbered 1 to 87. The tree is analysed by considering the types of indicators that have been grouped together at the lowest part of the tree. These have been labelled 'Group 1' to 'Group 22'. Groups that are similar can be simplified into clusters. These can also be seen in Figure 4, and have been labeled 'Cluster 1' to 'Cluster 7'. These clusters form the lowest part of a diagrammatic map that sets out the priority of the indictors which is explained further in section four, 'Findings and Discussions'.

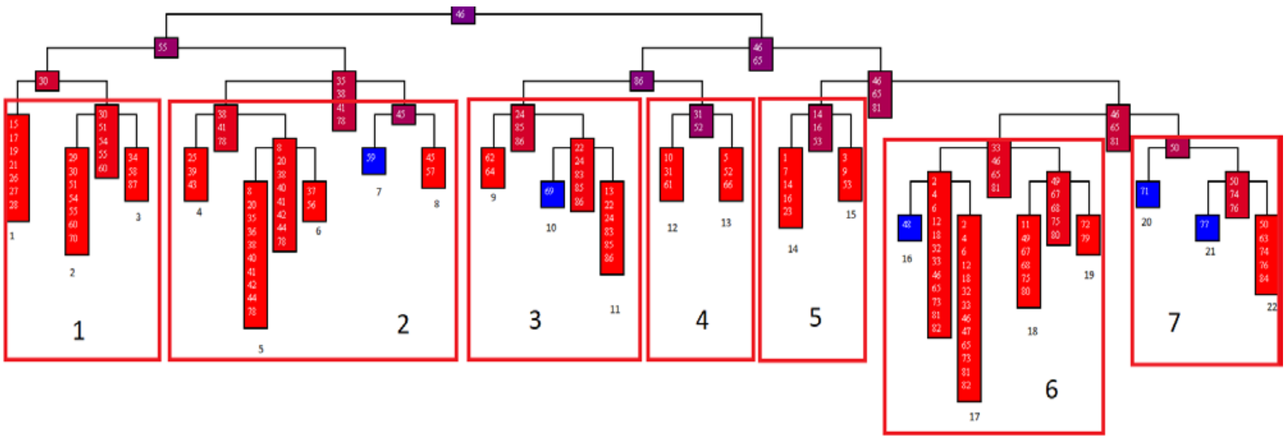

Figure 5: Indictors arranged in sets by how linked they are according to the matrix in hierarchical analysis, groups and clusters identified
Source: Created by authors (2022)

4 Findings and Discussion

4.1 Hieratical decomposition programming analysis

4.1.1 Cluster one

Cluster one is formed by groups one, two and three. This cluster has 17 indicators total; four concerning 'Disaster Risk Reduction' (DRR), six from 'Community Recovery' and seven from 'Effective Implementation' combining principles of multi-hazard-based land-use planning, phycological and social recovery with institutional mechanisms and monitoring and evaluations. the factors that links these indictors concerns the need to have an informed, educated, well advised and support community so they may actively participate in the recovery. Cluster one concerns addressing community and social drivers first which in turn is only achieved by enforcing mechanisms that allow good communication, full transparency of decisions and strong information management. This also is a foundation to facilitate ‘cluster two’

4.1.2 Cluster two

Cluster two is formed by groups four, five, six and seven. This cluster has sixteen indictors; three concerning ‘DRR’, ten from ‘Community Recovery’ and three from ‘Effective Implementation’ combining principles of structural resilience, multi-hazard-based land-use, early warning and DRR education, economic recovery, institutional mechanism and legislation and regulation. The factors that link these indictors is promoting well advised and supported industry and businesses. Cluster two is supported by first addressing economic and livelihood recovery drivers. As mentioned, this can only be done once mechanisms of good communication, full transparency and strong information management are enforced. Cluster one and cluster two form one branch of this diagram. The overarching priority that emerged is to choose a local level body (either existing government organization or new recovery authority) most suited to the local context to plan, implement and manage recovery activities, and facilitate coordinating and partnership between stakeholders involved in recovery.

4.1.3 Cluster three

Cluster three is formed by groups nine, ten and eleven. This cluster has only five indicators, only one from ‘Community Recovery’ and four from ‘Effective Implementation’. The principles of economic recovery, institutional mechanisms and legislation and regulation. The factors the link these indicators are in the promoting of education in DRR and promoting lessons learnt to the community and to all other stakeholders.

4.1.4 Cluster four

Cluster four is formed by groups twelve and thirteen. This cluster has nine indicators, four from ‘DRR’, four from ‘Effective Implementation’ and only one from ‘Community Recovery’ combining principles of structural resilience, multi-hazard-based land-use planning, early warning and DRR education with monitoring and evaluation. The factors that link these indicators are in the expanding and improving of knowledge. Cluster three and cluster four extend from a common priority of addressing the understanding of existing risks and future impacts to avoid community recovery activities that would exacerbating an unknown issue.

4.1.5 Cluster five

Cluster five is formed by groups fourteen and fifteen. This cluster has eight indicators, seven from ‘DRR’ and one from ‘Effective Implementation’ combining principles from structural resilience, multi-hazard-based land-use planning, early warning and DRR education and monitoring and evaluation. The factors that link these indicators are physical reconstruction drivers that facilitate safer rebuilding practices.

4.1.6 Cluster six

Cluster six is formed by groups sixteen, seventeen, eighteen and nineteen. The largest cluster by far with twenty-two indicators linked. Six from ‘DRR’, two from ‘Community Recovery’ and fourteen from 'Effective implementation'. Combining principles from structural resilience, multi-hazard land-use planning, economic recovery, institutional mechanisms, legislation and regulation, and monitoring and evaluation. The factors that link these indicators are concerning the expediting recovery drivers the need to be addressed.

4.1.7 Cluster seven

Cluster seven is formed by groups twenty, twenty-one and twenty-two. This cluster has seven indicators all from 'Effective Implementation' category. Combining all three of its principles, institutional mechanisms, legislation and regulation, and monitoring and evaluation. The factors that link these indictors concerns funding mechanisms. Clusters five, six and seven stems from a group which repeats twice in the tree. This group has three indictors, they are from 'Effective Implementation' and concern choosing appropriate institutional mechanisms, legislation compliance, and monitoring and evaluation. This can be called 'quality and compliance monitoring mechanisms' which need to be addressed before proceeding to the clusters under it.

From this analysis a hierarchical diagram can be produced (Figure 6) which would guide the priorities of activities when engaging in a BBB framework approach.

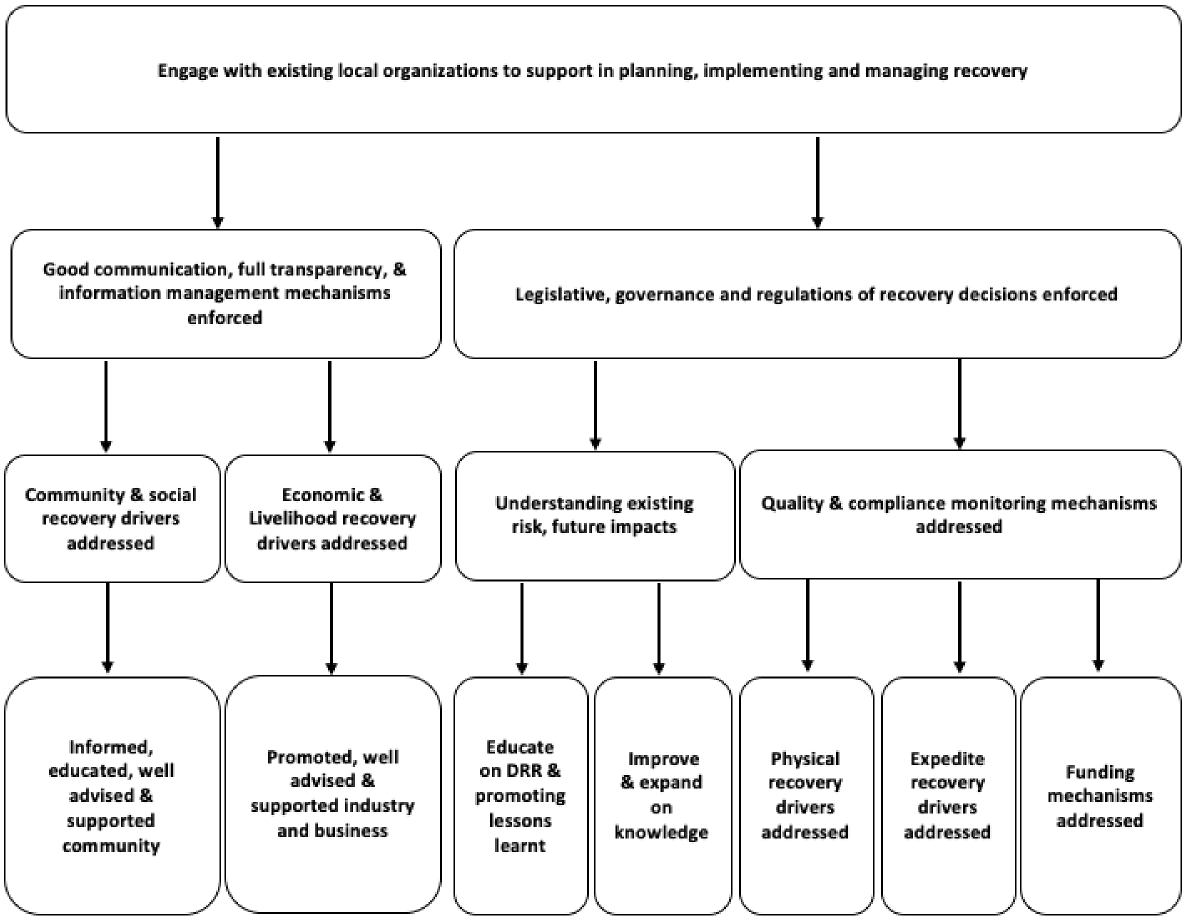

Figure 6: Priority diagram of BBB clusters
Source: Created by author

4.2 Reflection on case study

Here we see that BBB using a NBZ policy failed because its focus was solely on the legislative, governance and regulation cluster. While vitally important, this cluster is equal to several others which would give a vital foundation or grounding. The review of this response, using the findings from this paper, shows that the NBZ was not going to work. There were no community, social recovery drivers addressed especially given that there was no communication, transparency and information management mechanism enforced. Likewise, no economic recovery drivers nor quality and compliance mechanisms is evident from the lack of any action even five years after typhoon Haiyan. There was evidence of legislation and regulation being enforced but, as previously mentioned, this was selectively applied. It is so bad that one wonders how such a decision was made and wonders about the future application of NBZ with the additional weight of climate change. The final report of the Typhoon Haiyan (Yolanda) Shelter Response produced in May 2016 concluded that

"land issues indirectly underpinned almost every challenge related to the recovery of affected populations. Lack of access to safe sites led not only to affected households remaining in NBZ but also to lack of implementation of build-back-safer due to lack of permission to build stronger structures and lack of incentive to build secure structures with durable materials that would later have to be taken apart or were in any case not felt to be intended for long-term use. Lack of safe land near livelihoods and community facilities meant that some relocated communities were travelling long distances for all services and livelihoods. Shelter agencies tried several strategies to mitigate challenges faced due to land issues. Rental assistance had been given to households with damaged houses in NBZ; legal assistance was provided to households to facilitate longer-term tenancy with landowners; some tried coordinating with governmental agencies to procure land; and relocation sites were searched for near livelihoods and services."

The suggestion from that report is that BBB indictors should be appropriately linked and prioritised and that in doing so would make good future proofing.

5 Conclusion and Further Research

It is evident from the literary review that over the twenty-sum years of BBB, there have been hundreds of success indicators identified. These indicators, which are discoveries from extensive case study research, regularly repeat. This suggests that there is no need for 'new' indicators but rather that they are not being sufficiently applied to guide activities to achieving outputs in a BBB approach. This being established logically implies that knowing how to approach established indicators and principles of BBB could improve the chances of delegates applying them successfully, as seen in the NBZ case study in the Philippines where identifying more indicators of success then those already established would not contribute to long term sustainable solution but rather knowing how to approach them (or prioritise them) would. This paper has shown one such way of developing a priority diagram to assist in that approach through hierarchical decomposition analysis of the most recent indicators in the 'Build Back Better' framework.

Further research needs to be done to refine the priority diagram that was produced here. Likely this would be by repeating the method of analysis on similar frameworks with differing indicators and comparing the results. It would also benefit from engagement with practitioners who would offer much needed insight to why it appears current indicators are sufficient but are not being used to guide activities. This is some of the initial findings which form part of a larger PhD study. It is intended that this work supports and contribute to the existing BBB framework and indicators not to be a replacement for them.

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Buildings' Indoor Environmental Conditions: A Thematic Analysis of Verbatim Comments from University Library Stakeholders

De-Graft Joe Opoku[1*], Srinath Perera[1], Robert Osei-Kyei[1], Maria Rashidi[2], Keivan Bamdad[1] and Tosin Famakinwa[3]

[1]Centre for Smart Modern Construction (c4SMC), School of Engineering, Design & Built Environment, Western Sydney University, Locked Bag 1797 Penrith NSW 2751, AUSTRALIA
[2]Centre for Infrastructure Engineering (CIE), School of Engineering, Design & Built Environment, Western Sydney University, Locked Bag 1797 Penrith NSW 2751, AUSTRALIA
[3]Teaching and Research Technical Services (TRTS), Built Environment and Engineering Cluster, Western Sydney University, Locked Bag 1797 Penrith NSW 2751, AUSTRALIA

d.opoku@westernsydney.edu.au; srinath.perera@westernsydney.edu.au; r.osei-kyei@westernsydney.edu.au; m.rashidi@westernsydney.edu.au; k.bamdad@westernsydney.edu.au; t.famakinwa@westernsydney.edu.au
* Corresponding author

Abstract:
Building users' comfort and satisfaction are significant factors in ensuring the overall productivity levels of its users. In recent times, considerable attention has been geared towards managing building occupants' comfort, energy use and improving the indoor environmental quality (IEQ) of buildings. However, little attention has been focused on the occupants themselves. The lack of attention to building users, their perceptions and opinions hinder the ability to fully address the users' comfort to improve their productivity within these buildings. Therefore, this paper examines the building's indoor environmental conditions from the users' perspective to improve their comfort, satisfaction and productivity. Semi-structured interviews were carried out with users of a university library building in Australia who were purposively selected. This library building is used as a case study for this research. The results from a thematic template analysis revealed energy consumption patterns and disturbing indoor environmental conditions experienced in buildings. Further, the results disclosed significant strategic measures to improve building users' comfort and productivity. These measures include shifting energy costs from weekends to weekdays, introducing daylight harvesting systems, ensuring greater external shading, introducing adequate blinds and shutters, and avoiding extensively large openings in buildings. The study outcomes present significant strategies for building managers in improving facility management. In addition, the findings can aid in enhancing building users' comfort, satisfaction and productivity. Finally, the findings contribute to knowledge on improving the IEQ of buildings.

Keywords:
Indoor environmental parameters, Occupant behaviour, Productivity, User comfort, University library

1 Introduction

Buildings consist of both physical and spatial aspects with the former providing the shape and decoration of elements, whilst the latter establishes patterns of activities and relationships (Hillier 2007). Occupants of the building interact with the building in several diverse ways. These interactions involve daily routines, which include closing and opening of building's doors and windows, switching of lighting systems, regulating of HVAC systems, among others. The behaviour of occupants of buildings can therefore be classified into adaptive and non-adaptive actions (Hong et al. 2017). These behaviours have the potential of influencing the indoor environmental conditions within the building. Further, these occupants-building interactions present quantitative variables that have the possibility of influencing the overall energy usage and consumption, and comfort in the building (Wang, C & Zhu 2016). Notwithstanding, available studies (Jia et al. 2018; Jung & Jazizadeh 2019; Park et al. 2019) reveal that occupants are normally dissatisfied with the performance of the building systems and predefined set points for designing buildings do not guarantee energy efficiency as well as the comfort of the building users.

The indoor environmental quality (IEQ) parameters which determine the quality of lives of occupants in a building include thermal comfort, visual comfort, air quality and acoustic comfort (Dounis & Caraiscos 2009). Jazizadeh et al. (2014) indicated that ambient factors such as temperature, lighting, and air quality could greatly influence occupants' productivity and behaviour in indoor environments. The temperature within the building determines the thermal comfort of the occupants of the building. The auxiliary heating and cooling system is employed to regulate the temperature within the building to maintain occupants' comfort (Ali & Kim 2013). The lighting levels provide an indication of the visual comfort of occupants within the building (Wang, L et al. 2019). Further, the electrical systems within the building are used to manage the lighting levels whilst the concentration of CO_2 within the building is used as an index to measure the air-quality (Ali & Kim 2013). A combination of all these parameters therefore determines the comfort of the occupant of the building.

Despite the numerous studies advanced towards managing building occupants' comfort, energy use and improving the indoor environmental quality (IEQ) of buildings, little attention has been focused on the occupants themselves. The lack of attention to building users, their perceptions and opinions hinder the ability to fully address the users' comfort to improve their productivity within these buildings. Therefore, this paper examines the building's indoor environmental conditions from the users' perspective to improve their comfort, satisfaction and productivity. Three objectives were formulated to assist in achieving the stated aim:

- To identify indoor environmental parameters that impede occupants' comfort in buildings.
- To explore energy consumption patterns and improvements in buildings.
- To determine strategic measure for improving building users' comfort and productivity.

The novelty of this study lies in the fact that it determines the comfort of building users from the perspective of the users themselves based on their perceptions and opinions. It is therefore anticipated that the research outcomes would aid building managers in enhancing the comfort of building occupants.

2 Literature Review

The indoor environmental conditions of a building are key to the enhancing the productivity of its occupants. Building occupants' interaction result in several impacts on the building. The preferences and habits of occupants affect energy consumption in the building. Delzendeh et al. (2017) defined occupants' behaviour as the interaction with building systems to regulate the indoor environmental conditions for health, and to obtain thermal, visual and acoustic comfort inside the building. The desire of humans to control factors that affect the environment is not only restricted to the external environment but also within living spaces (Endler 1993; Lee, LN & Kim 2020). The improvement in thermal comfort, acoustic conditions by avoiding unwanted noise and vibrations, aesthetic status, and also visual or lighting quality through the controlling of luminance ratios, glare and reflections are prerequisites for building occupants to adequately adjust building components and systems to meet their comfort (Bluyssen 2009; Tekce et al. 2020).

Available literature including Delzendeh et al. (2017) indicated that the overall energy consumption of buildings is impacted by both the passive generation of metabolic heat by the building users and their active usage of energy. The passive metabolic heat generation is normally catered for in the energy simulations' occupancy section. The desired levels of building occupants are generally different from one user to the other. The various ways in which user interact with buildings include opening and closing of windows, using of lighting as well as the control of solar shading (blinds adjustment), usage of HVAC systems (air-conditioning regulating using on or off buttons, and thermostat temperature adjustments), hot water usage as well as the utilisation of electrical appliances.

Furthermore, Rijal et al. (2011) stated that the choices made by the building users to arrive at their comfort levels depends on the simplicity of their usage, efficiency of the controls as well as the challenges encountered whilst using these controls. Several actions and inactions are implemented to manage the thermal discomfort experienced by different occupants of buildings. Some of the actions used to manage building occupants' discomfort include clothing adjustments, opening of windows as well as thermostat temperature regulation and adjustments (Hong et al. 2015). Furthermore, other occupant behavioural strategies such as relocation with the building, and minimal discomfort tolerances are seen as inactions for addressing thermal discomfort. The building is therefore influenced by these strategies in terms of its usage of energy, and for that reason, there is the need to recognize the correlation that exists between the living styles of occupants and the building as well as their behaviour towards the usage of energy (Chen et al. 2015; Hong et al. 2015; Schakib-Ekbatan et al. 2015). Notwithstanding the extant literature focusing on building occupants comfort and productivity, only a limited number has really considered the perceptions and opinions of the occupants themselves.

3 Research Methodology

A similar methodology as utilised by Perera et al. (2022) and Opoku et al. (2019) was adopted in this research. The John Phillips Library building was chosen as the case study for this research.

3.1 Background of John Phillips Library

The John Phillips Library building is located on the Kingswood campus of Western Sydney University (WSU), Australia. The library building was selected based on its constant interaction with its occupants. The building is a five-storey building and has a total floor area of 6700 square meters. The library building includes several spaces for the day-to-day running of the facility and includes study spaces (open study areas, student group study rooms, quiet study areas, silent study areas, and access rooms), printing areas, collection areas, and office spaces. It is strategically located within the Kingswood campus and is an efficient, inspiring and user-friendly library. The library is designed in a boxlike form with a slight curve in elevation. According to the designers, the library is designed and built with redbrick retaining walls to merge with existing campus buildings. In addition, the ground floor has extensive glazing to provide visual statements while creating a feeling of warmth and accessibility. The designers utilised contemporary, modern as well as innovative technology in the process of design and construction. The library is open from 8:00 am to 7:00 pm on weekdays and 9:30 am to 4:30

pm on weekends. Figure 1 shows the selected library building used as the case study for this research.

(a) South-end view (b) West-end view

Figure 1. John Phillips library building on Kingswood campus at WSU

3.2 Design of interview questions

Semi-structured interviews were carried out with the stakeholders of the library, which include library managers, librarians, and students who frequently visit the library. The interviews were conducted between March 2021 and September 2021. The research adopted interviews to enable a critical examination of the problem (Walther et al. 2017). Further, interviews provide a vivid explanation of a phenomenon (Cassell 2015). In order to better understand the complexities experienced in the library, a qualitative approach to research was used in this study. The qualitative approach was selected in order to discover existing knowledge to aid in understanding the conditions in the chosen case study. This would make it easier to interpret the findings in line with the focus of the study. Further, the methodology employed in this research was also considered to enhance the achievement of the research objectives. The interview questions were developed to include the following: 1) What indoor environmental parameters impede comfort in the library? 2) How do we improve energy consumption in the library? 3) What is your level of comfort with the indoor environment in the library? With these questions, the major theme; the building's indoor environmental conditions from the users' perspective is explored.

3.3 Selection of interview participants

There is a need to select respondents who have a thorough understanding regarding the issues under investigation. Therefore, the purposive sampling was utilised to identify the stakeholders of the library for the interviews. A pre-defined set of criteria was used to select these respondents. The criteria included; 1) the interviewee should be someone who visits the John Phillips library frequently, 2) the second to be considered was that the interviewee must be 18 years or above, and 3) interviewee must be willing to take part in the study. The stakeholders of the library comprised library managers, librarians and students. A total of sixteen respondents (4 library staff and 12 students) were identified for the study. It must be noted that the set criteria for selecting the interview respondents enhanced the genuineness of responses for further analysis. Further, Marshall et al. (2013) mentioned that the recommended number of respondents for a qualitative research should be 2-10 respondents so as to obtain rich and reliable data for the study.

3.4 Interview process

The interview questions were pre-tested to minimise ambiguities and correct errors that were likely to occur during the interviews. All the interviews were carried out in a relaxed manner through zoom (online) due to the COVID-19 restrictions that were in place. The interviews were recorded with the consent of the interviewees. The total time for each of the interviews was between 30 and 60 minutes. The data from the interviews were transcribed and analysed using the thematic template analysis technique. The information gathered from literature was used in analysing the data gathered. Several codes were developed to ascertain the themes for the study. In addition, various patterns were also developed by classifying the identified themes under categories. Detailed explanations of the issues being studied were then derived from the patterns created (Aspers & Corte 2019). The research results were then presented using simple descriptive statics like cross-tabulations. Table 1 presents the background information of the interviewees. To ensure anonymity, the names of respondents are denoted with codes; LS1, LS2, LS3, LS4, ST1, ST2, ST3, ST4, ST5, ST6, ST7, ST8, ST9, ST10, ST11 AND ST12.

4 Findings and Discussion

4.1 Background of interviews

From Table 1, it is evident that all participants are people who regularly visit the library and therefore have extensive knowledge of the indoor environmental conditions in the library. In addition, the respondents were all above 18 years and were fully responsible for their submissions. More so, the interviewees were willing to take part in the research. The background information of respondents therefore underpins the credibility and reliability of the information for the study.

Table 1. Background of interviewees

Interviewee (Code)	Position	Age	Willingness to partake in study
LS1	Library Staff	Above 18 years	Willing
LS2	Library Staff	Above 18 years	Willing
LS3	Library Staff	Above 18 years	Willing
LS4	Library Staff	Above 18 years	Willing
ST1	Student	Above 18 years	Willing
ST2	Student	Above 18 years	Willing
ST3	Student	Above 18 years	Willing
ST4	Student	Above 18 years	Willing
ST5	Student	Above 18 years	Willing
ST6	Student	Above 18 years	Willing
ST7	Student	Above 18 years	Willing
ST8	Student	Above 18 years	Willing
ST9	Student	Above 18 years	Willing
ST10	Student	Above 18 years	Willing
ST11	Student	Above 18 years	Willing
ST12	Student	Above 18 years	Willing

4.2 Buildings' indoor environmental conditions

The views of the interviewees regarding the indoor environmental conditions are discussed in the following subsections:

- Energy consumption
- Disturbing environmental parameters
- Comfort of building occupants

4.2.1 Energy consumption

Interviewees were of the view that energy consumption is of great concern to facility managers and therefore there should be ways of managing them in buildings. However, the heating of buildings was indicated as a significant parameter that consumes a lot of energy. This challenge specifically relates to the operation of HVAC systems in these buildings. In a building as large as the library, which also runs through the weekend, heating the building on Mondays presents an unpleasant introduction to the week. There seems to be a notable flaw in the effect of reducing consumption costs and how air conditioning in buildings is managed. This has to do with how long it takes to arrive at a comfortable temperature within the building. Further, the maintenance of the energy efficiency measure incorporated in modern buildings sometimes presents other challenges. It is also worthy to mention that in terms of the lighting, interviewees believed that although it was aesthetically pleasing, too many lights were always switched on which could add to the amount of energy being consumed. Interviewees commented on these positions as follows:

"…..imagine air conditioners are turned off over the weekend go off on Fridays and come on Mondays and it's been a hot 38-degree weekend in summer. Starting work on Monday is not as refreshing as it could be since it takes longer for the building to reach a satisfactorily comfortable condition" (Interviewees LS1, LS3, LS4, ST7, ST10 and ST12).

In addition, interviewees' LS2 and LS4 indicated that *"......one other issue I can think of is the fact that most of the energy efficiency measures that were built into the building haven't necessarily been maintained in the way they were intended and that contribute to the energy consumption"*.

Jazizadeh et al. (2014) mentioned that almost half of a building's energy usage is attributed to heating, cooling and ventilation purposes. Notwithstanding, the findings of this study also confirm Wenqi and Mengchu (2009) argument that although a high rate of energy is utilised for building's indoor environmental conditioning, a significant portion of occupants is still unsatisfied with code-defined indoor thermal conditions in buildings. The authors also mentioned that it affects the health and productivity of the building occupants.

4.2.2 Disturbing environmental parameters

The interviewees were required to indicate the most disturbing indoor environmental parameters that affected their concentration in the building. Respondents acknowledged the fact that modern technologies have been incorporated into the building to regulate some of these parameters. However, depending on where a user is seated in the building, it is sometimes difficult to get enough visible light and that affects productivity since one would have to either change positions or manage with the limited lighting level. Again, depending on the user's position heat could also be a challenging parameter in buildings. Most users would there prefer to be in the building during the mornings and evenings to avoid these challenges. This is evident from interviewees LS4, LS2, ST4, ST7, ST11 and ST12 that:

"…..it depends on where in the building you are and whether a student or staff member. Sometimes the amount of light that comes through the western windows is too much". Interviewee LS2 also mentioned that *"….we also get a lot of complaints about heat from the northern windows. I mean the campus backwards windows"*.

Furthermore, interviewees ST1, ST3, ST4, ST5 and ST6 indicated that *"….especially in summer when you sit in the silent areas facing the west, it gets really hot in there during the afternoons. So I would prefer to be in there during the morning or evening"*. It can therefore be deduced that; notwithstanding the level of technology incorporated in buildings, these buildings can be exposed to certain environmental parameters such as heat that can affect the comfort and performance of their users (Lee, MC et al. 2012).

4.2.3 Comfort of building occupants

The ambient factors such as temperature, humidity, lighting, and air quality are critical in influencing building occupants' productivity and behaviour in indoor environments. Auxiliary heating and cooling systems are employed to regulate the temperature whilst electrical systems are used to manage the lighting levels (Ali & Kim 2013) (Wang, L et al. 2019). In addition, the concentration of CO2 within the building is also used as an index to measure the quality of air in buildings. The interviewees were therefore required to indicate their level of comfort within the building. The majority of the respondents indicate that they were comfortable in the building. However, some respondents reported discomfort with the level of heat and glare, especially during the afternoons of hot summers. This is evident in the interviewees' comments. Interviewees ST9, ST5, and LS3 mentioned that *"….there is too much glare in the mornings so it is difficult reading from your screen and that affects concentration"*.

Interviewees ST7, ST4, ST10 and ST12 also stated that *"…..in the afternoons it's almost impossible to study in there because you get the sun coming straight at you and it is very uncomfortable. You can't work the way you want to work". "…..we are forced to always keep moving from one position to the other due to the glare coming in there"* (Interviewees ST1, ST5, ST8 and ST11).

4.3 Strategic measures to improve buildings' indoor environmental conditions

The interviewees were also required to provide some strategic measures that could be employed in improving the indoor environmental conditions in the building. Notwithstanding the fact, various studies have provided some measures, the perspectives and opinions of the occupants themselves were not taken into consideration. This therefore hinders the effective implementation of measures in ensuring comfort in buildings. Interviewees LS2, LS4, ST10, ST7 and ST5 identified some of the strategic measures that could be implemented to enhance the environmental conditions of a building as:

- Shift energy costs from weekends to weekdays
- Daylight harvesting systems in buildings
- Greater external shading to buildings
- Adequate blinds and shutters introduction
  Avoid extensively large openings.

The findings revealed that there is the need to shift energy costs from weekends to weekdays although the building is opened throughout the week. This strategic measure emerged as a new strategy to optimise energy consumption whilst ensuring the comfort of the building occupants is maintained. This is evident from the interviewees comment below:

" …..there is a flaw on effect in terms of how long it takes to either heat or cool down the library on Mondays. It does present a very unpleasant introduction to the week. This does not necessarily seem to be the most efficient way to meet energy consumption needs versus energy efficiency needs within a building as large as the library" (Interviewee LS2 and LS4).

In addition, interviews LS4 and ST5 mentioned that *"…..imagine the air-conditioners are turned off over the weekend, and it's been a hot 38-degree weekend in summer. Starting work on Monday is not as refreshing as it could be and it can take a long time for comfort in the library to reach a satisfactory condition"*.

Other strategies that emerged from the study were utilising daylight harvesting systems, ensuring greater external shading, using adequate blinds and shutters, and avoiding the introduction of extensively large openings in buildings. These identified strategies confirm Delzendeh et al. (2017) and Hong et al. (2015) assertion that to several diverse measures would have to implemented to manage building occupants comfort and most of them must be integrated into the building systems.

5 Conclusion and Further Research

The paper has identified a number of issues relating to building's indoor environmental conditions based of on the perceptions and opinions of building users to improve their comfort and productivity within buildings. Though the emphasis of these findings are based on a specific building specifically a library building, the findings could have profound implications on other similar type of buildings. In line with the methodology adopted in this study, energy consumption patterns, disturbing indoor environmental conditions experienced in buildings, and strategic measures to improve building users' comfort and productivity are identified and discussed. It is recommended that the perceptions and opinions of building users should always be considered when focusing on ensuring comfort in buildings. A critical attention given to the opinion of building occupants will enhance the various measures that implemented to improve building's indoor environmental conditions. The study results do not only fill the gaps in knowledge regarding improving building's indoor environmental conditions, but also provide significant reference for facilities management. Further research should be geared towards increasing the number of case studies to enhance the generalizability of the findings.

Despite the contributions of this current study, one limitation of the study was that only one case study was utilised in this research. This was due to several restrictions that were in place at the time of the study. It is important to mention the use of one case could affect the generalizability of the study. Nonetheless, the experiences and knowledge of the interviewees regarding the chosen building still enhances the genuineness of the current research for further discussions.

6 Acknowledgement

We acknowledge the Western Sydney University (WSU) for funding this study through the Western Sydney University Postgraduate Research Scholarship. This study forms part of a

research project being conducted at the Centre for Smart Modern Construction (c4SMC) at WSU.

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A Conceptual Framework for Carbon Trading in the Construction Industry

Augustine Senanu Komla Kukah[1*], Xiaohua Jin[1], Robert Osei-Kyei[1] and Srinath Perera[1]

[1]School of Engineering Design & Built Environment, Western Sydney University, Locked Bag 1797 Penrith NSW 2751, AUSTRALIA

19916688@student.westernsydney.edu.au; xiaohua.jin@westernsydney.edu.au; r.osei-kyei@westernsydney.edu.au; srinath.perera@westernsydney.edu.au

* Corresponding author

Abstract:
The need to control and reduce greenhouse gases has become urgent throughout the world. Emissions trading has been established to be a reasonable panacea in curbing future levels of emissions. Carbon trading systems were originally not designed for the construction industry and has little application in the construction sectors. The overall aim of this ongoing study is to develop a construction tailored carbon trading system. However, this paper presents on the first stage which is the development of a conceptual framework for carbon trading in the construction industry. Systematic literature review methodology was adopted to obtain documents from Scopus which were then synthesised. From the findings, the major constructs comprising the conceptual framework are construction market, construction plan, construction strategies and construction policies. This framework aids the construction industry in its climate change mitigation and further proposes to develop trading system unique to the features of the construction industry.

Keywords:
Carbon trading, Conceptual framework, Construction industry, Greenhouse gases

1 Introduction

Carbon trading is a market-based system that aims to reduce the amount of greenhouse gases emitted by businesses, especially those burning fossil fuels (Finch and van den Bergh, 2022). Carbon trading scheme breaks down carbon into 'allowances' or 'certificates' which quantify carbon (Diaz-Rainey and Tulloch, 2018). The construction industry is an energy-intensive industry, whose energy consumption is still increasing (Rodrigo *et al.*, 2020; Kukah *et al.*, 2022). It is consistently one of the major contributors to carbon emissions due to the large quantities of energy and significant material utilization (Lin and Liu, 2015). The construction industry's on-site activities contribute to approximately 19% of total global carbon emissions (Chen *et al.*, 2022).

As compared to some industries that only emit operating carbon, the construction industry is unique as the input, processes and outputs involve both embodied and operating carbon. The World Green Building Council defines the embodied carbon of a building as the carbon emissions associated with the materials and construction processes throughout the whole life cycle of a building (World Green Building Council, 2021). Relative contribution of operating carbon and embodied carbon to the total life cycle carbon in buildings do considerably vary (Victoria and Perera, 2018; Rodrigo *et al.*, 2019). This is dependent on function and type of building (Nebel *et al.*, 2011); location, massing of building, type of fuel used, building orientation, climate, etc. (Akbarnezhad and Xiao, 2017). For conventional buildings, embodied carbon in their life cycle carbon can be as low as 20% or even lower for some office and conventional residential buildings. It can however be as high as 80% for some buildings such as warehouses (Bastos *et al.,* 2014).

The construction sector has not had a carbon trading system unique to only the industry. One of the reasons can be attributed to the lack of proper greenhouse gas (GHG) accounting and measurement (Sizirici *et al*., 2021; Pervez *et al*., 2021; Woo *et al*., 2021). Furthermore, current applications of carbon trading that relate to the construction industry focus largely on the operation phase with little attention to the materialization phase that consists of labour and carbon-intensive materials like cement (Shu *et al*., 2022).

Current carbon trading systems have little application in the construction industry (Shen *et al.,* 2016; Wang *et al.,* 2017; Song *et al.,* 2018). Even though the European Union Emission Trading Scheme (EU ETS) is the largest multi-national implemented carbon trading scheme in the world, it covers a number of economic sectors but little on construction (Song *et al.,* 2017). Other typical emission trading schemes also do not focus on the construction industry. These trading systems include the New South Wales Greenhouse Gas Abatement Scheme (NSW GGAS) in Australia; the Chicago Climate Exchange (CCX) in US and the Regional Greenhouse Gas Initiative (RGGI) also in US (Shen *et al.,* 2016).

As one of the most important sources of carbon emissions in the world, the construction industry is facing a great challenge in encouraging countries and firms to achieve carbon emission reduction targets (Rodrigo *et al.,* 2019; Akomea-Frimpong *et al.,* 2021). Thereby, there is the urgent need to apply carbon policies/carbon trading to the construction industry to control its carbon emission (Lin and Jia, 2019). This study therefore seeks to develop a conceptual framework for carbon trading in the construction industry.

2 Literature Review

The European Commission in the year 2000 delivered a green paper titled “Greenhouse gas emissions trading within European Union”. This provided some first ideas which designed the European Union’s emissions trading system (EU ETS) (Le Treut *et al.,* 2006). Emissions trading has been established to be a reasonable panacea in curbing future levels of emissions (Zhang, 2016). This has made emissions trading an attractive choice for several governments (World Bank, 2021). Other studies further suggest that emissions trading easily attains political support through its strategic use of free allocation of emission allowances (Skjærseth and Wettestad, 2016).

With the Paris Agreement being ratified by almost all countries, these accords have led to the setting of national targets for emissions as well as the regulations in backing them (Oke *et al*., 2017). The 1997 Kyoto Protocol and 2015 Paris Agreement are international accords that spelt out carbon dioxide and other greenhouse gas emissions targets. Emissions trading (ET) has been deemed as the main pillar of the Kyoto Protocol and United Nations Framework Convention on Climate Change (UNFCCC) (Ciesielska-Maciągowska *et al.,* 2021).

In emission trading systems, the authority responsible sets a cap/limit on the total emissions that can be emitted in a particular sector or sectors of the economy (PMR, 2015). Tradable allowances are then issued out which should not exceed the cap level. Each allowance equals one unit of emissions. Allowances are often measured in tonnes (Zhao *et al.,* 2017). The participants in the emissions trading scheme are mandated to surrender one allowance for each unit of emissions they emit. For the start, they may gain free allowances from the government, or they may buy them (PMR, 2015). Participants may also choose to either bank their allowances for future use or trade them. Participants are eligible to use other eligible units like domestic offset credits or international offset mechanisms. Placing caps on allowances is an incentive to decrease emissions. Strict caps imply low supply of allowances thereby causing an increase in allowance price, thereby increasing the incentive to reduce emissions (Zhang, 2016).

There currently exist two major types of carbon trading systems. These are: i. cap and trade and ii. baseline and credit schemes (Oke *et al.*, 2017). These are further grouped into statutory and non-statutory. Statutory schemes are initiated and operated by the government and are compulsory. Non-statutory schemes do not involve government participation and members can join voluntarily (Vorster *et al.*, 2011).

There have been policy regulations and instruments in addressing emissions reductions in the construction industry (Song *et al.*, 2017). However, as compared to some of these policy instruments, carbon trading has a number of advantages for the construction sector. For example, when compared to traditional mandatory instrument like green building code, carbon trading leads to active adoption of low carbon technologies (Wang *et al.*, 2014). Furthermore, carbon trading offers higher incentives in promoting technology investment (Huang *et al.*, 2022). Another advantage of carbon trading is that it can be applied both internationally and domestically (Song *et al*., 2017). International collaboration is advised since it aids in the easier implementation of emissions reduction arising from uniform roles and auditing scope (Koeppel and Ürge-Vorsatz, 2007).

3 Methodology

This study adopted systematic review of literature method. In line with existing guidelines, existing literature were searched for and synthesised. Analysis of prior theoretical and empirical evidence from peer reviewed papers, irrespective of the year of publication was undertaken in this study. This paper comprehensively provides a large outcome of evidence on the area going beyond varying scope and empirical methods and reducing potential biases in literature.

Scopus database was the main source used for this review. Scopus was adopted because of the advantages it has over other databases such as Web of Science and Google Scholar. According to Parmentola *et al.* (2022), Scopus database has a broader thematic and geographic scope. It also spans many subject areas and this database is widely used in academia for reviews. The first search combination used was: "carbon trading" AND "carbon emissions trading" AND "carbon trading systems" AND "carbon trading schemes". The purpose of this search combination was to produce literature on various carbon trading systems and the components involved in them. An initial search combination including the words ‘construction’, ‘construction sector’ and ‘construction industry’ were included but yielded almost no papers. This is not surprising as carbon trading schemes were originally not designed for the construction industry. They were therefore excluded leaving only search words covering carbon trading. Initial search produced 180 document results. Moving forward inclusion criteria were applied to filter the search results.

Non-English articles were excluded as the study is being conducted in English language. Document types was not restricted and hence documents included books, journal articles, conference papers and government reports. Abstracts, titles and full texts were then screened to ensure they were relevant to the themes of carbon trading, carbon emissions trading, carbon trading systems and carbon trading schemes. There was no limitation in publication date. After filtering, 39 document results were obtained. These papers formed the basis for further analysis of deriving the components of carbon trading systems and further developing a construction tailored carbon trading conceptual framework.

4 Components of carbon trading systems

A study by Zhao *et al*. (2017) indicated the major components of carbon trading to constitute market, plan and policies. Another study by Xia *et al*. (2021) indicated strategies as another major component of carbon trading.

Market is explained at the combination of institutions, systems, procedures, infrastructure and social relations for parties to exchange goods or services. This exchange may be done through barter. However, exchange in a market is often done using money. Market is the process for establishing goods and services. In carbon trading, Zhao *et al*. (2016) and Fang *et al*. (2018) indicated a constituent of market to be capacity comprising of demand and supply. Zhang *et al*. (2019) explained another constituent of market to be structure where the market is classified to be either perfect competition, monopolistic competition, oligopoly, and monopoly. Shen et al. (2021) identified price setting as a constituent of market in carbon trading while Spash (2010) explained type of good as another constituent of market.

Strategies explain how end goals are attained. Strategy often comprises setting priorities and goals. Relating to carbon trading, strategies detail the actions to execute in achieving set goals (Zhao and Yang, 2018). Strategy can evolve as a pattern of activity which an organisation adapts to. Strategies are broken down into strategic thinking and strategic planning. In a carbon trading system, the end goal is to contribute to the reduction in greenhouse gas emissions (Xia *et al*., 2021). When the carbon trading system is running and operational, it is expedient to measure its efficiency to see if it is achieving its set goals (Wang et al., 2022). A study by Liu et al. (2015) indicated trading methodologies under strategies.

Plan involves a list of consistently arranged steps that are set before undertaking a trading deal. Plan serves as an objective guidance in trading and serves as a reminder of overall long-term and short-term goals. Trading plan differs from trading strategy, which is rather a determinant of trade entry and exits. Plan in carbon trading encompasses an orderly arrangement of parts of an overall goal, design or objective in developing carbon trading schemes/systems (Montagnoli and De Vries, 2010). After the strategies have been formulated in a carbon trading system, a plan is next required. Zhao *et al*. (2017) posited that financial resources are required in running a carbon trading system. Hepburn et al. (2017) explained the need for cashflow management in carbon trading while another research by Montagnoli and De Vries (2010) and Akomea-Frimpong *et al*. (2021) indicated the role of risk management as a constituent of plan in carbon trading systems.

Policy comprises of deliberate systems of guidelines that help achieve satisfactory outcomes and guide decision making. Policies are mainly adopted by governance bodies within organisations (Talberg and Swoboda, 2013). In carbon trading, policy comprise statements of intent and are implementable protocols or procedures specific to the trading. Relating to carbon trading system, Zhao *et al*. (2017) opined that policy is a major component in the development of carbon trading. Studies by Zhao *et al*. (2018) and Bobadilla *et al*. (2018) found supervision to be a constituent of policy. Perdan and Azapagic (2011) researched into banking mechanisms as constituent of plan. Zhao *et al*. (2017) and Talberg and Swoboda (2013) explained legislations as being part of policy in trading systems. Hart and Zhong (2014), Werber (2011) and Hasselknippe (2003) in their studies found compliance to be constituent of plan in a trading system. Table 1 below summarises the components of a carbon trading framework. The major constructs (level one) are indicated as well as the sub-components that comprise them (level two and level three).

Table 1. Components of carbon trading

Major constructs/Level One	**Level Two**	**Level Three**	**References**
Market	Structure	-	Zhang *et al*. (2019)
	Capacity	Demand	Zhao *et al.* (2016)
		Supply	Fang *et al.* (2018)
	Price	-	Fan *et al*. (2015); Shen *et al*. (2021); Bunn and Fezzi (2007)
	Good(s) to be traded	Homogenous	Spash (2010)
		Heterogenous	Spash (2010)
	Trading platform	Distributed ledger technology	Mandaroux *et al.* (2021)
		Xpansiv marketplace	Kyrylovych (2022)
		CORE marketplace	www.afr.com
	Coverage scope	Sector/Industry	Hepburn (2007)
		Types of emitters	Li *et al*. (2018)
Strategies	Reduced emissions by the construction industry	-	Xia *et al*. (2021)
	Efficient trading system	-	Zhao *et al*. (2017); Wang *et al.* (2022)
	Trade methodologies	-	Liu *et al.* (2015)
	Cap setting	-	Xu *et al.* (2021)
	Allocation	-	Han *et al*. (2017)
Plan	Financial resources	-	Hepburn (2007)
	Cashflow management	-	Zhang *et al*. (2019)
	Risk management	-	Montagnoli and De Vries (2010)
	Capacity building	Personnel training	Ma (2019); Kihulla (2014)
		Innovative research and development	Liu *et al*. (2021)
Policy	Supervision	Government supervision	Zhao and Yang (2018)
		Non-government supervision	Bobadilla *et al*. (2018)
	Banking mechanisms	-	Perdan and Azapagic (2011)
	Legislations	Mandatory legislations	Talberg and Swoboda (2013)
		Related rules and legislations	Zhao *et al*. (2017)
	Compliance	Incentive for Compliance	Hart and Zhong (2014)
		Accountability system for compliance	Hart and Zhong (2014); Werber (2011)
		Penalty for non-compliance	Hasselknippe (2003)
	Monitoring Reporting and Verification (MRV)	-	Tang *et al*. (2018); Wang *et al*. (2021)

4.1 Conceptual framework for carbon trading in the construction industry

This study proposes a conceptual framework for carbon trading in the construction industry. This is based on the major components of carbon trading and further goes to contextualise these components to the construction industry. The major components in this framework are termed as Construction Market, Construction Plan, Construction Strategies and Construction Policies.

Figure 1 below shows the conceptual framework of the highest-level components of carbon trading framework for the construction industry.

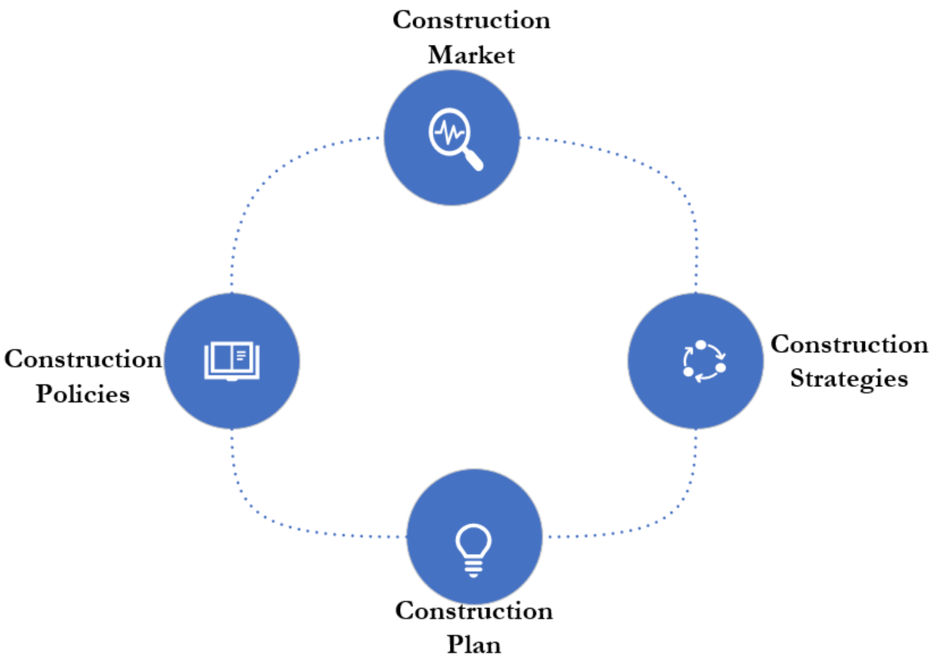

Figure 1. Conceptual framework for highest level component of carbon trading for the construction industry
Source: Authors' construct (2022)

The mechanism behind the operation of carbon trading is that entities that undertake emissions ought to surrender enough amount of credits or permits in covering the output of their estimated emissions (Talberg and Swoboda, 2013). Emissions units are acquired via different methods. Carbon trading has been presented and framed in different ways and this is evident in the various names in different versions used to represent it. These comprise: tradable permits, allowances, cap and share, carbon rations and quotas (Bristow *et al*., 2010; Parag and Fawcett, 2014). From Figure 1, it can be seen that there are linkages among the four major constructs that comprise a carbon trading framework for the construction industry. Alberola *et al*. (2008) posited that carbon price change might be influenced by the design of the market. Amount of emissions by entities in the construction industry have an impact on carbon price. In our carbon trading framework, price was a sub-component of construction market. Furthermore, in the European Union Emission Trading System (EU ETS), carbon emissions allowance and its allocation was a significant factor in the running mechanism of the trading scheme (Zhang and Wei, 2010). In this framework, these are captured under construction policy component.

Carbon trading schemes/systems that are unique to the construction industry will be incomplete without the development of strategies (Chen *et al.,* 2015). Specific requirements that relate to energy efficiency in buildings and the construction sector as a whole ought to be issued by local or central governments (Blay Jnr *et al.,* 2021). These include series of energy saving and efficiency standards (Chen *et al.,* 2015; Kukah *et al.*, 2021; Seidu *et al.*, 2022). In this study, one of the components under construction strategies is the reduction in emissions by the construction industry. Past literature shows carbon trading schemes are cost-effective mechanisms in attaining low carbon activities especially by the construction industry. To achieve set targets of lowering global emissions and keeping average temperature under 2 degree Celsius above pre-industrial levels, carbon trading schemes have a crucial role to play (Oke *et al*., 2017).

5 Conclusion and Further Research

As a significant contributor of carbon emissions in the world, the construction industry is facing a great challenge in encouraging countries and firms to achieve carbon emission reduction targets Emissions trading has been established to be a reasonable panacea in curbing future levels of greenhouse gas emissions. A conceptual framework was developed based on the highest-level components of carbon trading for the construction industry. These major components were construction market, construction strategies, construction plan and construction policies. The framework developed has theoretical, empirical, practical and wider implications. Notably, a study that combines and reveals the pertinent components in carbon trading and how they relate to the construction industry is lacking and this study fills the gap. Theoretically, this paper constitutes the foremost exclusive assessment of the generic and significant components that is inherent in carbon trading. From a theoretical lens, this paper further extends knowledge on the checklist of carbon trading components and will contribute to the development of related theories. Practically, the sub-components identified will act as managerial guide for carbon trading in construction related projects. Policy wise, this paper is beneficial to the built environment sector in general as steps are taken to minimise the impact of the sector’s contribution to climate change. This study will inherently serve as a standpoint for further studies in the field.

As an ongoing study, this study proposes to develop a theoretical framework based on the conceptual framework established in this study. The interactions in the carbon market will be modelled using system dynamics (SD). Furthermore, a carbon trading implementation and management framework will be designed based on the unique features of the construction industry.

6 Acknowledgement

This research study is fully supported through research funding for the first author through Western Sydney University postgraduate scholarship.

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Improving Decision-making of Building Projects towards a Smart and Sustainable Future via the Integration of Life Cycle Sustainability Assessment and BIM-based Digital Twin

Karoline Figueiredo[1*], Vivian W.Y. Tam[2], Ana C.J. Evangelista[3] and Assed Haddad[1]

[1]Programa de Engenharia Ambiental, Universidade Federal do Rio de Janeiro, Rio de Janeiro 21941-901, BRAZIL.
[2]School of Engineering Design & Built Environment, Western Sydney University, Locked Bag 1797 Penrith NSW 2751, AUSTRALIA.
[3]Engineering Institute of Technology, Perth, AUSTRALIA.

karolinefigueiredo@poli.ufrj.br; v.tam@westernsydney.edu.au; ana.evangelista@eit.edu.au; assed@poli.ufrj.br
* Corresponding author

Abstract:
Buildings play a critical role in sustainability due to the massive environmental, social, and economic impacts generated throughout their life cycles. Although the search for sustainability is growing globally, developing sustainable building projects continues to be a challenging task linked to multiple criteria. The Life Cycle Sustainability Assessment (LCSA) methodology appears as a possible solution to meet the requirements of a sustainable built environment by adopting a lifecycle perspective and simultaneously accounting for all sustainability pillars. Nevertheless, compared to other assets, a building sustainability assessment requires extensive data processing. In this context, integrating LCSA and BIM-based Digital Twin from the early design stages of building projects, when it is possible to ensure maximum control over project decisions, to the building's end-of-life seems appropriate. A building Digital Twin can improve real-time data visualisation and develop self-learning building capabilities. Besides, the digital model can facilitate the simulations and data collection required to generate detailed results on impacts during sustainability assessments. Therefore, this study aims to extrapolate the discussion on integrating BIM and LCSA by adding the Digital Twin concept throughout the whole building's life cycle and inserting real-time data, thus transforming the application into a dynamic LCSA. To this end, this study proposes a conceptual framework with the steps to integrate LCSA and BIM-based Digital Twin throughout the entire building lifecycle to improve the design, fabrication, construction, operation and deconstruction processes. The advantages and challenges of using these concepts to achieve a smart and sustainable construction industry are discussed.

Keywords:
BIM, Decision-making, Digital Twin, Life Cycle Sustainability Assessment, Sustainable Construction.

1 Introduction

Seeking more sustainable projects in construction has become a primary goal worldwide. The importance of this becomes clear when analysing the massive number of environmental impacts the construction industry generates annually, with significant consumption of freshwater resources (Mannan and Al-Ghamdi, 2020) and fossil energy (Gao *et al*., 2022). Moreover, this industry is responsible for influencing multiple social and economic aspects, directly contributing to the global employment of labour (Saka *et al*., 2021) and the global gross domestic product (GDP) (Fu *et al*., 2022). As a result, it is critical to look for ways to create more sustainable construction projects based on a triple-bottom-line (TBL) strategy, simultaneously considering environmental, social, and economic aspects.

In this vein, Life Cycle Sustainability Assessment (LCSA) emerged as a comprehensive methodology based on the life cycle thinking approach that considers that all phases in a product's life cycle cause environmental impacts and socio-economic consequences, and to achieve sustainability, all these issues need to be assessed. When applied to building projects, the life cycle is understood by all the existing phases, from the raw material extraction to the building demolition and the consequent disposal, reuse or recycling of materials and components. Nonetheless, several difficulties emerge when analysing the whole life cycle of a building due to the large number of data that must be considered.

Therefore, it seems appropriate to utilise tools and technologies that assist in lifecycle data collection, simulations, and real-time data visualisation required to generate detailed results on impacts during the building sustainability assessment. On the one hand, a commonly utilised concept in the construction scenario is Building Information Modelling (BIM), which refers to a working methodology based on a digital representation of the facility and information exchange, allowing the collaboration of all stakeholders involved and making data accessible throughout the project's life cycle (Kubicki *et al*., 2019). On the other hand, the current state of BIM only provides static data of building projects and is incompatible with the Internet of Things (IoT) integration, a tough challenge currently discussed in the literature (Boje *et al*., 2020).

IoT adoption is critical for accurate building sustainability assessments since IoT allows the digital building model to be updated in real-time, enabling the performance of what-if scenarios to be assessed (Hunhevicz *et al*., 2022). Building static data, which describes time-invariant features and parameters, are unquestionably significant for assessing sustainability (Yuan *et al.*, 2021). Nevertheless, in order to evaluate the long-term viability of constructed assets thoroughly, various time-dependent aspects must be considered, such as the effects of seasonal fluctuation, changes in user behaviour, climatic conditions, and the evolution of the physical structure through time. In this context, the concept of a BIM-based Digital Twin arises. Conceptually, a Digital Twin (DT) is a virtual representation of an asset, serving as the real-time digital counterpart of the physical object or system during its life cycle (Kuo *et al.*, 2021). From the construction standpoint, DT may be viewed as a new approach to improving existing building processes through cyber-physical synchronicity (Boje *et al*., 2020).

Of particular relevance in this research is the improvement of the decision-making process of building projects during the whole life cycle of the asset. In the literature, very few studies utilise DTs to improve the three pillars of sustainability based on a life-cycle perspective. Specifically, this study aims to benefit the project decisions from the early design stages of building projects, when it is possible to ensure maximum control over project decisions, until the building's end of life, when several choices must be carefully analysed to minimise the generation of solid waste, the formation of dust and the emission of greenhouse gases, in addition to the importance of assessing the socio-economic aspects associated with it.

Therefore, this study elaborates on viable ways to integrate the LCSA methodology with a BIM-based digital twin to benefit the decision-making process of building projects throughout their whole life cycle regarding sustainability aspects. This research culminates in presenting a conceptual framework that intends to critically discuss how this integration can benefit sustainability in construction and contribute to the advancement of research in this field.

2 Methodology

This study contributes to achieving a smart and sustainable built environment by proposing the integration of different methodologies and tools, considering the three pillars of sustainability in the proposed assessments. Besides, environmental, economic and social assessments of a building are considered here as an evolutionary process that spans the entire life cycle of the building, i.e., the analyses must occur from the early design stages to the construction's end of life.

In order to achieve this, a literature review of the techniques and methodologies to be employed, namely LCSA, BIM, and digital twin, is proposed. This literature review is expected to allow a profound discussion about this subject, with the definition of potential improvements and applications. As a result, the literature view will introduce the broad notions related to these topics and the role they can play in developing a sustainable built environment. The following steps were performed in conducting this method:

Stage 1 consists of searching for relevant articles and filtering them based on the topics that need to be addressed. Stage 2 involves the evaluation of the filtered documents. Stage 3 defines potential BIM-based Digital Twin applications to improve the LCSA application in the construction industry. Finally, by establishing the challenges and future exploratory directions associated with integrating BIM-based digital twins and the LCSA methodology, Stage 4 aims to propose an exemplary method for integrating the analysed topics throughout the entire life cycle of the building, using real-time data in the whole process. Therefore, a conceptual framework will be presented with the steps to be taken to achieve this outcome.

3 Literature Review

In order to determine the most recent research status on the integration of BIM-based Digital Twin and LCSA in the built environment, a bibliometric survey was carried out in October 2022, using SciVerse Scopus as the search engine due to its comprehensive and user-friendly interface. The search formula was determined as shown in Figure 1. Only English-language materials were considered during this process. Unfortunately, BIM-based Digital Twin applications integrated with LCSA are still not much discussed in the literature, which is proven by only eight papers on this topic. Therefore, it was decided to expand the search, focusing on BIM-based Digital Twin with a focus on sustainability in general. After title and abstract screening, 26 articles were filtered to be evaluated, and the conclusions are stated in the following sections of this work.

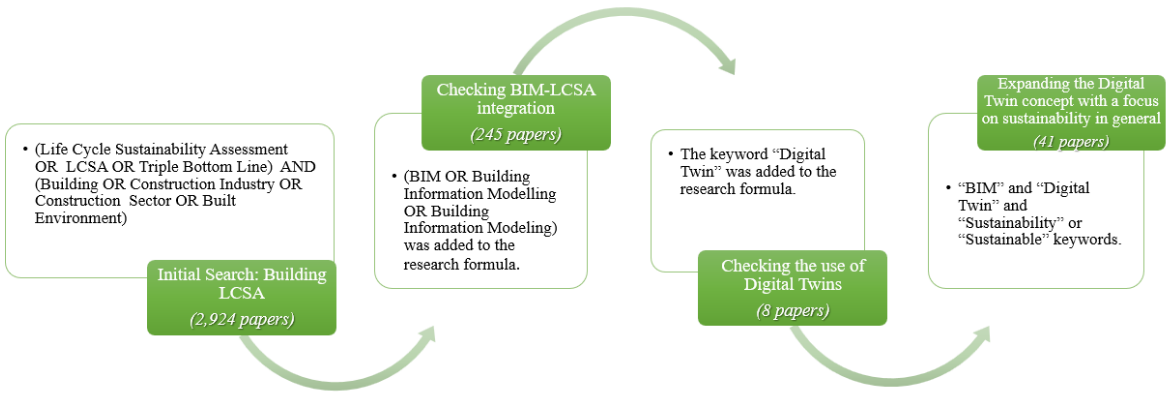

Figure 1. The process adopted in this study for the literature review search.
Source: The authors.

3.1 Life Cycle Sustainability Assessment (LCSA)

Life Cycle Sustainability Assessment (LCSA) is an interdisciplinary framework that simultaneously examines the environmental, social, and economic impacts of products and activities, thus integrating the triple dimension of sustainability. In this way, the LCSA methodology consists of three major components: i) Life Cycle Assessment (LCA), a technique that represents the environmental dimension; ii) Social Life Cycle Assessment (S-LCA), which describes the social dimension; and iii) Life Cycle Costing (LCC), a technique related to the economic dimension. These three techniques follow the same methodological structure, based on the ISO 14040 standard, which is composed of four steps: Goal and Scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation (ISO, 2006).

Although the LCA, LCC and S-LCA techniques have similarities, significant differences in each methodology have been identified in the literature (Llatas *et al.*, 2020). For example, not all the social and economic indicators can be estimated as a function of the study's functional unit, resulting in a significant drawback in result interpretation (Fauzi *et al.*, 2019). In this context, numerous issues concerning the full use of LCSA remain unanswered, and many studies continue to execute only a portion of the evaluation. This is primarily due to the varying maturity levels of the three sustainability pillars, which impedes the widespread adoption of LCSA.

Researchers have focused on applying decision-making techniques such as LCSA during the early stages of building design. Nonetheless, when considering using this methodology in different stages of the building's life cycle, a new challenge arises related to the lack of temporal information in the assessments. It becomes necessary to consider a dynamic LCSA approach in which a dynamic life cycle inventory (D-LCI) is considered, along with time-dependent characterisation factors, to assess the impacts by considering real-time impact scores for any time horizon (Levasseur *et al.*, 2010). This is still very little discussed in the literature, especially when considering studies that validate this concept in building case studies.

3.2 Building Information Modelling (BIM)

The BIM methodology intends to centralise all building data in a single three-dimensional model, enabling multiple analyses and simulations. Besides, BIM allows practitioners to create an n-Dimensional model, making it possible to add new layers of development to the building project (Fernández-Mora *et al.*, 2022). Thus, a BIM model can be seen as a digital building prototype containing both geometric and semantic data of building materials, components and systems.

Evidence suggests that BIM is a crucial methodology to achieve a smart and sustainable built environment and can be satisfactorily combined with Life Cycle Sustainability Assessment (LCSA). Modelling the building using a BIM platform allows the automatic generation of material quantities and the insertion of sustainability data into the digital model. This also enables simulations to be carried out of the building, which can be helpful in generating additional data for the LCSA application.

In the BIM domain, the Industry Foundation Classes (IFC) data model is utilised to guarantee software-agnostic data interoperability. IFC is a standardised and digital way of describing data in the built environment, including buildings and civil infrastructure (ISO, 2018). For this, the IFC schema codifies the identity, attributes, semantics and relationships of objects, processes and people associated with a project. Nevertheless, regarding the use of BIM as the starting point for DT implementation, robust and knowledge-oriented semantic data storage, which can be exploited by Artificial Intelligence (AI) technologies, is needed (Boje *et al.,* 2020). In this context, a Web Ontology Language (OWL) for IFC, representing a connecting point between semantic web technologies and the IFC standard, is preferable and is called ifcOWL.

3.3 Digital Twin in the Construction Industry

A digital twin represents a collection of realistic models that simulates the physical asset's real-time attributes, condition, and behaviour throughout its existence (Haag and Anderl, 2018). Using a digital twin is essential in representing physical assets in a corresponding virtual environment (Lu and Brilakis, 2019). This notion has been employed in various sectors and businesses, including construction. A building digital twin is a contextual model of an entire building environment, bringing together third-party data and resulting in a dynamic digital replica that can be used to solve a wide variety of issues (Coupry *et al.*, 2021). The benefits of using a building digital twin range from real-time data visualisation to continuous asset monitoring and the development of self-learning capabilities (Ramos *et al.,* 2022).

Unlike BIM, which focuses on the centralisation of data and information and is typically used as a single digital shadow, a building DT can timely optimise suggestions based on the building lifecycle mirroring of current status (Peng *et al.*, 2020). For this, digital twins of constructed assets may present different levels of complexity from design to handover, depending on the model's sophistication and the available data (Seaton *et al.*, 2022). Several contributions of using DT in the construction sector are discussed in the literature, such as the real-time building's remote monitoring and management and the maintenance and planning estimation (Celik *et al.,* 2021). Nevertheless, a closer look at the literature reveals some gaps and shortcomings. Although the DT concept already provides solutions to current problems in building projects, research on this subject continues mainly at a theoretical level. Several articles that apply a building DT in a case study upgraded existing modules of a BIM model to a DT system without considering real-time data, thus only partially realising a building DT (Peng *et al.*, 2020).

Regarding sustainability assessments, some papers have already presented specific goals for using BIM-based Digital Twins, such as maximising the recycling and reuse of demolition waste (Kang *et al.*, 2022) and developing Zero Energy Districts (Agostinelli *et al.*, 2022). However, the application intended to improve the LCSA methodology is still briefly addressed in the literature. For example, (Tagliabue *et al.,* 2021) discuss the usage of a BIM-based digital twin for life-cycle sustainability assessment. Still, the case study encompasses the design and operational phases with a primary focus on energy efficiency, not considering all sustainability pillars.

3.4 Contributions of the proposed work

This work intends to contribute to advancing the discussion on the use of BIM-based digital twins to achieve sustainable standards in construction, particularly considering a lifecycle approach based on the LCSA methodology. Therefore, the contributions of this paper are based on the presentation of a conceptual framework and a discussion intended to answer the following research questions (RQ):

(RQ1) Is it feasible to extrapolate the discussion on the integration of BIM and LCSA, typically focused exclusively on the early design stages, via the application of different levels of Digital Twins throughout the entire life cycle of the building?

(RQ2) Can a BIM-based digital twin assist in solving the LCSA limitation of typically not considering real-time information throughout the assessment, thus transforming the application into a dynamic LCSA?

4 Conceptual Framework Development

The conceptual framework proposed in Figure 2 addresses the integration of a BIM-based digital twin and the LCSA methodology to ensure sustainability goals. For this, it will be considered that the DT model will evolve and achieve different levels of complexity depending on the available data in each stage. The lowest level will be called a BIM-based descriptive digital twin, which includes detailed information and descriptive data such as construction material characteristics. This 3D model will assist practitioners in collecting and visualising data during the concept design stage. In this phase, the LCSA is used as a decision-support tool to help choose construction materials and methods.

From the later design stages (i.e., detailed design and technical design), DT will evolve into an informative model utilised to run comprehensive building simulations. This level contains more detailed information about the project, and different strategies can be used to collect and analyse data. Some authors suggest exporting the Bill of Quantities (BoQ) from the BIM software to an LCA-specific tool or using plug-ins and add-ons to conduct the LCSA calculation in the BIM tool (Filho *et al.,* 2022). On the other hand, some studies encourage the inclusion of environmental, economic, and social data within the BIM model, using different data sources such as Sustainable Product Declarations (SPDs) (LLatas *et al.*, 2022). This last approach is the most supported here since it represents the evolution of the building's digital model with the centralisation of more data and information, thus transforming a digital shadow in BIM into a building's digital twin.

In turn, during the construction phase, represented in the second part of the framework, real-time data regarding the construction process must be collected and inserted into the digital counterpart of the building. Therefore, the digital model becomes a comprehensive DT, representing a bi-directional connection between the digital and the physical asset. This synchronisation allows real-time data to be used during the LCSA application, resulting in a better decision-making process and the development of a construction data repository to be used in future projects. This BIM-based comprehensive DT also allows constant monitoring and improvement of the construction process since it is possible to conduct construction simulation, virtual job site planning and safety planning using the digital twin model. Direct effects on the three pillars of sustainability could be observed, such as worker safety and the minimisation of material waste during construction.

Finally, during the post-construction, DT may be updated with static data from numerous sources, such as impact databases and data repositories from previous projects, and with dynamic data making use of IoT by installing devices and sensors to capture real-time data. Artificial intelligence (AI) technologies and machine learning can also be used to improve building assessments. Therefore, transitioning to an autonomous and connected DT is expected, reducing dependence on human interventions. Building LCSAs should be applied when renovation or maintenance works are needed, in addition to the possibility of simulating different end-of-life scenarios for the building, so that the project's decisions can follow sustainable goals and a continuous improvement in the physical building is guaranteed. The BIM-based digital twin is expected to facilitate building construction, maintenance, and management, improving sustainability through integration with LCSA.

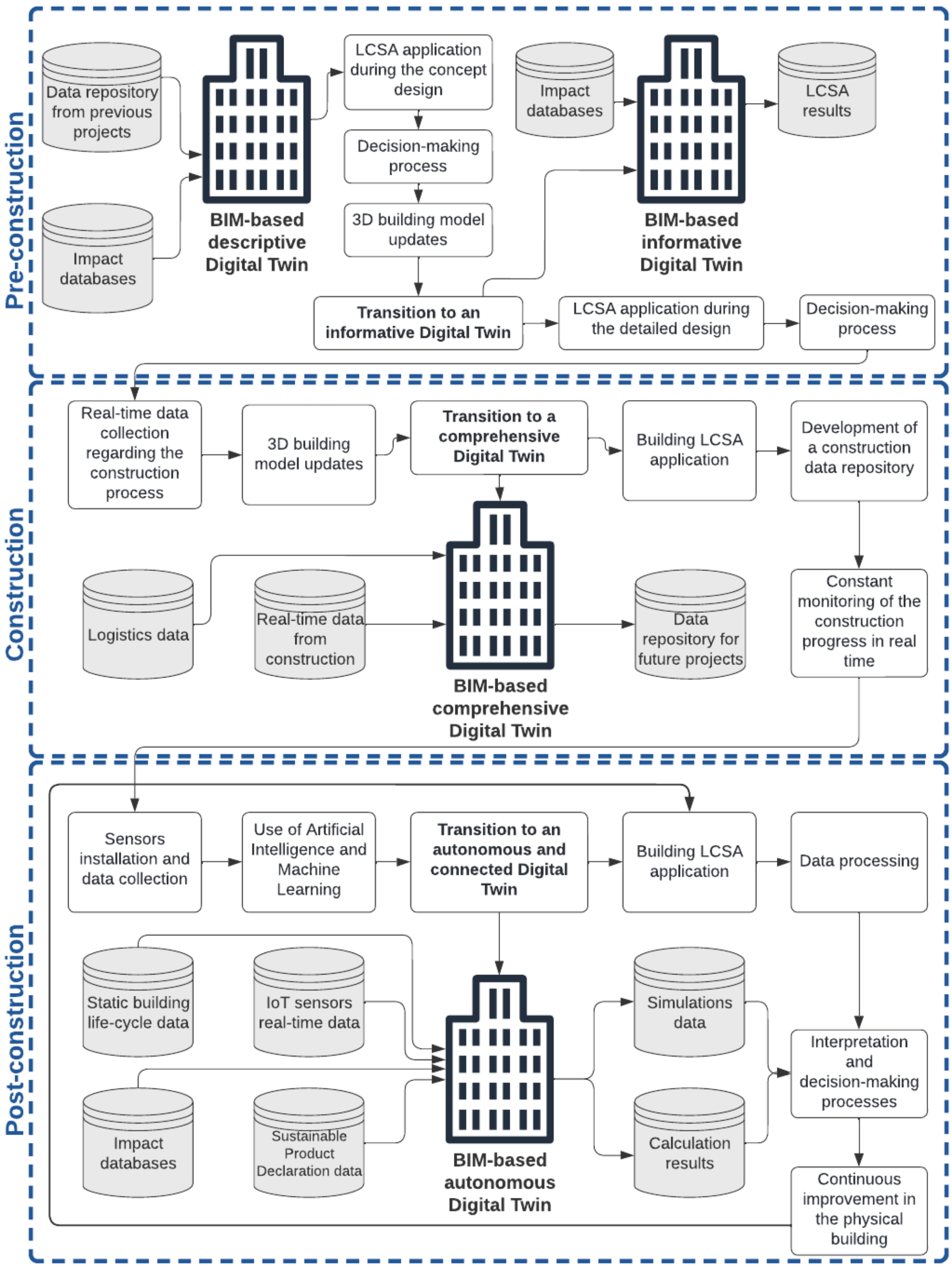

Figure 2. The conceptual framework proposed in this research.
Source: The authors.

5 Findings and Discussion

Although the conversation about sustainability in construction has been gaining steam worldwide among professionals and researchers, the literature still lacks accurate and comprehensive case studies on sustainable construction. This is particularly notorious if one considers the joint assessment of the three pillars of sustainability (i.e., environmental, social, and economic). More recent studies usually focus on the generation of impacts from a particular building material or element (Sharma *et al.*, 2022), sometimes considering only environmental aspects and not satisfying the needs of a complete and realistic sustainability assessment.

From the investigation conducted so far, key findings emerge: it is understood that the construction industry still lacks an integrated and systematised methodology for assessing the triple-bottom-line sustainability of building projects, considering the impacts generated from the extraction of raw materials to the building end-of-life phase and benefiting the decision-making process throughout the whole building lifecycle. In addition, there is still a need to develop more guidelines related to the social and economic impacts generated by construction so that the sustainability assessment encompasses the three pillars comprehensively. This is a significant research gap, directly affecting the achievement of more sustainable buildings.

In this context, the proposed framework adds to a growing corpus of research showing the steps to be taken to create an iterative building sustainability assessment. This addresses RQ1 by offering a strategy to extrapolate the discussion on BIM-LCSA integration, usually focused exclusively on the early design stages of a building project. The workflow proposed in this study demonstrates the possibility of applying LCSA during different building phases with the aid of a building digital twin. By centralising data and information in the same digital model and adopting a project management methodology focused on achieving sustainable goals, it will become much easier to carry out life cycle assessments at different stages of the building's life cycle via the application of different levels of Digital Twins.

Many researchers support the integration of BIM and lifecycle techniques during the building design stage, as at this stage, there is a great ability of stakeholders to influence the project, which decreases as the project progresses toward completion. However, the LCSA methodology is severely limited by the lack of information available at the beginning of the project. Therefore, thinking of sustainability assessment as an iterative process, which evolves along with the building, is essential. It is proposed that the LCSA results in the pre-construction phase improve design decisions and that, later, the digital model continues to be fed with real-time data so that new LCSAs can be applied and assist in the construction, renovation, and maintenance of the building. It is also expected that practitioners consider the future of individual elements and components since their impacts can be calculated and analysed through the integration of LCSA and BIM-based digital twin. Deconstruction practices should be tested and compared in order to benefit the decision-making process during the building's end of life.

In turn, one primary application that a BIM-based digital twin can play a significant role in is ensuring that the sustainability assessment of a building takes into account temporal information. As implemented in conventional LCSA, using a fixed time horizon deprives practitioners of essential information, making sustainability assessments less realistic. The proposed framework, therefore, addresses RQ2 by offering a dynamic LCSA approach to be carried out in different stages of the building. With the aid of the BIM-based digital twin, LCSAs are always expected to be based on real-time data. Using IoT sensors and devices will make it possible to collect the data automated and improve sustainability assessments. Dynamic LCSA can then be applied whenever new decisions need to be made during the building's life cycle.

6 Conclusion and Further Research

This paper elaborates on viable ways to integrate a BIM-based digital twin with the LCSA methodology, focusing on the sustainability assessment of buildings. This integration is proposed considering the building sustainability assessment as an iterative process, evolving from the earlier design stage to the building's end of life. Although research has illuminated the importance of combining different technologies to aid the application of LCSA to buildings, the integration of LCSA, BIM, and Digital Twin in a building remains briefly addressed in the literature. The combination of these concepts can be used to benefit the decision-making process of which materials and methods would be most suitable for construction, as well as the most appropriate decisions during construction and post-construction, considering the three pillars of sustainability in the assessments.

Ultimately, applying LCSA as an iterative process based on a digital twin of the building is strongly recommended as it helps deal with the subjectivity of choices made by the decision-makers and, therefore, offers an avenue to achieve a more sustainable built environment. The proposed integration can be advantageous throughout the information supervision of building processes, with direct effects on the three pillars of sustainability. Besides, the proposed framework allows continuous monitoring and improvement of the built asset, with real-time analyses performed. The application of LCSA in this context is very beneficial, as it becomes a dynamic approach that considers time-dependent parameters and, therefore, is much more reliable and realistic.

The limitations of this work can be stated as follows. Analysing the lifecycle sustainability of a building while considering the three pillars of sustainability is extremely difficult since it necessitates a thorough understanding of uncertainties as well as the processing of large amounts of data. As a result, several technological challenges may arise while integrating LCSA and BIM-based digital twins. Future works by the authors will focus on addressing these challenges. Besides, future research will concentrate on the practical application of this framework, with validation of its use through an actual building case study.

7 Acknowledgement

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) – Finance Code 001.

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Self-rated Motivational Drivers for Occupant Behaviours: A Case Study of Tertiary Office Buildings

Achini Shanika Weerasinghe[1*], Eziaku Onyeizu Rasheed[1] and James Olabode Bamidele Rotimi[1]

[1]School of Built Environment, Massey University, East Precinct, Gate 1, Albany Expressway (SH17), Albany 0632, NEW ZEALAND

A.Weerasinghe@massey.ac.nz; E.O.rasheed@massey.ac.nz; J.Rotimi@massey.ac.nz
* Corresponding author

Abstract:
Occupant behaviour is a significant contributor to the energy consumption of buildings. Dynamic and complex factors drive occupant behaviours, necessitating a focus on how occupants' comfort preferences, perceived user control, and other subjective factors influence such behaviours. Therefore, this paper presents findings from a case study of occupants' perceived environmental beliefs, individual control, and multi-domain reasons for their behaviours, considering the seasonal variance and time-related factors in a New Zealand tertiary office building. The data were collected through online surveys from 99 office occupants and evaluated using descriptive analysis to highlight the relationships between the study variables. The results highlight that the occupant behaviours are motivated by their comfort preferences and other subjective aspects. However, occupants may be conservative in evaluating the perceived indoor environmental quality (IEQ) satisfaction and control, and their influence is relatively unknown. Therefore, the study will help researchers, policymakers, energy modelers, and building managers to identify these hindrances to improving occupant behaviour models.

Keywords:
Building control, comfort preferences, energy saving, indoor environment, occupant behaviours

1 Introduction

Despite the high energy-consuming systems in buildings to improve user comfort, research reports occupants' dissatisfaction over these generally accepted indoor environmental conditions (Cheung *et al*., 2022). Interaction between building occupants and the indoor environment creates unique challenges in building energy use, overall performance, and occupants' comfort satisfaction (Bavaresco *et al*., 2021; Hong *et al*., 2015). Previous research indicates that occupant behaviours (i.e., window use, blind use, thermostat adjustment, lighting adjustment, and appliance usage) generate 47% more heating energy in commercial buildings (Schakib-Ekbatan *et al*., 2015). Therefore, unpredictable and random occupant behaviours are possible depending on access to building systems to modulate the building's thermal, air quality, visual, and acoustic conditions for their preferences (Heydarian *et al*., 2020). As Azar *et al*. (2020) showed, building occupants and buildings have a two-way interaction where existing indoor environmental conditions influence the occupant behaviours, which in return, the way occupants behave influences the future status of the indoor environment. For instance, the occupants adjust the thermostat to cope with the indoor environment, which can aggravate the dissatisfaction and deviate the actual energy consumption from what was predicted (Hong *et al*., 2015). Recently, the influence of occupant behaviours in buildings gaining attention to optimise occupant comfort and energy efficiency in buildings (D'Oca *et al*., 2017).

1.1 Previous research

The existing occupant behaviour models are primarily based on building physics, occupancy presence, and movement (Yan et al., 2017). The literature already supports the influence of indoor environmental parameters such as thermal, visual, air quality, and acoustic on occupant behaviours (Hong et al., 2015). For example, office building occupants mostly tend to open windows in the summer rather than winter (Bourikas et al., 2018). Similarly, Park and Nagy (2020) introduced HVACLearn, an Occupant-Centric Controller (OCC) for thermostats, that occupants could express the thermal sensation as too cold or too hot. In another study, He et al. (2019) explained that indoor or outdoor temperatures are the primary triggers of fan usage. The researchers have produced occupancy models for accurate building simulations incorporating occupant schedules and thermal set points to improve the predictions on random walk patterns (Das et al., 2019). Unlike the above behaviours, the occupants determine the blind position based on solar radiation, illuminance, and glare (Bavaresco and Ghisi, 2020). Apart from the above environmental factors, studies suggested that comparing perceived satisfaction and effectiveness over the individual control of the indoor environment in buildings is relevant to addressing occupants' random behaviours (D'Oca et al. 2017). For instance, Vellei et al. (2016) discovered that occupants' perceived control promotes energy-saving adaptive behaviours, such as wearing more clothes when they feel cold and controlling the windows more effectively. The occupants' response to the availability and accessibility of building control systems were concerns of a considerable amount of studies (D'Oca et al., 2017). Some studies also focused on time-related aspects as crucial factors of occupants' interaction with building systems and appliances, particularly the day and time. Different approaches have been used to evaluate the window opening frequency, and it was found that the opening frequency increases at specific times (Stazi et al., 2017). Furthermore, the occupants tend to switch on lights upon arrival and keep them on until they leave the office (Norouziasl et al., 2019). However, the scope of studies is limited to one or a few behaviours, and the most influential set of factors at a time. Therefore, a comprehensive study focusing on most behaviours and the combination of influential factors is timely needed.

1.2 Research aim and questions

Significant interest has been given to investigating the influence of IEQ satisfaction and multi-domain comfort preferences on occupant behaviours (Bavaresco et al., 2021). However, the scope of these studies is limited only to a few of the selected behaviours, like operating windows, blinds and shades, adjusting thermostats, and switching on/off artificial lights. Although these studies focus on seasonal variance and its influence on IEQ satisfaction and comfort preferences, the focus is not on particular time-related factors. At the same time, the previous studies emphasise the influence of extending these investigations to different geographic locations (i.e., countries and regions). To this end, this study aims to evaluate the office building occupants' perceived beliefs on indoor environmental quality (IEQ) and the availability of individual control over building systems and appliances, then analyse the multi-domain reasons that drive occupant behaviours giving due consideration to the seasonal variance and time-related factors in the New Zealand context. Within the scope of this study, the focus has been given to investigating occupant behaviours like windows, doors, lighting, shades and blinds, fans, thermostats, computers, drinking beverages, adjusting clothing levels, and moving through spaces. The specific questions that the study is trying to answer are; RQ1. What do occupants perceive about their indoor environment and the availability of control? RQ2. What are the multi-domain reasons that drive specific occupant behaviours? RQ3. How do occupant behaviours differ at different time instants in a typical day?

2 Research Methodology

The study investigates the relationship among office building occupants' perceived beliefs on IEQ, the availability of individual control over building systems and appliances, and the multi-domain reasons for their behaviours in a university case in New Zealand. The study adopted a survey approach. A questionnaire was developed referring to the knowledge from IEA EBC annex 66 on the definition of occupant behaviours (Yan et al., 2017), factors affecting occupant behaviours (Fabi et al., 2012), and thermal, visual, acoustic, and air quality discomfort-related and other subjective drivers (i.e., physiological and social psychological reasons) (Bavaresco et al., 2021). For instance, Yan et al. (2017) explained that "occupant behaviour includes occupant presence, movement, and interaction with building energy devices and systems". Fabi et al. (2012) divide the factors influencing occupant behaviours into five categories physical environmental, contextual, psychological, physiological, and social, including internal and external factors. Within the scope of this research, the study focus on physical environmental (i.e., IEQ satisfaction, season) and contextual (i.e., availability of control, time-related) factors.

The questionnaire consists of three sections. The first section includes questions relating to different IEQ parameters: indoor temperature, indoor air quality, lighting (natural and artificial light), and noise (inside and outside noise) for both seasons according to a unique five-point Likert-type scale for each parameter. The two extremes of the Likert scale were coded as 1 (too cold, too stuffy, too dark, too quiet) and 5 (too hot, too draughty, too bright, too noisy). Section two asks about the control available for workplace appliances and building systems using a three-point Likert-type scale (no control – 1 and full control – 3). Also, if any appliance and system were unavailable at the workplace, occupants were given a choice to select "not available." In the third section, the multi-domain reasons and the occurrence of behaviours during different time instants (i.e., upon arrival, during the daytime, and upon leaving) in terms of interaction with windows, doors, lighting, shades and blinds, fans, thermostats, and computers, as well as other behaviours like drinking beverages, adjusting clothing levels, and moving through spaces. These questions were given in check-all that-apply questions format. The questionnaire was distributed online through the Qualtrics survey platform from August 2021 to January 2022. Individual links were sent to 1258 office occupants of three office buildings in the university, which had the most participants during the COVID and post-lockdown period in New Zealand. However, there were only 266 participants who were the primary occupants of the selected offices. Accordingly, 99 valid responses were collected, excluding the incomplete responses, and the responses came from occupants who did not work in office space. The response rate is 37% from the 266 primary occupants. The data collected were evaluated using descriptive analysis to highlight the relationships between the study variables using MS Excel and Visual Paradigm Online software.

3 Findings and Discussion

3.1 Participant profile

As seen in Table 1, respondents comprise most males (53%) and building occupants aged 30 or older (92%). Ethnicity-wise, most respondents were New Zealand Europeans (70%). Amongst the respondents, 77% have been working in the building for a year or more, 67% have worked in the current workplace for a year or more, and 52% work five days or more every week. These higher percentages on work duration provide insights into that most occupants are familiar with their surroundings.

Table 1. Demographics of the participants

Demographic		Count	(%)	Demographic		Count	(%)
Gender	Male	52	53%	Work duration in the building	A year or more	76	77%
	Female	47	47%		Less than a year	22	22%
Ethnicity	NZ European	69	70%	Work duration present workspace	A year or more	66	67%
	Asian	10	10%		Less than a year	32	32%
	Māori or Pacific	3	3%	Days of work	5 days or more	51	52%
	Other	17	17%		Less than 5 days	47	47%
Age	30 or older	92	93%	Age	Under 30	7	7%

3.2 Occupants' perceived beliefs on indoor environmental quality (IEQ)

Figure 1 shows the percentage of occupants' perceived beliefs on each parameter. An average of 45% in temperature, 63% in air quality, and 70% in inside and outside noise indicated "About right". Although occupants' beliefs in natural light and artificial light show a slight deviation, it shows a similar pattern in winter and summer, while a majority (more than 45%) believe the noise is "Above right". Additionally, when considering the temperature parameter, 43% of participants responded, "Too cold" and "Cold" in winter, while 49% responded, "Too hot" and "Hot" in summer. In terms of air quality, more than 20-30% of participants indicated that the environment is "Too stuffy" and "Stuffy" in winter and summer. Another parameter influenced by seasonal factors is lighting, where 40% indicated the natural lighting is "Too dark" and "Dark" during winter.

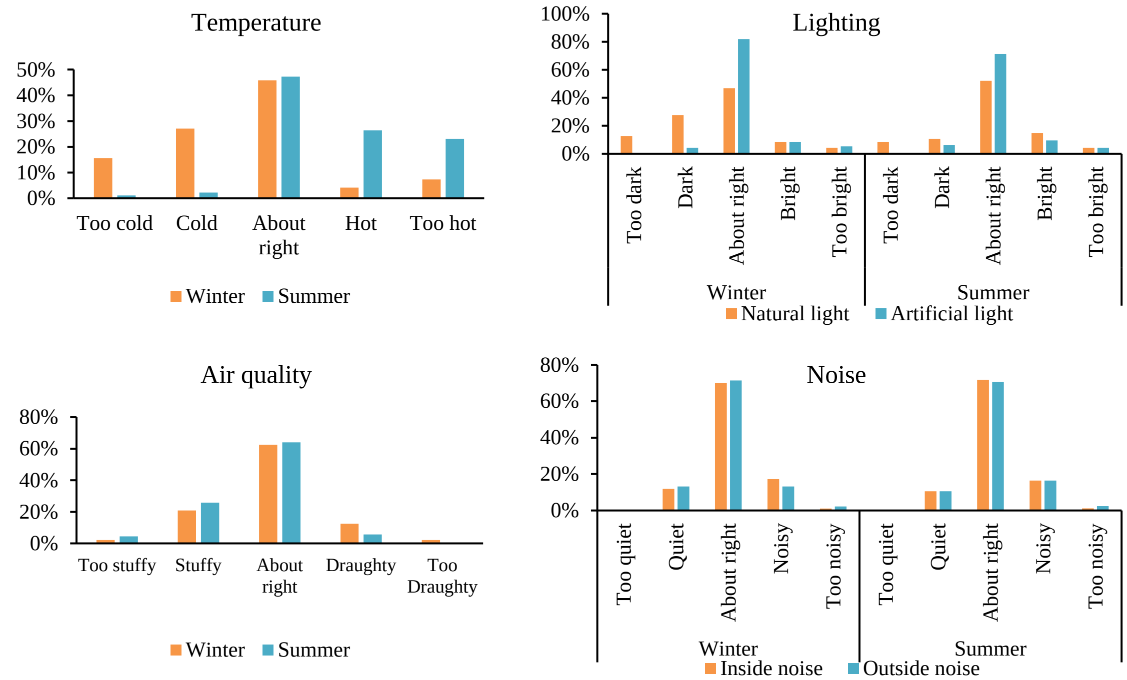

Figure 1. Occupants' perceived beliefs on temperature, air quality, lighting, and noise

3.3 Availability of individual control over building systems and appliances

Figure 2 illustrates the percentage of occupants rating the availability of individual control over the indoor environment and building systems at their workspace. As shown in Figure 2, more than 50% of participants have full control over windows, doors, shades and blinds, artificial lights, personal fans, and computers. Compared to the above systems, full control over portable heaters (38%) and thermostats (17%) is significantly less. However, some participants have somewhat control over portable heaters and thermostats; therefore, overall control over these two items is slightly higher than 50% but comparably less than the other systems. The appliances and systems with the least control are ceiling fans (less than 10% control). The amount of control available on building appliances and systems can significantly influence the occupants' behaviours. With this in mind, the forthcoming section analyses the multi-domain reasons for these related behaviours to determine the influence of IEQ satisfaction and individual controls motivating occupant behaviours.

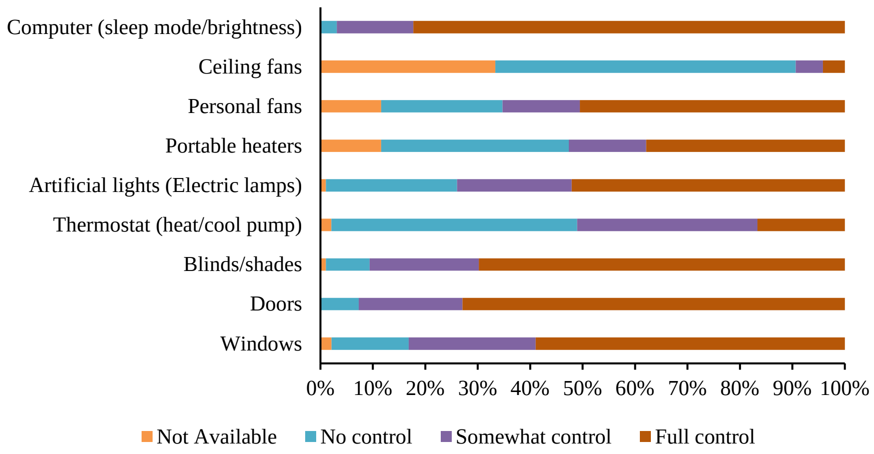

Figure 2. Occupants' rating for the availability of individual control

3.4 Multi-domain reasons for their behaviours

In this section, the paper analyses the multi-domain reasons for occupants' behaviours. The self-disclosed multi-domain reasons for these behaviours are illustrated in Figures 3 to 6, and the sum of responses is greater than 100%. For a given action (e.g., opening windows during the summer to feel cooler), each percentage represents the proportion of that particular action compared to other actions.

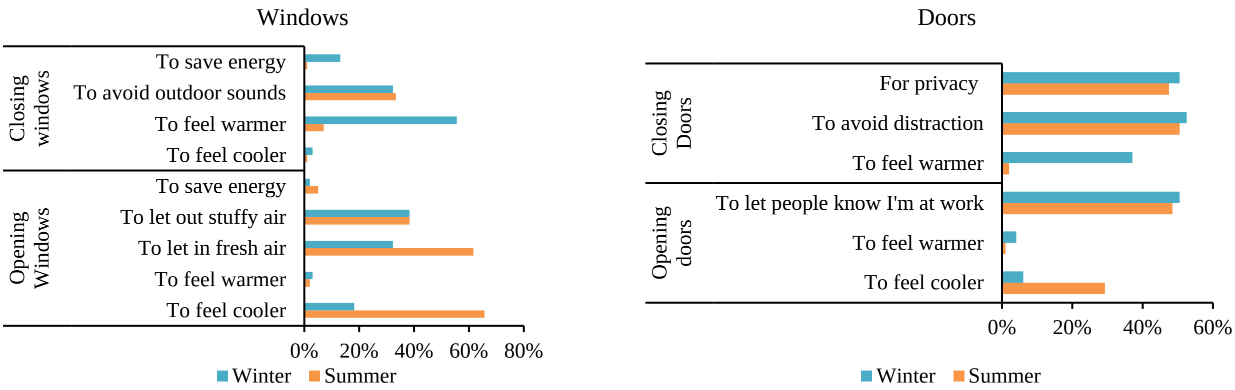

Figure 3. Multi-domain reasons for adjusting windows and doors

As seen in Figure 3, the occupants mainly open windows to feel cooler (66%) and to let in fresh air (62%) in summer. In winter, more than 32% of occupants open windows to let in the fresh air. On the other hand, occupants close windows mainly to feel warmer (56%) in summer. However, some drivers seem unaffected by seasons – 30-40% responded to opening windows to let out stuffy air and closing windows to avoid outdoor sounds. Other motivational drivers: saving energy received fewer responses in both seasons, highlighting that occupants mainly prioritise their personal needs when adjusting windows. The seasonal effect was mainly observed when occupants opened doors to feel cooler (29%) in summer and closed doors to feel warmer (37%) in winter. However, other subjective drivers are unaffected by seasons. An average of 50% of occupants reported opening doors to let people know they were at work and closing doors for privacy and to avoid distraction. In both cases (windows and doors), most occupants show opposite actions to feel cooler and warmer.

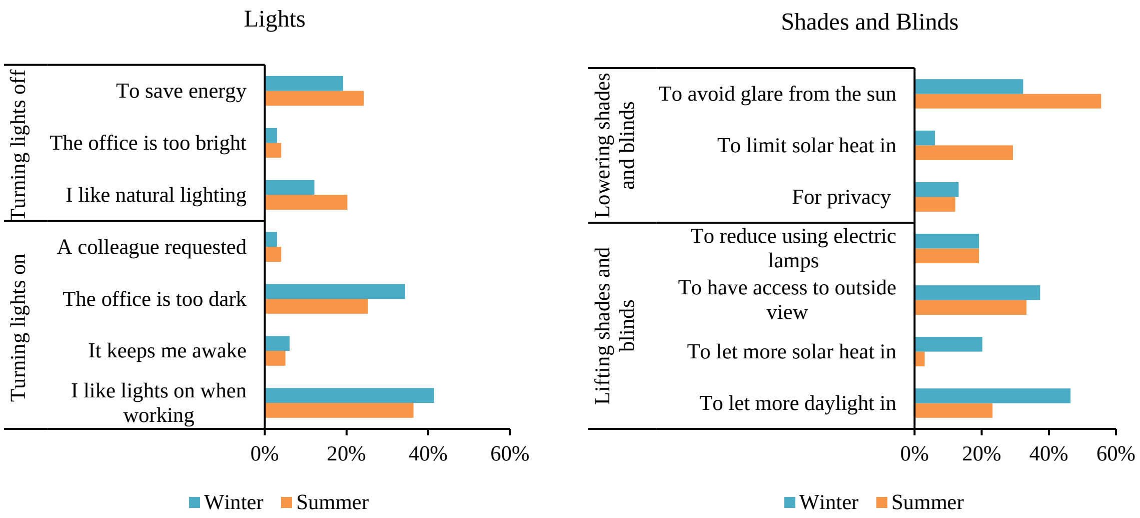

Figure 4. Multi-domain reasons for adjusting lights and shades and blinds

As illustrated in Figure 4, although lighting adjustments were investigated considering the seasonal variance, all drivers seem unaffected by the season. Most occupants turn on lights because they like lights on when working and the office is too dark. These drivers show slight changes (less than 10%) across summer and winter: like lights on when working (36% in summer and 41% in winter) and the office being too dark (25% in summer and 34% in winter). Also, what stimulates turning on lights does not necessarily influence turning them off. Occupants reported that they turn off the lights to save energy (24% in summer and 19% in winter) and because they like natural lighting (20% in summer and 12% in winter). Other subjective drivers showed fewer responses and were unaffected by the seasons (i.e., it keeps me awake, a colleague requested, the office is too bright). Like windows and door adjustments, the multi-domain comfort preferences (thermal and visual) influence the adjustments of shades and blinds with the effect of seasonal variance. Most occupants reported that they lift/open shades and blinds in winter to let more daylight in (46%) and to let more solar heat in (20%), while they lower/close shades and blinds to avoid glare from the sun (56%) and to limit solar heat in (29%). However, visual preferences are essential in both seasons, and a considerable number of participants responded that they lift/open shades and blinds to let more daylight in (23%) in summer and lower/close shades and blinds to avoid glare from the sun (32%) in winter. The occupants also lift shades and blinds to access the outside view (~35%), unaffected by the season. Other motivational drivers that were unaffected by the season are to reduce using electric lamps (19%) and privacy (12%).

As seen in Figure 5, motivational drivers on occupants' adjustments of ceiling fans, portable fans, thermostats, and computer brightness were investigated, giving due consideration to seasonal variance. Most occupants (66%) responded that they adjust portable fans to feel cooler in summer. In terms of fans, that is the only significant response received, while the other motivational driver: saving energy, does not add up to this behaviour. Moreover, most (40%) reported that they adjust thermostats to feel warmer during winter, while another 11% reported that this behaviour is motivated by their preference to feel cooler in summer. Thus, adjusting the thermostat is significantly influenced by seasonal variance. Unlike other behaviours, adjusting computer brightness received less than 20% responses for each motivational driver and was only slightly influenced by the seasonal effect. The opposite actions were observed across the two seasons, where occupants adjusted computer brightness due to ambient lighting being too dark in winter (18%) and too bright in summer (16%).

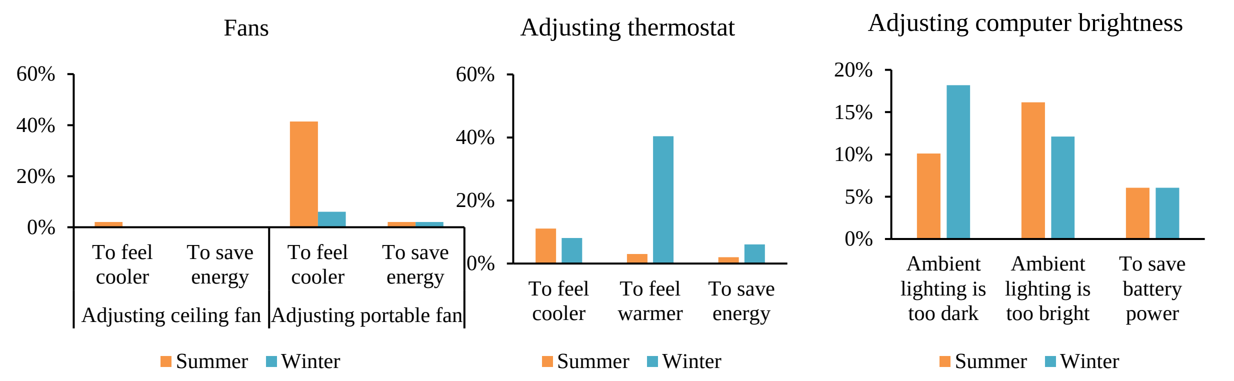

Figure 5. Multi-domain reasons for adjusting fans, thermostats, and computers

As presented in Figure 6, drinking beverages are motivated by thermal comfort preferences and other subjective drivers affected by the season. The opposite actions were reported where occupants drink cold beverages to feel cooler (51%) in summer and drink hot beverages to feel warmer (44%) in winter. Occupants also drink beverages to take short breaks during work, which is again affected by the seasonal variance. While the choice of drink (cold/hot) has been unchanged during summer (54%), a significant decrease was observed in drinking cold beverages (44%) and an increase in drinking hot beverages (64%) in winter.

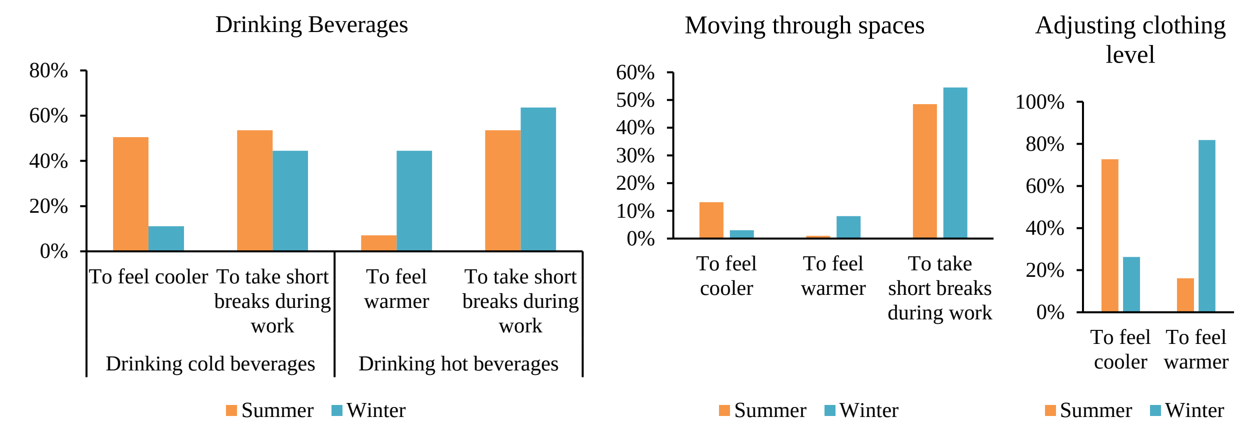

Figure 6. Multi-domain reasons for drinking beverages, moving through spaces, and adjusting clothing levels

Similarly, moving through spaces was significantly motivated by occupants' preference to take short breaks during work. Notably, 55% of occupants reported moving through spaces in winter, and 48% reported moving through spaces in summer to take short breaks during work. The seasonal influence is not apparent relating to this motivational driver. However, fewer occupants responded that they move through spaces to feel cooler in summer (13%) and warmer in winter (8%). Therefore, moving through spaces behaviour was slightly influenced by the season. Possibly offset by the following behaviour: adjusting clothing level. A clear majority indicated that they adjust their clothing to feel cooler in summer (73%) and warmer in winter (82%). Depending on the indoor temperature level during the two seasons, 26% of occupants also reported the clothing behaviour to feel cooler in winter, while another 16% responded to this behaviour as feeling warmer in summer.

3.5 Time-related drivers influencing occupant behaviours

The occupant behaviours were assessed regarding their occurrence during different time instants: upon arrival, during the daytime, and upon leaving. Figure 7 illustrates the punch card diagram drawn using the number of responses (counts) received for each behaviour for these three time-related drivers.

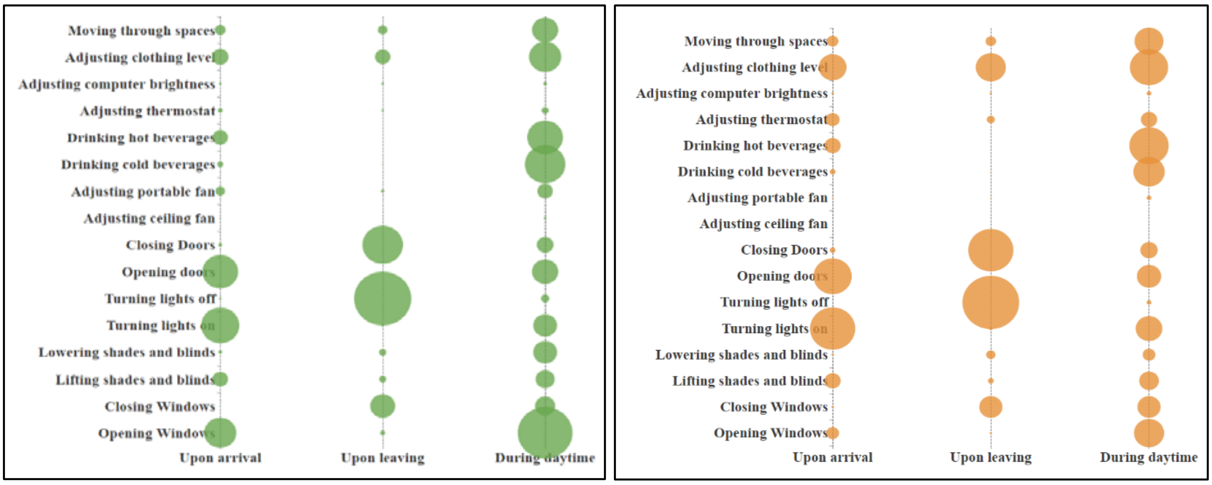

Figure 7. Occupant behaviours during different time instants: upon arrival, upon leaving, and during the daytime in Summer (left side) and Winter (right side)

As shown in Figure 7, most occupants turn lights on and open doors upon arrival in both summer and winter. Although most occupants practice opening windows upon arrival in summer, it is significantly less in winter. Rather many occupants responded that they adjust their clothing upon arrival in winter, highlighting the influence of seasonal variance on their behaviours. Other considerable behaviours upon arrival in both seasons are drinking hot beverages and lifting shades and blinds while adjusting the thermostat, mainly in winter. Upon leaving, most occupants responded that they turn off lights and close doors and windows in both summer and winter while adjusting clothing in winter before they leave the workplace. Compared with arrival and leaving, most behaviours occur during the daytime in both summer and winter, and most behaviours are unaffected by the season. The seasonal influence was significantly visible for opening windows, while adjusting portable fans and thermostats was slightly affected by season. Other behaviours: drinking hot/cold beverages and adjusting clothing levels were significantly practiced by occupants during daytime compared to arrival and leaving and were unaffected by season. A few more behaviours were identified that were unaffected by the season. Notably, moving through spaces and lowering shades and blinds behaviours were higher than arrival and leaving instants, while occupants showed lesser practice on opening doors and turning lights than upon arrival. Similarly, closing doors is less during daytime compared to upon leaving. However, closing windows showed a similar pattern upon leaving and during daytime, while lifting shades and blinds had a similar pattern upon arrival and during daytime.

3.6 Discussion

The results show mostly a neutral belief on thermal, air quality, visual, and acoustic parameters in the workspace, thus indicating occupants' satisfaction or being in the comfort/acceptance range. However, a significant proportion of occupants also reported thermal discomfort mainly influenced by seasonal variance, and comparably fewer occupants reported discomfort in other parameters. Our results partially align with Cheung *et al*. (2022), who reported the most satisfaction with artificial and natural lighting and the least satisfaction with the stuffiness, noise level, and air movement compared to the temperature. Overall perceived control for portable heaters and thermostats was limited compared to other building systems and appliances. Thermal and air quality satisfaction levels increased when perceived control over building systems and appliances increased (Vellei *et al*., 2016). However, our study needs in-depth evaluations to validate this relationship further.

Multi-domain drivers for occupant behaviours were highlighted in the current study. Notably, personal comfort preferences (a combination of physical environment and physiological factors) play a significant role in opening and closing windows and doors in summer and winter. The literature supports occupants' tendency to open windows in the summer rather than winter (Bourikas *et al*., 2018). Furthermore, occupants open windows to have fresh air and close windows to reduce outdoor noises (Bavaresco *et al*., 2021). Additionally, our results suggest that occupants' door behaviour is mainly driven by subjective factors, unlike windows. Our results highlighted that habitual reasons mainly cause occupants' lighting behaviours than ambient features. Our results highlighted that habitual reasons mainly cause occupants' lighting behaviours than ambient features. Regarding shading and blinds, our results support that occupants tend to adjust those depending on the radiation, illuminance, and glare (Bavaresco and Ghisi, 2020). Also, appreciating the outside view and the concern about their privacy are other motivating drivers of this behaviour. Thermal comfort preferences were highlighted as the main drivers of adjusting portable fans and thermostats than occupants' intentions to save energy. However, ceiling fans are rarely adjusted because they are unavailable in many offices, and occupants do not have control over them. The current study's findings support the literature that explains occupants' thermal expectations as the primary triggers of fan usage and thermostat behaviour (He *et al*., 2019; Park and Nagy, 2020). Although most occupants have control over their computers, an average of 35% of occupants adjust computer brightness based on ambient lighting and their intention to save energy. The responses to drinking beverages, moving through spaces, and adjusting clothing levels highlight that many occupants prefer personal adjustments to thermal preferences together or instead their interactions with building appliances and systems. Drinking beverages and moving through spaces are mostly habitual and contributing factors to metabolic rate, thus widely influencing indoor thermal comfort (Fabi *et al*., 2012; Hong *et al*., 2015). Considering time-related factors, occupants mostly turn on lights and open doors upon arrival and turn off or close them when leaving, which has also been reported in the literature regarding lighting behaviour (Norouziasl *et al*., 2019). Although open and closing windows are also practiced upon arrival and leaving, most occupants tend to adjust windows during the summer, when the indoor temperature gradually increases during the day (Stazi *et al*., 2017). At the same time, personal adjustments like clothing, drinking beverages, and moving through spaces are also primarily visible during the day.

4 Conclusion and Further Research

This study enables the important links between IEQ beliefs, user control, and the multi-domain drivers for occupant behaviours. From a theoretical point of view, IEQ satisfaction and control availability may significantly influence occupant behaviours. Similarly, our results highlight that the occupant behaviours are motivated by their comfort preferences and other subjective aspects. At the same time, the results highlighted that occupants might be conservative in evaluating the perceived IEQ satisfaction and control, and their influence is relatively unknown on the occupant behaviours. Therefore, the research can be further extended by integrating physiological factors (gender, age, ethnicity) and social-psychological factors (attitudes, norms, interventions) to dot the missing links between occupant decision-making on their behaviours. Compared to the existing studies in this field, the study investigated the multi-domain reasons and time-related patterns of occupant behaviours relating to windows, doors, lighting, shades and blinds, fans, thermostats, computers, drinking beverages, adjusting clothing levels, and moving through spaces, while the previous studies limited to only a few of the behaviours at once. Accordingly, the study will help researchers, policymakers, energy modelers, and building managers to identify these hindrances to improving occupant behaviour models. However, the data is collected from three selected buildings of one case study; therefore, the occupant behaviour could be affected by the energy culture and other characteristics of the selected case study. Therefore, further research is recommended with an increased number of cases.

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Sustainability-Enabling Field in Mega Transport Projects: Insights from Two Cases in India

Nicola Thounaojam[1], Ganesh Devkar[2] and Boeing Laishram[1*]

1Department of Civil Engineering, Indian Institute of Technology Guwahati, Guwahati, India
2Faculty of Technology, CEPT University, Ahmedabad, India

nicola@iitg.ac.in; ganesh.devkar@cept.ac.in; boeing@iitg.ac.in
* Corresponding author

Abstract:
Many mega transport projects (MTP) have been planned and implemented worldwide to improve urban mobility and promote sustainable transportation. These MTPs provide enormous opportunities to reduce carbon footprints and improve socio-economic activities in an urban setting. In recent years, there has been an increasing interest in investigating the sustainability principles of MTPs because of short-to-long-term environmental and socio-economic impacts and shortfalls in efforts from governments and public and private parties. MTPs are not closed systems; influences in institutionalising sustainability come from interactions and interventions of actors in the field and institutional drivers. Therefore, using the lens of the organisational field and empirical data from two metro rail projects in India, this study attempts to examine the elements that frame the institutionalisation of sustainability in mega transport projects. This study used multiple data sources (interviews, documents, media reports) to identify various sustainability-enabling fields aspects, including actors in the field, institutional logics and governance arrangements. The findings show emergence of diverse field actors and governance arrangements, some parallels between the two projects and some arranged differently. In addition, the findings reveal multiple logics co-existing in the projects that aid or impede field actors from engaging in sustainable performance and outcomes of sustainable practices. Projects' institutional environments related to institutionalisation of sustainability differ; therefore, comparing the two cases provides an interesting context to examine the dynamics of institutional logics and context-specific institutions. Understanding the field and dynamics that trigger and support sustainability actions is critical for decision-makers in advancing sustainable development in megaprojects.

Keywords:
Infrastructure, Institutional Theory, Megaprojects, Organisational Field, Sustainable Development.

1 Introduction

Many mega transport projects (MTPs) have been planned and implemented in developed and developing countries to compete against rapid urbanisation, economic competitiveness, and growing social and environmental challenges. Despite these projects being capital intensive, governments are going for mass and light rapid transport and monorail. These MTPs provide enormous opportunities to reduce carbon footprints and improve socio-economic activities in an urban setting. However, the construction of public transportation infrastructure has a range of immediate and long-term impacts on the environment (Gharehbaghi *et al.*, 2022), including effects on groundwater, noise and vibration, pollution, and erosion or geological impacts (Harris *et al.*, 2018). They typically cause widespread population displacement and disagreements amongst the many project stakeholders, which poses major social sustainability issues that ultimately hinder the successful completion of these megaprojects (Jonny Klakegg, 2009). In addition, there are severe shortfalls in efforts from governments and public and private parties, endangering the achievement of targets set for sustainable development goals (Sankaran *et al.*, 2020). In India, the main flaws that negatively affect progress toward sustainable development include incomplete environmental impact assessments and social impact assessments, a lack of local and stakeholder participation, high bid and transaction costs, high user fees, improper risk allocation, a lack of transparency and accountability, conflicts of interest between the public and private sectors, and a lack of sustainability expertise and knowledge (Agarchand and Laishram, 2017; Thounaojam and Laishram, 2021).

Therefore, there is an urgent need for a “sustainability sublime” to drive megaprojects’ decision-makers in integrating sustainable development principles (Sankaran *et al.*, 2020). However, the megaprojects' decision-making, management, and coordination process are affected by the interactions of numerous actors with various conflicts of interest, politics, and institutional factors (Li *et al.*, 2019). There are intricate and dynamic relationships between and within organisations, and these relationships give rise to distinct organisational fields. Therefore, megaproject's sustainability is influenced by various parties, which implies a wide range of sustainability-related issues from the outset (Romestant, 2020). Additionally, several coexisting logics in megaprojects may serve as motives for engaging in sustainable performance and outcomes. Given this complex social context, little effort is put into analysing how various players interact and intervene when influenced by sustainability-enabling institutions and divergent logics of goals to achieve sustainability. Organisational field is as apt for analysing this interesting scenario (Thounaojam *et al.*, 2022). Therefore, using the organisational field approach of institutional theory, this study aims to examine the elements that frame the institutionalisation of sustainability in the megaproject field.

2 Theoretical Foundations

2.1 Organisational Field

The field concept is a keystone in institutional analysis and draws attention to how field actors embed within the system of relationships as the enabling condition for actions towards institutions (Jacob *et al.*, 2022). An organisational field is “a community of organisations that partakes of a common meaning system and whose participants interact more frequently and fatefully with one another than with actors outside of the field” (Scott, 1995, p.56). Jooste and Scott (2012); Scott (2014) highlighted three salient aspects of organisational field concept: actors, logics and governance arrangements. Together, these aspects coerce and enable action within the fields and thereby mould the behaviour and characteristics of organisational participants (DiMaggio and Powell, 1983). Organisational field actors include “both individual actors (persons) and collective actors (organisations)” (Scott, 2012, p.31), as they perform socially designated roles and functions within the field. Institutional logics refers to “the beliefs systems and associated practices that operate within a field” (Scott, 2012, p.30). And the action in organisational field is shaped by these logics. They constitute cultural cognitive elements that provide the “basis for field construction, allowing a shared understanding of what is going on in the field” (Scott, 2014, p.225). Governance arrangements refer to “those arrangements which support the regularised control, whether by regimes created by mutual agreement, by legitimate hierarchical authority or by non-legitimate coercive means of actions of one set of actors by another” (Scott, 2014, p.231).

2.2 Organisational Field in Megaprojects

Few scholars in infrastructure studies have recently embraced organisational field approach to examine how interactions of various field actors govern the complexities and challenges of projects. For instance, a study on PPP (public-private partnerships) (public-private partnerships) adopted organisational field concept to explore how actors respond to institutional structuration in transforming an airport from a government entity into a PPP model (Biygautane *et al.*, 2020). Furthermore, Narayanan and Huemann (2021) studied project managers' activities to address the challenges of organizational fields in an emerging economy context. Jooste and Scott (2012) adopted organisational field approach to investigate the emergence of diverse organisations that enables and governs infrastructure PPPs in three international contexts. While prior research on sustainability has adopted institutional theory to provide practical insights into how institutional elements affect sustainability-related practices (Glover *et al.*, 2014; Misopoulos *et al.*, 2018; Ullah *et al.*, 2020), these studies did not provide nuanced understanding and analysis of how these institutional elements appear, interact and interpose in an organisational field (Thounaojam *et al.*, 2022).

Apart from the many sustainability-related problems such as noise and air pollution, waste generation, and greenhouse gas emissions, megaprojects have diverse stakeholders with conflicting interests who govern the project's sustainable actions. These problems demand the decision-making of megaprojects to consider a wider organisational field and examine the interconnections between the social actors (Li *et al.*, 2019). Actors in megaproject field normally do not act in isolation but act together to influence and imitate one another (Thounaojam *et al.*, 2022). Therefore, the field approach is relevant to this study to understand the interplay between field actors in governing sustainability in projects.

Within the megaproject sustainability field, key organisational actors include project-specific companies (such as the executing agency, the contractors, and consultants), governmental agencies (such as environmental or pollution control boards), international bodies (such as the funding agencies, green organisations), the general public, special interest groups, non-governmental organisations (NGOs), and project-affected peoples. Actions within megaproject field act under the demand of multiple organisational actors and may have to tackle two or more contrasting institutional logics (Matinheikki *et al.*, 2021; Thounaojam *et al.*, 2022). Together, sustainability is often criticised for being intangible or lacking intelligibility as to what is to be sustained and by whom (McNally *et al.*, 2009). Therefore, exploring institutional logics and comparing them between projects can be valuable in explaining the dynamics and factors that trigger and support sustainable practices in the field.

The governance arrangements in megaprojects involve various formal and informal systems, with each organisation field actors employing a combination of regulatory and normative mechanisms over activities within the field. Regulative mechanisms are apparent and primarily coercive, and they usually emerge from government departments through governmental laws and regulations, contract clauses, legal penalties and market incentives (Thounaojam *et al.*, 2022). On the other hand, normative mechanisms originate from prescriptive and obligatory dimensions through self-regulatory systems, such as international management standards (ISO 14001), voluntary green certifications or eco-labelling.

3 Research Methodology

In many megaproject studies, case studies have been prominently used as a research method (Zidane *et al.*, 2015; Harris *et al.*, 2018; Cantarelli, 2022; Tsagkari *et al.*, 2022). As Hartley (1994, p.208) put it, case studies allow a "detailed investigation of one or more organisations, or groups within organisations, with a view to providing an analysis of the context and processes involved in the phenomenon under study". This study aims to examine the elements that frame the institutionalisation of sustainability by the actors in the field of mega transport projects. And case studies can be a helpful research method for this study. However, as different projects have unique actors with different institutional logics, which is shaped under the influence of regulative, normative and cognitive institutional elements in the field, a comparative case study would be more apt to explore the interactions and interventions of actors in the different fields. In addition, Yin (2003) suggests that single-case design is vulnerable and that multiple case studies may have valuable analytical benefits. The cases need a significant level of difference in the elements of interest but be similar enough to allow for comparison (Stake, 2013). Therefore, this study has chosen two mega transportation infrastructure projects in India from similar sector, metro rail and implemented under the engineering, procurement and construction (EPC) model, which differ in their institutional field. Besides these theoretical considerations, data accessibility has also been considered in case selection, and researchers often use this criterion in case study research (Cantarelli, 2022).

Data for the study were collected through searching and screening relevant documentation and semi-structured interviews with different project actors. Interviews were conducted with nine experts comprising of executing agency, international funding agency, NGO, and governmental green body. The selection of these interviewees is to have representativeness with the field actors. Every respondent represents a senior-level official with 25.5 years of average experience, showing the richness of the data. The current study also analysed various publicly available documents, such as detailed project reports (DPR), environmental impact assessment (EIA) and social impact assessment (SIA) reports, court orders, and newspaper articles. The interviewees were asked to identify various organisational actors and describe their interplay in the sustainability-enabling field. Details were sought regarding their role in the field and the role of governmental rules and regulations, norms and standards that shaped their sustainability efforts in the project. All the interviews, each lasting between 25 and 80 minutes, were recorded in digital format and later transcribed for treatment and analysis.

The description of the case studies is shown in Figure 1. Case A (hereafter DREAM) affected 2,856 built structures, comprising residential, commercial and others, and 2,736 PAF were identified. On the other hand, Case B (hereafter GARDEN) affected 108 structures, especially at the proposed metro station locations. A total of 4,175 and 1,248 trees on the median and station locations were affected for DREAM and GARDEN, respectively. While the alignment of GARDEN does not pass through any forests and eco-sensitive zones, DREAM alignment passes through forest and mangrove areas.

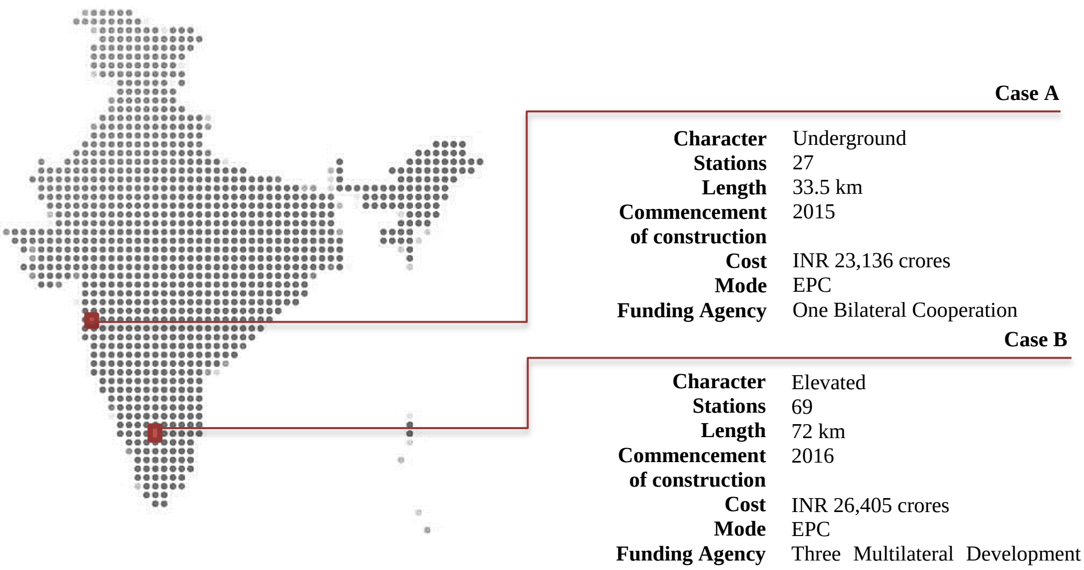

Figure 1. Case Studies Description

4 Findings and Discussion

The findings of this study are presented below in three themes, which are the salient components of organisational field concept: actors, institutional logics and governance arrangements.

4.1 Field actors

The comparative analysis of this study begins with a look at various actors that play a role in the sustainability-enabling field. This section first considers the common field actors both the cases have and thereafter broadens the lens to compare the distinct actors in each case field.

In both cases, the role played by field actors such as the executing agency, international funding agency, consultants, contractors and governmental regulatory bodies is similar. The know-how and interest of the *executing agency* (EA) play a vital role in the sustainability-enabling field (Biswas, 2019). The EA ensures overall compliance with the central and state level social and environmental policies and the safeguard policies of the funding agency. They are also responsible for recruiting consultants for contract supervision, collaboration with NGOs, and monitoring and evaluating environmental sustainability. This study proposes that EA not only act as the prime field actor but could also be contemplated as the essence of promoter for sustainability in the field. The expert from NGT (National Green Tribunal) underlines this:

> *The departments that typically carry out the project are the first and most obvious answer to this. They are the main actor. There is no denying that external departments have some impact. But if you are serious about practising sustainability, it has to start from within the company.*

In both cases, the EAs are joint ventures (JV) of the Government of India and the State Government. These JVs establish *project implementation units* (PIUs) headed by respective project directors. These units, overall, conduct preconstruction activities, monitoring resettlement plans and other project activities. The EAs also directly interact with various *ministries and state-level authorities* for activities such as environmental clearances and pollution control approvals. In addition to these interactions, the EA of DREAM had intense and prolonged interactions with the *residents, NGOs and community-based organisations (CBOs)* for various litigations due to loss of trees and green cover.

International funding agencies (IFA) are appraised for their strict environmental and social safeguard policies and called as “trendsetters on the sustainability front” (Caspary, 2009, p.63). In both cases, IFAs played a crucial role in enabling the project to achieve sustainability in many facets, especially in R&R (Rehabilitation and Resettlement) activities. A single bilateral funding agency funds DREAM, whereas three multilateral development banks fund GARDEN. While the EAs play a part mainly in the engineering aspects of the project, IFAs have a keen eye on social and economic aspects of the project along with funding of megaprojects. In line with this, the expert from IFA of GARDEN commented:

> *So that is where I think organizations like [IFA] try to add value because we really cannot do much on engineering […] the initial projects entirely focus on doing the project and running people from one point to another. But how they connect into the feeder, how they live in that environment, what are the value capture options, […] the transit-oriented development taking around the line, these are the areas where I think value additions are required […] we think that [IFA]or organizations like ours play a huge role in ensuring that this is taken care.*

Metrorail projects often are not financially sustainable as the social welfare component outweighs the typical business considerations such as recovery of capital and operational expenditure and making profits. To overcome this concern, the IFA of GARDEN project stimulated additional value by ensuring financial sustainability of the project through Transit Oriented Development (TOD) and Value Captured Financing (VCF). As the expert from GARDEN IFA noted:

> *Because [GARDEN IFA] as a board also does not want us to give money. They [Government of India] will also want for value addition […] So both of them [TOD & VCF] go towards sustainability of the project. Otherwise, all metros will lose money if you just look at the ticket fare. There is no way they will sustain. So, unless all this is captured, it will end up like many other projects that fail. You can construct it, but it will not run.*

Law and judiciary departments also play a role in ensuring that the projects do not cause any damage to the environment, persons or properties. With DREAM project increasingly involved in disputes due to various environmental reasons such as trees cutting, displacement and pollution, several litigations were filed against the EA. The active role of NGT, a specialised environmental forum, can be seen in this case.

In addition, from the documents and interviews, it came to light that the resources made available by professional associations like United Nations Framework Convention on Climate Change (UNFCCC) were crucial in the sustainability-enabling field. The clean development mechanism (CDM) of UNFCCC is seen adopted in DREAM, and the project is estimated to reduce 26,19,680 tonnes of CO2e in 10 years, allowing the project to earn saleable certified emission reduction (CER) credits. Self-regulatory mechanisms can be seen in DREAM as normative control. The project's station buildings obtained IGBC Green Building certification. On the other hand, GARDEN is still in the process of registering for the same certification for one of its stations.

4.2 Institutional logics

Institutional logics operate more generally at a field-wide level, as general assumptions and beliefs are shared broadly within a field. In an attempt to get the underlying logics, the authors asked experts to express why they think sustainability is essential in the project and what could be the obstacle to embracing sustainability. In addition, the underlying logic was also examined from the rest of the interview data and documents. Understanding the underlying logic can help interpret the processes that drive field actors to interact more frequently and with consequence (Wooten and Hoffman, 2008). Through the "pattern-inducing technique", this study attempted to capture five logics by analysing qualitative data from a bottom-up, inductive approach (Reay and Jones, 2016). This section particularly paid attention to the emergence of cultural-cognitive institutions that would positively and negatively influence sustainable principles in megaproject field. Understanding these logics can help comprehend why specific actions and institutional contexts aid or impede megaproject sustainability.

The formal and informal project appraisals often become challenging when the project environment is politically driven (Lehtonen, 2019). The first logic is *political logic*. Decision-makers in such large projects neglect to incorporate users' needs in articulating project objectives due to political interference (Thounaojam and Laishram, 2021). Such influence of politics may last throughout the project's lifecycle because these large construction projects are often part of election promises and political agendas (Clegg *et al.*, 2017). Such interference can be seen in DREAM project. With the formation of a new ruling party in 2015 and 2019, expert committees were also formed multiple times to find an answer to the project's car depot impasse. Every time a committee was formed, there was a different opinion and decisions kept altering on the siting of the car depot of the metro rail, giving evidence for unruly political alignments in decision making. Nevertheless, aspects of political influence are largely overlooked in the literature on megaproject evaluation, and this calls for attention (Rizzo, 2020). On this note, the expert from Director of DREAM noted,

> *You are aware that occasionally, in addition to a flaw in public consultation, other elements vary from one government or establishment to another. It is a delicate issue.*

Mega transport projects differ from traditional infrastructure projects not only because of their scale, size and complexity but also because they have to be interacted and work together with other functions to fulfil the purpose of the system. The second logic is *system thinking logic*. Their strategic formulation and impact at the national level also differentiate them from other traditional projects (Gharehbaghi *et al.*, 2022). Strategies to improve the performance of such large-scale transport projects can be better understood by examining their linkages and interactions between components (Love and Luo, 2018). As the expert from GARDEN IFA noted:

> *So I think the key issue seems to be that these projects in India are still treated as engineering and separate projects, but urban projects do not stand alone; they have to fit into the urban environment. And that is, I think that if you're talking about sustainability at the broader level, it is not just a project outlook, but an element inside an urban planning scenario […] It should be basically looked at the entirety of sustainability.*

Field actors such as NGOs and CBOs are strongly driven to support sustainable development for intrinsic motives. The third logic is *intrinsic logic*. They are naturally driven to adopt sustainability and want to contribute to social progress (Fifka *et al.*, 2016). This logic can be observed evidently in DREAM, where the NGOs and residents vehemently defended the city's green cover and filed applications to amend the orientation and placement of the car depot simply because they believe it is their "responsibility" to stop environmental destruction. The Director of an NGO added:

> *Governmental rules and laws, as well as normative components, have a significant impact on the organisations' sustainability policies. The cultural cognitive component, however, is the most crucial, and everyone in the organisation should be very honest in putting these ideas into reality; only then can we advance.*

In addition, the intrinsic motivation of the leaders also plays a crucial role in attaining sustainability in the project. The motivation from transformational leaders through professional development and shared vision driven by internal drive and rewards can develop a fair environment that increases the intrinsic motivation of other field actors (Li *et al.*, 2020). Beyond the legal requirements and policies, what additional value is added depends on the softer side and the culture of the decision-maker. As an expert from GARDEN IFA added:

> *The managing director (MD), kind of draws and sets the tone for the entire organization, then comes to the culture of the state or the city where it is working, and then, there could be the culture of the officers who are picked in. But, there are too many; it is a soft subject and difficult to generalise. Sometimes when MD changes, the thinking changes.*

Through interviews, it came to light that addressing sustainability issues in the projects added value to the project. The fourth logic is *value-based logic*. For instance, the CDM adopted in DREAM became a tool to represent the project's viability and help in acquiring the public's acceptance. Mahmood and Uddin (2021) emphasised economic gains, reputational gains, branding, and shareholder value as the underlying logic of motivation for sustainability reporting, which aligns with these findings. The expert from DREAM IFA commented:

> *Sustainability offers the project a degree of viability and stability, both of which benefit the public's affirmation. You must demonstrate that sustainability is one of your primary anchor characteristics if you wish to issue green bonds, [...] sustainability enters the picture if you want to obtain a facilitated loan. As a result, these factors are what motivate sustainability.*

The expert from GARDEN IFA also added:

> *So urban transport or any project must be sustainable to draw value. Just constructing a building does not give anybody any value. So, the project itself has to be driven by sustainability. The project should be determined by sustainability, not the other way round.*

Sometimes, organisations mimic successful sustainable and innovative models from other projects to attain sustainability. The fifth logic is *imitative logic*. In the case of DREAM, the idea of the regenerative braking system, which saves energy costs and produces roughly 8 crore KWh of electricity for other metro stations, is taken from Delhi Metro, influenced by CDM. On the other hand, implementation arrangements for TOD and VCF models in GARDEN were facilitated by other international projects. As the expert from GARDEN IFA added:

> *Singapore MRT, and Hong Kong, are great models for Transit Oriented Development, and Value Capture Financing. So we basically arrange for agencies from India to visit these countries to see what is happening. So that is part of the game, and that also the government of India wants in our value addition.*

4.3 Governance arrangements

Each organisational field is delineated by "a somewhat distinctive governance system composed of a combination of public and private actors employing a combination of regulatory and normative controls over activities and actors within field" (Scott, 1995, p.231). Some field actors exercising these functions are the regulatory bodies, law and judiciary systems, professional bodies and NGOs. Regulatory controls emphasise clear-cut regulatory processes, guiding organisational action by coercion or legal sanctions (Ju and Rowlinson, 2020). On the other hand, normative controls influence organisational beliefs and actions through professional associations and consultants. The following discussion begins with governance arrangements as rules governing practice. Then, the discussion focuses on the normative elements that facilitate the field's sustainability dialogue.

Since both projects are from similar sectors, some regulatory mechanisms' influence remains similar. For instance, in both cases, some of the common regulatory requirements that are relevant to the project include Environmental (Protection) Act, 1986; EIA Notification 2006; The Air (Prevention and Control of Pollution) Act, 1981 and The Water (Prevention and Control of Pollution) Act, 1974; Noise Pollution (Regulation and Control) Rules, 2000; Forest (Conservation) Act, 1980; Construction and Demolition Wastes Management Rules, 2016. However, because DREAM project is set in the coastal region of India, CRZ notification 2011 applies to the project. These rules and acts keep in check to ensure that environmental and social impacts are timely mitigated. On this note, the expert from NGT added:

> *I think the governmental laws; government regulation is very conducive to this particular sustainability of any project.*

Adding to this, an expert from GARDEN IFA added:

> *So, in India, like every other subject, not just infrastructure, we have more than enough laws and policies, but we do not know what to do with them. It is the implementation that kind of falls flat.*

Furthermore, there is also an issue of ambiguity in the legal language and uncertainties. Some of these rules and regulations are communicated in a broad context and are unrealistic from the perspective of large construction projects. Commenting on the very generic nature of the noise pollution rules, the Director of DREAM added:

> *Things need to be improved. While the Indian government or state officials believe that megaprojects are necessary for the city, some regulations are confusing. For example, there was legal action against construction noise. Now, construction noise is not covered in the law [...]. People cannot just consider the law applicable to no construction zone. So, if construction is necessary and large machinery is used, the legislation should include these elements specific to construction activities.*

There is a need for policies, specifications and strategies with a comprehensive control programme for construction noise that balances the community's and workers' need for a healthy, peaceful and safe environment with the project's need to advance work (Thalheimer, 2000). As the expert from GARDEN IFA added,

> *The government is very supportive at the central government level, all policies are in place, and everywhere it talks of sustainability. The question is at the implementation level. Does it translate into engineering thinking and legal aspects, or does it translate into a broader picture of what the project is about? It is second part that needs more focus, not the first one.*

On the other hand, both projects are exempted from getting approval for environmental clearance. As per the EIA Notification 2006, rail-based systems have been excluded from the scheduled list under EIA. However, all the IFAs assisting the project must carry out EIA and SIA as per their safeguard policies. An expert from GARDEN IFA noted:

> *So, just like anything else, in [IFA], we have what is called the safeguards policy statement, which is mandatory. Any breach in that will mean suspension and cancellation of the loan. And then we have additionalities, which we call value addition, where we encourage the agencies to add some value to the project […] So, somebody checks out some 10 families without paying them; the project itself will not be funded. But if somebody is saying that, I will use, let us say, solar power cells panels on top of my station buildings to generate electricity […], it will be made a covenant.*

The TOD approach in GARDEN resulted from National Transit Oriented Development Policy 2017, with the Government of India targeting to alleviate air pollution in the city, in line with India's Nationally Determined Contribution to reducing global greenhouse gases gas emissions. And this approach is being implemented by IFA, established under the loan's attached technical assistance.

5 Conclusion and Further Research

Using the lens of the organisational field, this study attempts to examine the elements that frame the institutionalisation of sustainability in two metro rail projects. The findings of this study show that the field actors in the sustainability-enabling fields do not act independently but interact and intervene in promoting sustainability. The findings suggest that project executing agencies, international funding agencies and governmental agencies are among the most important field actors actively encouraging project sustainability. As noted, however, the involvement of other field actors, such as NGOs and CBOs differed depending on the presence of eco-sensitive issues. The general public, NGOs, special interest groups, and PAP are some of the actors frequently overlooked but significantly impact the project’s sustainability.

Based on the analysis of these two cases, five institutional logics that impede or promote sustainability in megaprojects were identified: political, system-thinking, intrinsic, value-based and imitative logic. In addition, a combination of regulatory and normative governance arrangements, including rules and regulations, safeguard policies, self-regulatory measures and norms from funding agencies, are found to influence the activities and actors in the field. These insights on how salient components of the organisational field concept facilitate sustainability actions in mega transport projects will help academics and practitioners advance studies on megaproject sustainability.

This study examined how various organisational actors' interactions and institutions affected sustainability implementation. Concerning limitations, the logics identified in this study may not be generalizable to other contexts, such as different contractual modes, countries or sectors. Future studies can examine how these organisational fields differ with different contextual factors, such as comparing projects with private-public participation and EPC mode. In addition, using methods like qualitative comparative analysis, understanding how different combinations of these institutional factors affect the capability of sustainable performance could also be helpful in future studies.

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Reaching Net-Zero Targets in the Construction Industry by 2050: Critical Review of the Role of Public-Private Partnerships

Isaac Akomea-Frimpong[1*], Xiaohua Jin[1] and Robert Osei-Kyei[1]

[1]School of Engineering, Design & Built Environment, Western Sydney University, Locked Bag 1797 Penrith NSW 2751, AUSTRALIA

19624802@student.westernsydney.edu.au; xiaohua.jin@westernsydney.edu.au; r.osei-kyei@westernsydney.edu.au

*Corresponding author

Abstract

In recent times, net-zero emission target has gone viral as the actionable step to cut down global carbon emissions to the lowest point. At COP26 (United Nations Climate Change Conference) held in Glasgow (UK) in 2021, world leaders pledged to formulate and implement policies to make this target a reality in all sectors including the construction sector. The construction sector is a key segment of the economy that emits huge percentage of carbon dioxide (CO_2). This calls for attention and concerted solutions from key stakeholders of the construction sector to tackle the problem. The partnerships between the public and the private sector, termed as, public-private partnership (PPP), is a viable project model to solve this problem. However, limited studies exist on the role PPPs can play in achieving net-zero in construction projects. Thus, this study aims at exploring the role of public-private partnerships in net-zero emission targets in construction projects. The study utilises three-step literature review methodology. It begins with a comprehensive retrieval of literature, followed by selection of relevant articles, and ends with analysis of the bibliographical data. The findings include risk sharing, financial investment, influence carbon regulations, awareness creation, and education that PPPs offer to minimise carbon emissions in the construction projects. The outcomes of the study are relevant to further studies, policies, and practice.

Keywords:
Carbon Emissions, Construction Industry, Net-Zero Target, Public-private Partnerships (PPPs)

1 Introduction

Growing concerns around the world about climate crisis and how its devasting impacts threaten human existence and development has heighten net-zero emission reduction targets in public and academic discourses (Van Song *et al.*, 2022, Lu *et al.*, 2022). So far, more than 130 countries have pledged to set an emission reduction target to zero by 2050 (UKParliment, 2021). Conferences such as Paris Climate Conference in 2015, and a recent United Nations Climate Change Conference (COP26) in Glasgow in 2021 together with Intergovernmental Panel on Climate Change (IPCC) offer practitioners and policymakers the opportunity to discuss the challenges of climate crisis and rampant carbon emissions with solutions (Cohen *et al.*, 2022). Among all the sectors of the global economy, one area known of high carbon emissions is the construction industry (Shi *et al.*, 2017).

The construction industry unleashes a significant number of pollutants into the environment, mainly carbon dioxide (CO_2) emissions. The generation of CO_2 in the construction industry is related to activities of construction, operation, and demolition phases of projects. Also, activities such as manufacturing of construction materials, supply and consumption of energy, and installation of new building members also contribute to the release of CO_2. In the nutshell, scholarly research pegs the percentage of CO_2 released by the construction industry to +35%

(Sudarsan *et al.*, 2022), 37% (Debrah *et al.*, 2022) and 30% to 50% (Tan *et al.*, 2022), making it one of the major contributors of global carbon emissions. These worrying figures and trends have shifted the focus of key players in the construction industry to find immediate solutions in align with global net-zero emission targets. Already, measures to tackle this problem include the usage of low-carbon construction materials of concrete and steel that minimise CO_2 by 267% (concrete) and 863% (steel), respectively (Oh *et al.*, 2017). Studies such as Wu *et al.* (2019) and Zhang *et al.* (2020) have also recommended the use of fly ash (FA), granulated-blast furnace slag (GBFS), low-embodied carbon installation materials and silica fume (SF) as an alternative to cement to address CO2 emissions in construction activities. Another prominent solution proposed to achieve net-zero targets in construction project management is Public-Private Partnership (PPP) (Zhao *et al.*, 2021, Osei-Kyei and Chan, 2015).

PPPs introduce private sector actors such as financial institutions, tech-companies, carbon platforms, enterprises, capital market and experts to the public space to join existing relationships between the government (state) and the public (Kirikkaleli and Adebayo, 2021). However, PPP arrangements differ from country to country, and industry to industry (Anwar *et al.*, 2021). Therefore, it is necessary to establish the key roles PPPs incentivise in reducing carbon emissions in the construction sector. Also, PPPs are known globally (including all sectors) as a viable model to deliver infrastructures and provision of services (Akomea-Frimpong *et al.*, 2022b). But its role in supporting and bringing together the best of public and private sectors to attain net-zero targets in the construction industry is not clearly known and researched in the construction management literature. Therefore, this paper aims at reviewing existing literature to identify the key relevant roles of PPPs in reaching net-zero emission targets within the construction industry.

The novelty of this paper is that it offers rare insight into the roles of public-private partnership arrangements to achieve low-carbon construction in record times. The study also provides relevant policy and practice directions for consideration in the construction industry such as emission tax limits, carbon trade-off projects, carbon trading models, new technologies for projects, alternative and energy-saving buildings as well as sustainable finance. The outcomes of this study provide valuable gaps and information for further studies to be conducted in the construction and engineering management field with the goal of designing models to tackle carbon emissions through PPPs. Subsequent sections of the paper include the methodology. This section details the steps of conducting this study. Next, demonstration of the results from the bibliographical data. The discussions of the key findings of the study comes after this section. The study ends with conclusions, gaps, and recommendations.

2 Methodology

In this study, the research method adopted for the retrieval and analysis of bibliographical data to address the study's objectives is a critical review with a systematic approach. According to Jesson and Lacey (2006) and Kwatra *et al.* (2020), a critical review is more than just a summary of different research topics, themes, and analysis of methodologies from past studies as opposed to other forms of literature reviews. Critical reviews offer researchers the opportunity to reflect, critique existing literature and provide useful recommendations to address a research issue (Kraus *et al.*, 2022, Zhang *et al.*, 2016). The details of the critical review approach in this article are outlined as follows:

Stage 1: Retrieval of articles

The primary data sources for this paper are Scopus and Web of Science (WoS). In construction and engineering management (CEM) research, the two bibliographical databases are prominent with large depository of literature as far back as 1800s (Eshun *et al.*, 2021). As a result of this, a number of scholarly literature reviews have been undertaken in the CEM using the two databases as the sources of relevant data (Xu *et al.*, 2021). Moreover, the databases have features that enhance downloading and assessment of published literature (Tijani *et al.*, 2021). Inputs into the databases to retrieve literature were keywords that included "net-zero", "carbon emissions", "net-zero emissions", "zero embodied carbon", “net-zero target” combing them with "PPP", "public-private partnerships", "public private partnerships", “construction industry”, “Built Environment”, “construction projects” “PPP projects”. The Boolean products of “AND” and “OR” facilitated the combination of the keywords in the search. Initial output from the search was 110 documents with 77 documents from Scopus and 33 from Web of Science. The search outcomes were restricted to journal articles and reviews excluding books, conference papers essays, and notes. The restriction also extended to the language with the consideration on articles published in English, but the search period was totally unrestricted. The outcomes of the 110 articles reduced to 64 after the restrictions of the search. In addition, 8 articles were found in bibliographical databases of Google scholar, PubMed, and ProQuest. In total, 72 articles were downloaded for the screening and selection stage.

Stage 2: Screening and selection of articles

At this stage, screening was first conducted to remove articles that appeared more than once in the bibliographic databases. Twenty-five (25) duplicate articles were removed from the 72 articles based on their titles and abstracts, and this brought the number of articles for further analysis at 47 articles. An inclusion and exclusion criteria were set to ascertain the most relevant papers for this study. The criteria composed of 1) an article must cover extensively the role of PPP in reaching net-zero emission targets in construction projects, and 2) the article should have been published in a top-tier journal. According to Akomea-Frimpong *et al.* (2022c), a top-tier paper is found within the first and second quartile journal rankings. Moreover, Utama *et al.* (2018) argued that the outcomes of top-tier journal articles make significant impact in academia, policy formulation and practice. The relevant articles based on the criteria was 26 articles with 21 articles removed. The adequacy of the 26 articles is justified in similar CEM research outputs that utilised fewer articles to conduct a literature review with reference to: Opoku *et al.* (2021) and Adabre and Chan (2019).

Stage 3: Analytical procedure

In this final stage, the 26 articles were subjected to critical review using qualitative content analysis. The approach started with the thorough reading of all the articles, and extraction of key statements, words, phrases, and paragraphs which are essential to this study (Brenya *et al.*, 2022). The extracted items were coded based on the common features and messages they convey. Then, the codes were transformed into themes to form the basis of the findings in the next section.

3 Overview of bibliographic data

3.1 Growth of published articles

Steadily, the trend of yearly research outputs shown in Figure 1 upward growth in interest in the topic. A rise in articles from one in 2012 to eight articles in 2022 is a sign of intense academic discourses on the measures to resolve climate crisis and reach net-zero emission targets (Cohen *et al.*, 2022, Kristjansdottir and Busch, 2019).

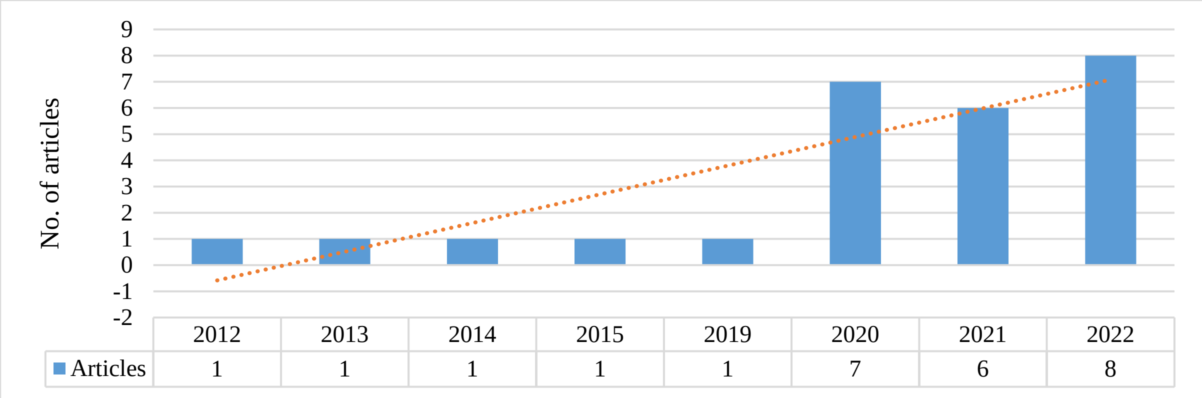

Figure 1. Trend of annual publications

3.2 Country-of- origin

In Figure 2, China recorded the largest number of publications of 31% representing eight studies. It is followed by seven studies with data taken from more than one country. Brazil records 11% of the publications whiles Malaysia and United Kingdom (UK) accounts for 7% and 8% of the studies respectively. India, United States, Bangladesh, and Iceland had 4% each of the total selected articles. The results demonstrate very little research on the topic especially Africa, an opportunity for future studies (Sudarsan *et al.*, 2022).

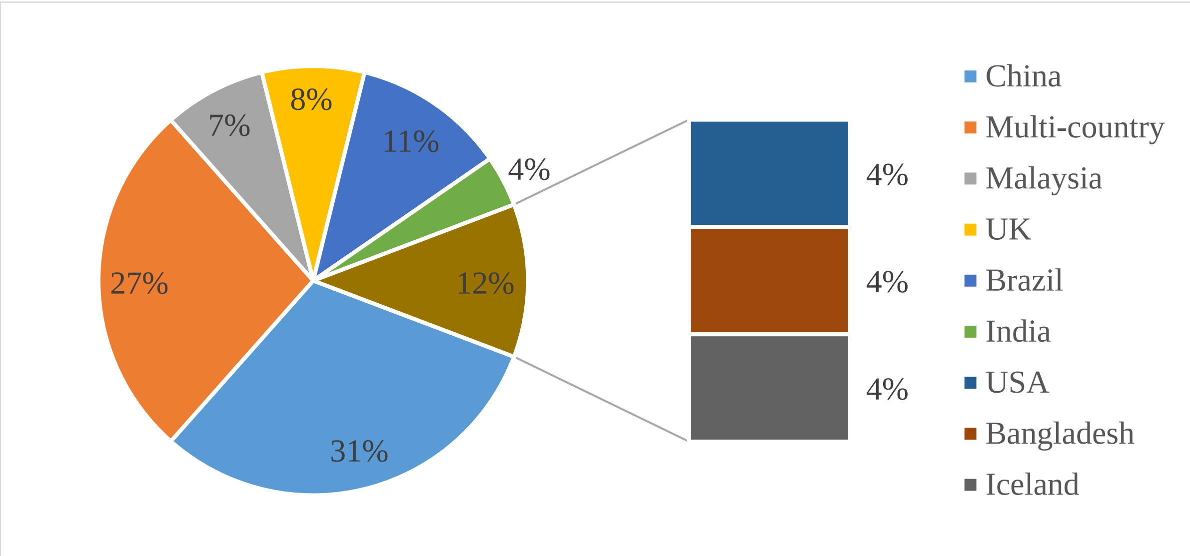

Figure 2. Summary of research origin.

3.3 Article impact analysis

A total of seven articles were found to be influenced with at least 50 citations presented in Table 1. The studies have been published in top-tier journals with a minimum h-index of 52 (International Journal of Pavement Engineering) and the highest of 232 (Journal of Cleaner Production). These outlets are avenues of relevant information for future studies and managerial decision-makings.

Table 1. Citation analysis of top seven articles

Article	Journal	Journal h-index	Article Citations
1.Evans and Karvonen (2014)	International Journal of Urban and Regional Research	199	375
2. Shahbaz *et al.* (2020)	Energy Economics	168	211
3. Kirikkaleli and Adebayo (2021)	Environmental Science and Pollution Research	132	117
4. Raza *et al.* (2021)	Sustainable Development	70	113
5. Huang *et al.* (2013)	International Journal of Pavement Engineering	52	56
6. Anwar *et al.* (2021)	Journal of Cleaner Production	232	56
7. Solaymani *et al.* (2015)	Energy	212	52

4 Discussion of findings

As a viable model, public-private partnership (PPP) has been identified as relevant to ensure low-carbon construction activities (Zhu *et al.*, 2022). Although, it is not well-developed on the specific contributions of PPPs in construction projects towards attaining net-zero targets, the reviewed articles provide some insights into this discourse as follows. Raghutla and Chittedi (2020) posited that PPPs provide better finance and risk-sharing packages to build and operate net zero carbon-conscious projects. Wang *et al.* (2020) and Sheng *et al.* (2020) gave details of this flexible, sustainable, and green financial commitments (packages) from both government and private investors that garner support for transitioning to low-carbon energy consumption and urban infrastructure development. The green project finance packages to support net-zero construction projects include green bond, green infrastructure finance, carbon finance and climate finance (Akomea-Frimpong *et al.*, 2022c). Further, Tan *et al.* (2022) mentioned that the state alone cannot ensure project managers embrace green funding products to achieve the transition to green projects. It takes the concerted efforts of the private sector and the state due to constraints of national budgets. The outbreak of coronavirus pandemic worsen these financial constraints resulting in economic crisis with rippling effects on the construction industry (Ogunnusi *et al.*, 2021). Davis *et al.* (2021) projected that the involvement of private financiers through bidding consortiums, special purpose vehicles and financial alliances could interplay between green revolution and sustainability of construction projects in the post-pandemic era. However, Anwar *et al.* (2021) and Berrou *et al.* (2019) argued that green private financial investment to attain net-zero comes with challenges ranging from the difficulties with the unfavourable macroeconomic conditions that put a cap on mobilising green investments to lack of clarity of what constitute green project finance for net-zero construction projects.

Another role PPPs play is to ensure the delivery of climate change targets within the construction sector. Yang *et al.* (2022) mentioned that it is the goal of every government who has committed to Paris Agreement and COP26 on climate to achieve low-carbon emissions in every sector. Although, the United Nations through Inter-governmental Panel on Climate Change (IPCC) has set the benchmark on lowest carbon emission reduction target, current national targets differ from countries as to when to achieve this target: Australia (2050), China (2060), India (2070), European Union and United States United Kingdom, United States (2050). The support of the private is needed in achieving this goal especially in the construction sector. Kirikkaleli and Adebayo (2021) argued that private sector could offer technical advisory services to the construction of climate-resilient infrastructures. Promotion of climate-resilient project investments to reduce greenhouse gas emissions, and proposals of robust resilience measures against climate crisis have become appealing to the construction industry players following the setting up of the United Nation's platform on climate-smart PPPs (Adebayo *et al.,* 2021). Buso and Stenger (2018) demonstrated the role of private entities and individuals towards climate action through pressure groups, awareness creation, education, and activism on and off social media on key infrastructure projects in a country. Climate activists and climate movements draw the attention of the dangerous anthropological construction activities , and pressure key players of construction industry to fulfil the unwritten social contract in protecting the environment, society and jobs (Kennedy *et al.*, 2014).

PPPs offer a great opportunity to resolve lapses in legislation and policies in the construction process, especially at the design phase of the projects (Ghayeb *et al.*, 2020). Influencing public policies to shift to low-carbon construction must be a priority of PPP arrangements in the built environment (Khan *et al.*, 2020). Renewable energy consumption in commercial and residential buildings should be monitored with new technologies at the direction of experts from both worlds (public and private sectors) of partnership. Drastic investments and government subsidies are necessary to ensure technological models are in place for decarbonization solutions of construction projects (Albino *et al.*, 2014). Caglar *et al.* (2022) encouraged researchers and private entities to take up this task and provide innovative technological support to projects through PPPs. However, these subsidies could be constrained because of insufficient government subsidies for research and development of carbon-neutral projects. PPPs provide upfront regulations in promoting collaborations, personal carbon accounts and carbon limits of projects (Zhao *et al.*, 2021). Together with carbon accounts, emissions trading schemes (ETS) could be viable market-based financial instrument to incentivise the reduction of greenhouses emissions in construction projects (Raghutla and Chittedi, 2020). ETS provides allowances and investments into construction firms from the financial market. Nevertheless, the sustainability and success of the ETS instrument is dependent on macroeconomic conditions of the project's geographical setting (Van Song *et al.*, 2022).

Table 2. Key roles of PPPs in attaining net-zero targets in the construction industry

Role	Reference (refer to Appendix)
Financial investment	1,2,4,5,6,7,9,12,14,17,19,20,21,24,26
Risk-Sharing	1,4,5,8,10,15,17,23,25,26
Transition to greener construction management	3,5,8,9,11,13,16,18,25
Innovation and new technologies	2,5,7,11,17,22,24
Low carbon/net-zero construction materials	3,5,9,14,17,20
Climate and emission policies	4,12,19,23
Provision of renewable energy	2,5,19,22
Climate activism	3,5,6,9
Promotion of personal carbon accounts	4,24,25
Influence decarbonisation legislations	6,9,14
Monitoring, supervision, and evaluation	5,10,19
Multi-stakeholder arrangements	4,5,20
International collaborations	9,22
Awareness and education	3,16

5 Conclusions

In this paper, we sought to identify the key roles of PPPs in reaching net-zero construction projects. The method utilised in this study is systematic literature review with data coming from major academic databases of Scopus, Web of Science, PubMed, and Google Scholar. The results of the roles demonstrate fourteen (14) critical roles of PPPs in achieving zero-carbon construction. They include risk sharing, financial investment, awareness and education of construction workers and project managers on carbon emission reduction strategies among others. The findings from the paper provide project teams the understanding on the need to accept PPPs in managing climate crisis and ensuring low-carbon construction activities. Aligning and complying with national policies and targets require in-depth insight about this topic. Therefore, this research outcomes point to outlets where relevant information could be retrieved to assist in decision making. Construction management researchers could investigate into this research area and develop carbon-models to minimising emission contents of projects based on the outcomes of this paper. The significant gaps that need further research and policy directions include the following:

First, PPPs as a carbon reduction strategy needs more research to offer definitive explanation, conceptualisation, testing, modelling, and validation with real case study of construction projects. Second, data and information gathering on PPPs, energy-saving and low-carbon projects remain a challenge. In many cases, it is expensive to gather and store data to feed software to run meaningful analysis on this topic. It is encouraged that future studies build a database for the construction sector. Third, renewable energy (solar and wind) is very essential to transition to zero carbon construction projects. Project managers must invest into scaling solar and renewable wind energy with the support of private funds. Fourth, there is an opportunity to introduce PPP green buildings as a solution on low-carbons and energy efficiency in the built environment. Lastly, climate (and green finance) is an open new financing models which combines both sustainable financing principles and environmental protection for projects. It will be interesting for researchers to delve into climate finance, PPPs, and carbon limits with carbon trading models in the construction industry.

Appendix: Selected journal articles for this study

Journal Article (Year)	Journal Article (Year)
1.Yang *et al.* (2022)	14. Adebayo *et al.* (2021)
2.Wang *et al.* (2022)	15. Wang *et al.* (2020)
3. Van Song *et al.* (2022)	16. Shahbaz *et al.* (2020)
4.Pinilla-De La Cruz *et al.* (2022)	17. Raghutla and Chittedi (2020)
5. Lu *et al.* (2022)	18. Khan *et al.* (2020)
6.Kirikkaleli *et al.* (2022)	19. Ghayeb *et al.* (2020)
7.Caglar *et al.* (2022)	20. Branco *et al.* (2020)
8.Akomea-Frimpong *et al.* (2022a)	21. Ahmad and Raza (2020)
9.Zhao *et al.* (2021)	22. Kristjansdottir and Busch (2019)
10.Raza *et al.* (2021)	23. Solaymani *et al.* (2015)
11.Kirikkaleli and Adebayo (2021)	24. Evans and Karvonen (2014)
12.Cheng *et al.* (2021)	25. Huang *et al.* (2013)
13.Anwar *et al.* (2021)	26. Lövbrand and Stripple (2012)

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DOI: 10.26183/a6pq-mg06