

NZBERS

New Zealand Built Environment Research Symposium

PROCEEDINGS OF THE

7TH NEW ZEALAND BUILT ENVIRONMENT SYMPOSIUM (NZBERS), 2022



**CREATING CAPACITY AND CAPABILITY
FOR THE FUTURE OF THE BUILT
ENVIRONMENT**



Editors:

Wajiha M. Shahzad, Eziaku O. Rasheed & James O. B. Rotimi

**17th & 18th February
2022**

**Atrium Building, Massey University
Campus, Albany, New Zealand**

WWW.NZBERS.MASSEY.AC.NZ

ISBN: 978-0-473-62031-8

PROCEEDINGS OF THE
7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM

17-18 February 2022
Auckland, New Zealand

EDITORS

Dr. Wajiha Mohsin Shahzad
Dr. Eziaku Onyeizu Rasheed
A/Prof. James Olabode Bamidele Rotimi

Organised by

School of Built Environment
College of Sciences
Massey University, NZ

Built Environment Engineering Department
School of Future Environments
Auckland University of Technology, NZ

School of Architecture
Victoria University of Wellington, NZ

School of Building Construction
Unitec Institute of Technology, NZ

ISBN 978-0-473-62031-8

©2022 NZBERS

All rights reserved. No part of this publication may be reproduced, stored and transmitted in any form, or by any means without prior written permission from the editors. The views expressed in the papers and extended abstracts are of the individual authors. The editors are not liable to anyone for any loss or damage caused by any error or omission in the papers, whether such error or omission is the result of negligence or any other cause. All and such liability is disclaimed. The reader should verify the applicability of the information to particular situations and check the references prior to any reliance thereupon. Since the information contained in the proceedings is multidisciplinary, international and professional in nature, the reader is urged to consult with an appropriate licensed professional prior to taking any action or making any interpretation that is within the realm of a licensed professional practice.

Contact/Enquiries:

Dr Wajiha M. Shahzad
Email: nzbers@massey.ac.nz
Tel: +64 (9) 212 7107
Web: <https://nzbers.massey.ac.nz/>

7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM
Creating Capacity and Capability for the Future of the Built Environment

7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM
Creating Capacity and Capability for the Future of the Built Environment

Contents

Sponsors.....	6
Organising Committee.....	7
Scientific Committee.....	8
Keynote Speakers.....	9
Panel Experts.....	12
Research Papers.....	15
Theme 1: Capacity and Capability of Built Environment.....	16
Asset Management for the Built Environment: Creating Capability and Resilience.....	17
In the Middle of the Pandemic: Experiences for Built Environment Education.....	42
Asset Classification for Roads – CONie, towards COBie-for-Roads.....	53
Development of BIM-Enabled Asset Management Planning Model: Using an Integrated Knowledge Complexity-Maturity Concept.....	71
Employee turnover in the construction industry: a comprehensive review.....	98
Lead extrusion damper force modelling for seismic protection application in buildings using finite element modelling.....	107
Regenerative public-spend projects in New Zealand built environment: perceptions from across the system on creating the conditions for success.....	115
Computer modelling and control system design for full scale concrete 3D printing using an industrial robotic arm.....	134
The Influence of Real-Time Applications on the Performance of BIM-Enabled Projects....	143
Predominant Causes of Delays within the New Zealand Construction Industry: Residential vs Commercial.....	155
Mapping Supply Chain to Enhance Capability and Capacity of Prefabricated Housing Supply in New Zealand.....	178
BIM and LCA Applications for Green Buildings in New Zealand.....	194
Evaluation of Structural System and Construction Material Properties of a Pre-1970 Building.....	204
4D sequencing on New Zealand's largest Infrastructure Project.....	214
Understanding the Factors Affecting Accuracy of New Zealand Public Housing Project Tender Price.....	226
Health and Safety Outlook of Offsite Construction (OSC).....	237
Computable Planning Rules for Automating Urban Land Development.....	247
Feasibility Analysis of Cross Laminated Timber (CLT) for the Christchurch Rebuild Project in New Zealand.....	256
Theme 2: Building Performance.....	276
An approach to construct Bayesian networks for use in living environment field, taking Chinese CCRCs as the example.....	277

7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM
Creating Capacity and Capability for the Future of the Built Environment

Comparative analysis of air-conditioners and energy consumption levels towards green retrofitting in Ghana.....	294
The humble curtain: a cheap and cheerful insulator?	302
Methods for assessment of space heating energy use in buildings: A literature review.....	312
Theme 3: Sustainability	320
A Parametric Study of Passive House Strategies in a Cooling Dominated Climate – A Case Study of Algeria.	321
Self-reported occupant behaviours and multi-domain comfort preferences in New Zealand tertiary office buildings.....	334
Logistics management as a sustainability solution for New Zealand construction: A literature review based research framework.....	343
Creating Capacity and Capability for the Future of the Built Environment Through a New Sustainability Maturity Assessment Model	370
The applications of building information modelling for the lifecycle performance of green buildings: a systematic literature review.....	385
Investigating the motivation and barriers for microgrids in New Zealand.....	397
Extended Abstracts	408
Real-Time Project Productivity Tracking System: Practical Case in Smart Construction Projects.....	409
Toward Improving Capacity and Capability of Prefabrication Construction in New Zealand’s Construction Sector.....	413
The Worst-Case Scenario in Mass Urban Evacuation.....	416
Sustainable Transitions in Removal of Toxic Chemicals from Construction Materials and Waste: A Preliminary Theoretical Framework	420
Carbon Footprint of Residential Building Construction in Christchurch	423
Critical Factors for Lean-BIM Integration in Construction Practice New Zealand.....	427
The Cost-Benefit Implications of Low-Emissions Concrete for Exterior Concrete Works ..	432
Consideration Watchpoints When Utilising “ArchiCAD” Software Across a VDI Network	437
Numerical/Computational Study of the Effect of Braced Stiffness Equipped with Nonlinear Viscous Dampers on the MDOP System	441
Thinking Musically About Garden Design for a More Immersive Experience.....	445
The Role and Challenges of Real-Time Employee Monitoring Technology (REMT) in the Digitalisation Transformation Process of the New Zealand Construction Sector	448
A Review of the Impacts of COVID-19 on the Construction Industry in Auckland, New Zealand.....	452
Evaluating Capacity and Capability of the Construction Sector: The Application of Big Data Tools	457
The Development of a Decision-Support System (DSS) for Selecting Best-Fit Zero-Carbon Building Materials; The Cases of Iran and New Zealand Building Industries	460

7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM
Creating Capacity and Capability for the Future of the Built Environment

Poster Presentations	466
Energy Efficient Building Design – Energy Audit	467
- A	467
Energy Efficient Building Design – Energy Audit	468
- B	468
Surviving or thriving? The resilience lessons of New Zealand construction sector from COVID 19	469

7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM
Creating Capacity and Capability for the Future of the Built Environment

Sponsors

The organizers of the 6th New Zealand Built Environment Research Symposium would like to thank each of these organisations for their generous contributions to the success of the symposium.



CanConstructNZ – Platinum Sponsor

MBIE Endeavour Grant Project, School of Built Environment, Massey University, New Zealand



Gold Sponsor

PO Box 448, Wellington 6140, New Zealand



Silver Sponsor

Level 4 Solnet House, 70 The Terrace, Wellington 6011, New Zealand



Award Sponsor

Level 8, 540 Wickham Street, Fortitude Valley, QLD 4006, Australia

7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM
Creating Capacity and Capability for the Future of the Built Environment

Organising Committee



Dr Eziaku Rasheed,
Massey University
Symposium Chair



A/Prof Morten Gjerde,
Victoria University
Symposium Co-Chair



Dr Wajiha Shahzad,
Massey University,
NZBERS President



A/Prof Ali
Ghaffarianhoseini,
Auckland University of
Technology (AUT)



A/Prof James Rotimi,
Massey University



A/Prof Linda Kestle,
UNITEC



Dr Don Samarasinghe,
Massey University



Dr Mostafa Jelodar,
Massey University



A/Prof Amirhosein
Ghaffarianhoseini,
Auckland University of
Technology (AUT)



Dr Priya Vishnu,
Massey University



Dr Azam Zavvari,
Massey University

Scientific Committee

We are grateful for the rigorous peer review done by the scientific committee:

Ali Ghaffarianhoseini

Amirhosein Ghaffarianhoseini

An Le Thi Hoai

Azam Zavvari

Daniel Paes

Don Samarasinghe

Eziaku Rasheed

Gregory Chawynski

Hennie van Heerden

Israr Wahid

James Rotimi

Juwita Razdi

Linda Kestle

Mikael Boulic

Mostafa Jelodar

Naseem Ameer Ali

Nasir Rasheed

Priya Vishnu

Ravindu Kahandawa

Susan Mander

Wajiha Shahzad

Wallace Enegbuma

Keynote Speakers



Professor Hugh Byrd, Lincoln University, UK

Speaker's Abstract:

As the climate warms, we use more electricity for cooling, causing more carbon emissions, causing the climate to warm further causing the use of more electricity for cooling and so on. This presentation looks at past and recent policies of energy efficiency for the cooling of buildings and asks the difficult questions of why it took almost 30 years to question our energy efficiency standards; why does NZ have some of the lowest energy efficiency standards in the OECD; why do we have no specific data on energy used for cooling in NZ; why do we have some of the highest electricity prices in OECD; why are households in fuel poverty subsidizing the cost of cooling commercial buildings? Why do current policies show little respect to our climate emergency?



**Associate Professor Terri-Ann Berry
(Environmental Solutions Research
Centre (ESRC), Unitec Institute of
Technology)**

Speaker's Abstract:

Meeting the global challenges of degrading environments, climate change, and increasing greenhouse gas emissions requires new research and innovation. ESRC aims to respond to these challenges through an economic, social and environmental lens. The main aim of this presentation is to discuss the story of ESRC; challenges; highlights; successes and failures but mostly its drive to provide practical and achievable solutions for the built environment.



**Associate Professor Jasper Mbachu
(Centre for Comparative Construction
Research (CCCR), Bond University,
Gold Coast, Australia)**

Speaker's Abstract:

To survive and thrive in the new futures, transformations – rather than reformations – are needed. Built environment professionals must develop and sustain agile and responsive capabilities to leverage the eminent changes as tailwinds with which to rise up to the challenges.

In his Keynote, Dr Jasper Mbachu will highlight the major shifts in the built environment future world of work, and the capabilities professionals need to develop in order to strategically reposition themselves to exploit the major shifts as opportunities to reach new heights.

7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM
Creating Capacity and Capability for the Future of the Built Environment



Dr Kara Rosemeier (Passive House Academy, New Zealand)

Speaker's Abstract:

Kara Rosemeier is the author of /Positive Energy Homes/ (with Robin Brimblecombe), a board member of the Passive House Institute New Zealand, leads the Passive House Academy New Zealand and teaches building science.

In her Keynote, Kara will speak on the topic: 'Strengthening capability for high-performance buildings'. She will highlight overseas approaches to main-streaming high-performance buildings and her involvement with one of such programmes.



Mr Graham Burke (NZ Construction Sector)

Speaker's Abstract:

Graham has worked in the construction industry for 40 years and holds numerous roles in industry bodies, including Executive Director of NZ Construction Industry Council, Executive Officer of NZ Specialist Trade Contractors Federation, Co-chair of ConCOVE, (Construction and Infrastructure Centre of Vocational Excellence), member of the Construction Accord Steering Group and board member of Construction Health and Safety NZ.

Graham is committed to leading change in the construction sector, moving emphasis from bottom price to value, safety, and quality.

Panel Experts

7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM
Creating Capacity and Capability for the Future of the Built Environment



Ralf Kessel (Concrete NZ)

Ralf is an architect, registered with the NZIA, AK Berlin and ARB UK. He authored the CCANZ Code of Practise for Weathertight Concrete and Concrete Masonry Construction, cited by the Ministry of Building, Innovation and Employment (MBIE) as New Zealand Building Code Clause E2/AS3. Ralf led was the design of a sustainable, energy efficient, apartment/ mix use development for the 'New Urban Village' competition organised in 2014 by Christchurch City Council, MBIE, Te Runanga o Ngai Tahu and CERA/CCDU.



Elrond Burrell (Director of VIA architecture Ltd)

Elrond specialises in Passive House and low-carbon architecture, and the current the chair of the board of Te Tōpūtanga o te Whare Korou ki Aotearoa, Passive House Institute New Zealand (PHINZ). He is also Principal Advisor Architecture & Design in the Building System Performance Branch of MBIE. Elrond is an international keynote presenter about Passive House and low-carbon architecture. He has presented at conferences in NZ, Australia, England, the US and Germany.



Mark Robert (Auckland Council)

Mark is a Senior Waste Planning Advisor at Auckland Council. He has three decades of experience in refining business, energy and waste systems for a wide range of organisations in New Zealand and the UK. Mark is currently working at Auckland Council on integrating deconstruction techniques and waste minimisation into the construction and demolition industry to provide positive social and environmental outcomes.

7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM
Creating Capacity and Capability for the Future of the Built Environment



Casimir MacGregor (BRANZ)

Casimir is a Senior Social Scientist and Programme Leader of the Transition to a Zero Carbon Built Environment research programme at BRANZ. Casimir is a sociologist who draws upon theory and methods of sociology, science and technology studies, and public health. His research is focused on enabling innovation and change within the building and construction industry to address climate change. Some of his recent and current research is focused on regulatory responses to the role of buildings in mitigating and adapting to climate change (with MBIE), and a new study examining how the building and construction industry is preparing for climate change.



Annette Day (Naylor Love)

Annie has experience as both a project manager and quantity surveyor. Annie chairs the Auckland Sustainability Committee at Naylor Love and has key responsibilities in aligning all regions in effective environmentally sustainable processes.

Annie looks for new construction trends and has influenced and implemented many within Naylor Loves operating practices.

Research Papers

Theme 1: Capacity and Capability of Built Environment

Asset Management for the Built Environment: Creating Capability and Resilience

Raymond Tan*, Eziaku Rasheed and James Olabode Bamidele Rotimi

School of Built Environment, Massey University, New Zealand.

*Corresponding author: rtan1@massey.ac.nz

Abstract

A built environment can be considered as a complex system with multiple layers and networked organisations, institutions, and users that collectively create value for all parties involved. The rapid transformational advances in technologies, increasing demands from stakeholders, and significant disruptions caused by natural disasters present many challenges for managers responsible for ensuring sustainable capabilities and capacities for their organisations are maintained to optimise value for all stakeholders.

In this study, we look at three perspectives that have emerged in response to such challenges in the strategic asset management literature: (i) the dynamic capabilities paradigm, (ii) a holistic systems approach, and (iii) the business model concept. With few exceptions, these multidisciplinary viewpoints have often been treated separately, leading to several limitations for their application in practice. While complex systems are fundamentally deterministic, successful organisations have created complex adaptive systems that exhibit flexibility and resilience in challenging situations. This article will explore the linkages of these perspectives and suggest a business model design that presents effective enablement of different tangible and intangible resources owned or controlled by an organisation and those in the wider networked environment. This enablement will lead to creating and extending the organisation's capability and capacity using its resource base.

This article contributes to asset management literature by using established theories to study a distinctly overlapping body of knowledge that applies to asset management in the built environment that is often absent. It is based on a systematic literature review for AM publications between 2014-2021, including a snowballing technique that led to relevant articles prior to the study period. The findings of this study will form part of an ongoing larger research study on optimising value through enhanced asset management capability for the New Zealand built environment.

Keywords

Asset Management, Dynamic Capabilities, Public Infrastructure, Resilience, Systems Thinking

Introduction

For centuries, the built environment created worldwide has played a substantial role in the sustained wealth, prosperity, and quality of life for billions of people. The rapid transformational advances in technologies, increasing demands from stakeholders, and significant disruptions caused by natural disasters present many challenges for managers responsible for ensuring sustainable capabilities and capacities for their organisations are optimised to create value for all stakeholders. Getting the most out of assets that make up the built environment is becoming a focus in many countries as it is no longer viable just by building their way out of capacity problems or asset underperformance due to poor practices

(Flyvbjerg, 2009). A 2013 global study of over 400 case studies by the McKinsey Global Institute identified the \$350 billion annual infrastructure gap faced by the world will triple to meet the United Nations Sustainable Development Goals targets in 2030. Study findings pointed to common issues of inadequate asset systems resulting from misaligned development efforts that failed to deliver the expected economic, environmental, or social objectives (Dobbs et al., 2013; Woetzel et al. 2016).

As with many countries in the world, New Zealand faces huge challenges tackling public infrastructure issues at scale widely documented in public reports from local and central government agencies. With over \$100 billion and \$250 billion physical assets managed by local and central governments respectively, one of the many concerns raised by the Office of the Auditor-General was the lack of asset management (AM) capability to deliver good sustainable assets that provide the required services at the right price and quality (OAG, 2017). Ineffective decision-making, poor adoption of appropriate technologies, inadequate asset information and poor-quality standards were highlighted. These inadequacies exist even though Treasury NZ requires most public sector organisations in New Zealand to develop strategic asset management plans (SAMPs) and demonstrate acceptable asset management maturity levels aligned to the requirements of the International Organisation for Standardisation - ISO 55001 asset management standard to justify capital budget requests and satisfy annual audit requirements (Audit NZ, 2010; Treasury NZ, 2017).

The current understanding of AM as a core multidisciplinary business capability and not just a support function is well supported by the recently published ISO 55000 suite of standards that defined AM as *‘the coordinated activity of an organisation to realise value from assets* (ISO, 2014a). An asset can be tangible or intangible, financial or non-financial, to be determined by the organisations and their stakeholders. In essence, AM is not about the assets; it is about the realisation of value with the assets through a holistic and strategic approach aligned to stakeholders’ expectations. Recent research has strengthened the claim there is a positive influence on the performance of asset-intensive organisations through the integration of asset management strategies with broader organisation strategic management efforts (Roda et al. 2016, Maletič et al. 2020). A growing body of published work provides evidence of both internal and external benefits of adopting the ISO 55000 suite of standards (e.g., Alsayouf et al., 2021; Bradley & Main, 2015; Kelly and Hardy 2018; Capela et al. 2020; de Almeida Pais et al. 2021; Tholana & Neingo, 2016; Ali, 2021; Maletič et al. 2019, Milina et al. 2017). Often case-specific, benefits include:

- *Financial*: reduction in operating costs, improved ROI, increased revenue, decreased insurance premiums
- *Customer*: Increase customer satisfaction, improve corporate image
- *Efficiency*: Process and organisation effectiveness, improved productivity, improved performance in working conditions, health and safety, product/service quality and reliability, decreased non-value-added activities, continuous improvement, and innovation
- *Learning and growth*: improved asset intelligence, increased employee motivation and commitment, increased employee development, increased innovation

Three common perspectives emerged from articles devoted to the strategic aspects of asset management responding to challenges of resource constraints, climate change and demand growth: (i) the systems approach (e.g Valencia et al. 2011; Gomez et al. 2020; Petchorompo & Parlikad, 2018; Grösser et al. 2017), (ii) the dynamic capabilities paradigm (e.g. Tranfield & Denver, 2004; Gavrikova et al. 2020), and (iii) the business model concept (e.g. Frolov et al. 2009; Roda et al. 2016; Lima & Costa, 2019; Hanski & Ojanen, 2020). There is a degree of conceptual similitude between these perspectives due to their epistemological similarities

grounded within the theoretical assumptions of systems thinking, complex systems, environmental dynamism and uncertainties. However, with few exceptions, these multidisciplinary viewpoints have often been treated under separate disciplines leading to limitations in their applications for AM, although incorporating these perspectives for better understanding asset management in the built environment can lead to better clarifications at an ontological level for effective application by practitioners.

This article will explore the linkages of these perspectives and suggest a business model design approach that presents effective enablement of different tangible and intangible resources owned or controlled by an organisation and those in the wider networked environment. This enablement will lead to creating and extending the organisation's capability and capacity using its resource base. From an open systems approach, these resources are not organisation-specific but rather organisation-centric, which includes those anchored within the organisation and other players in the value chain and broader ecosystem. The study is also a response to recent calls for the need for a theoretical framework to support the application of strategic AM practices in the built environment that has caused difficulties for practitioners (e.g. Gavrikova et al., 2020; Konstantakos et al., 2019, El-Akruti et al., 2018). It contributes to the AM literature by exploring the distinctly overlapping body of knowledge on established managerial and organisational theories that informs the successful implementation of effective asset management practices often absent in AM research.

The paper will begin by laying down the multidisciplinary discourses within the realms of AM for the built environment. It will then provide some background and context but not detailed discussions of all concepts as this study is only a small part of an ongoing, more extensive study of optimising value through enhanced asset management capability for the New Zealand built environment. Followed by an explanation of the methods used for the literature review and analysis will be provided before the findings and discussions are made on the significance of the three perspectives on AM. It will conclude with the identification of current study limitations and propose an empirical research framework going forward.

Background and Context

Asset Management

An Overview

AM, apart from continuously evolving, is not considered a new discipline but rather an emerging one. References to a holistic and systems approach for managing assets appeared from the 1960s under the term 'terotechnology' (White, 1975). Before the 1980s, AM research mainly belonged to the business economics domain (90%), and in the last ten years, engineering and asset-focus discussions made up more than 75% of the literature for specific industries in different countries. Whilst there is a lack of consensus regarding the origins or theoretical basis upon which AM is founded, there is agreement among researchers that the concept evolved from other disciplines such as finance, engineering, information technology, construction, etc. (Konstantakos, 2019).

With the involvement of both academia and practitioners from 31 countries, the International Organisations for Standardisation (ISO) developed a suite of AM standards and guidance documents listed below:

- *ISO 55000*: Overview, principles, and terminology (ISO, 2014a)
- *ISO 55001*: Management systems–Requirements (ISO, 2014b)

- *ISO 55002: Management systems—Guidelines for the application of ISO 55001* (ISO, 2018)
- *ISO 55010: Guidance on the alignment of financial and non-financial functions in asset management* (ISO, 2019)
- *ISO 55011: Guidance for development and application of public policy to enable asset management* (ISO, *under development/consultation*)

Underpinning these documents are four fundamentals (core principles) of the AM discipline (ISO, 2014a):

- *Value*: Assets exist to provide value to the organisation and its stakeholders
- *Alignment*: AM translates the organisational objectives into technical and financial decisions, plans and activities.
- *Leadership*: Leadership and workplace culture are determinants of value realisation.
- *Assurance*: AM gives confidence that assets will fulfil their required purpose

The ISO fundamentals of leadership, alignment and assurance that ensure value is realised implies that a strategic focus is required, which extends AM activities beyond just the building, plant or equipment levels but must encompass strategic corporate and business objectives. Consisting of 7 main clauses and 23 sub-clauses assigned to AM activities, ISO 55001 (2014) provides a framework (see Figure 1- Clauses and Subclauses of ISO 55001 Asset Management Activities) for organisations to establish the appropriate AM capability, including an effective AM system defined as “a set of interrelated or interacting elements of an organisation to direct, coordinate and control AM activities in a consistent manner that effectively manage risk and provide assurance that objectives will be achieved” (ISO, 2014).

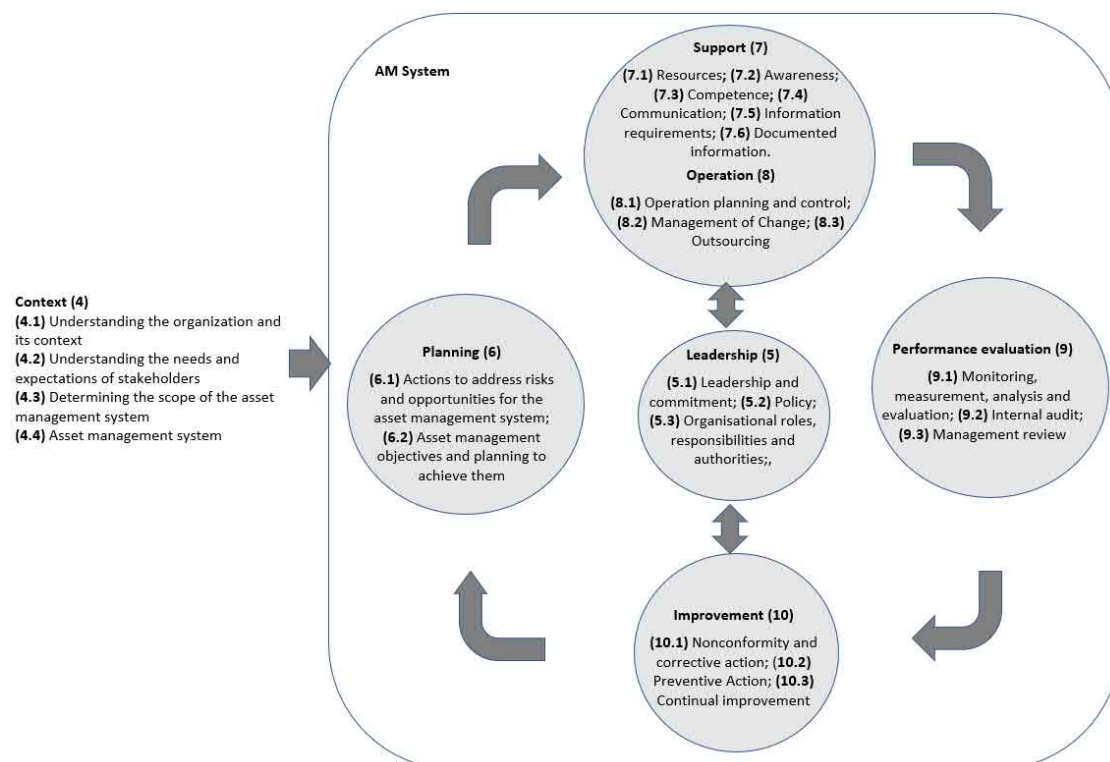


Figure 1- Clauses and Subclauses of ISO 55001 Asset Management Activities (Adapted from ISO 55000/1, 2014)

The AM System

Figure 2 below shows the relationships between the AM System and the organisation in relation to the key artefacts and processes.

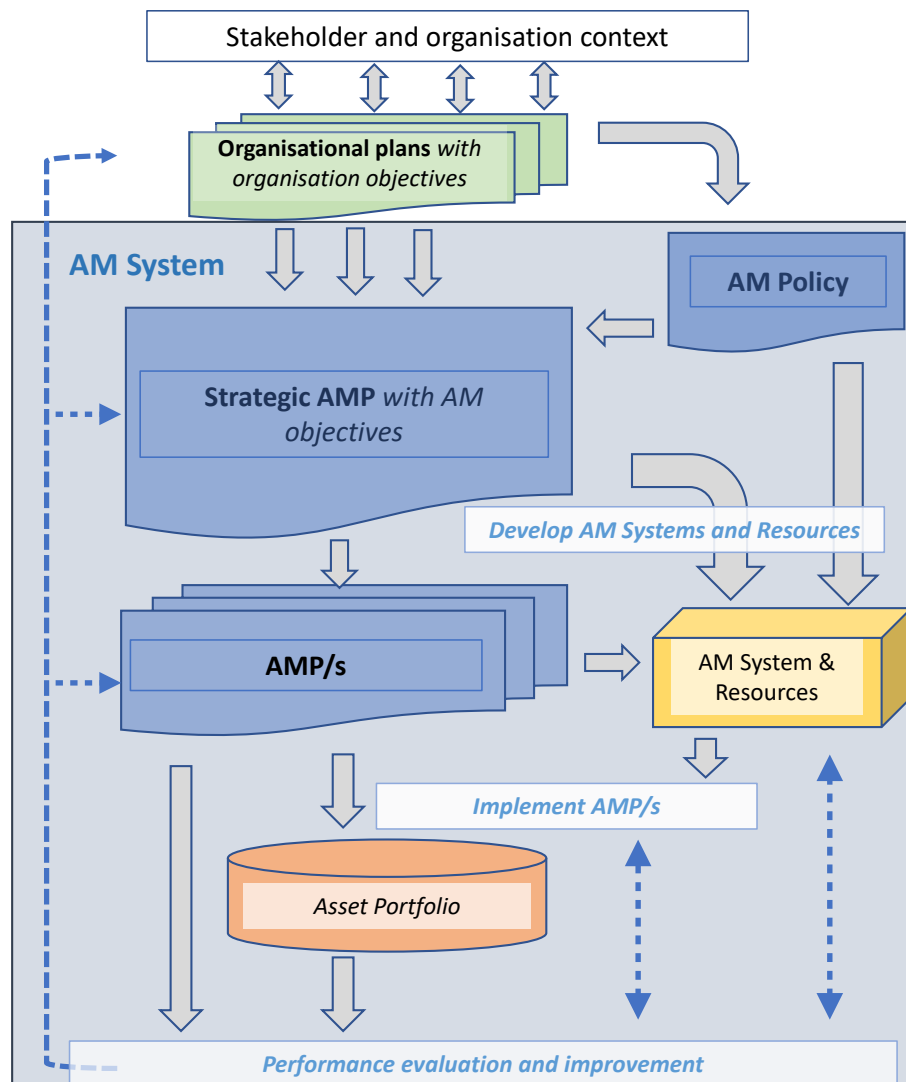


Figure 2 - Relationship between AM System elements (adapted from ISO 55002:2018)

The AM Policy document contains the strategic parameters that will influence all the AM functions within the organisation, their expected outcomes and outputs, including how they are measured. This document should ideally incorporate past experiences and experts' opinions wherever possible to ensure relevance and achievability of organisational objectives. The Strategic AM Plan (SAMP) is a key document that specifies how organisational objectives are converted into AM objectives, the approach for developing AM plans and the role of the AM system in supporting the achievement of the AM objectives (ISO, 2014b). With reference to system engineering principles, four pathways are pivotal to an effective AM system (ISO, 2018):

- Line of sight (alignment) from organisational context to all the AM elements and processes
- Hierarchy of objectives from organisation to strategic AM to tactical/operational AM translated into a similar order of key performance measures and indicators
- Consistent decision-making criteria and decision-making across the organisation
- AM risk management processes aligned to the broader enterprise risk management framework (assurance)

For ISO 55001 certification purposes, these standards and guidelines are used as a capability assessment framework that helps organisations determine the level of maturity of their asset

management capability based on seven areas that are consistent with other ISO management standards such as ISO 9001 (quality management), ISO 14001 (environmental management) and ISO 31000 (risk management), etc. summarised in figure 1.

Focus on the Value Concept

Applying the concept of ‘value’ as one of the fundamental in the standards require “*the need to understand the construct of how the identified realisable value is vertically cascaded in the organisational objectives and asset management objectives, purpose and use of the asset management system, asset management activities and assets*” (ISO, 2018). According to ISO, ‘value’ is realised through balancing costs (economic, social, environment), risks and opportunities, against the desired performance of assets to achieve the objectives of the wider organisational system (ISO, 2018). Noting that the value of the asset to an organisation can change over both the asset and the organisation life cycles, the standards acknowledged that the specification of ‘value’ for an organisation and its stakeholders could vary, even within the same organisation as different stakeholders gain different types of value from the way the assets are managed or utilised. ‘Value’ is not a single phenomenon as it is multifaceted and means different things to the different stakeholders of the organisation, specifically its customers, suppliers, employees, investors and any other interested parties in general (Hjelmrekke, Klakegg, 2013). Analogous to value creation, Yates et al. (2009) assert that the built environment in the healthcare system should be seen not only as a context but also as a resource that enables and potentially impacts operations, health, and service outcomes. In their view, the overall performance of a healthcare system is not only about cost, quality of service or time of delivery but should also be related to the benefits (value) realised from the equilibrium between resource utilisation (cost and time) and service provided (access and quality) using the assets (as a resource). This resource-based view applicable to all sectors argues that organisations can be regarded as a bundle of resources (Amit and Schoemaker, 1993; Rumelt, 1984). Resource management is critical to value creation because using resources is at least as important as possessing or owning them (Penrose, 1959). Indeed, physical assets seldom provide value on their own but contribute to the value generated at the system or network level and are often highly dependent on other assets within the system or between systems. (Srinivasan and Parlikad 2017). In other words, an asset provides the means for the realisation of ‘value’ for the organisation as the human input (capabilities) under a resource-based view plays an important role as they are responsible for creating new organisation value (Hodkiewicz, 2015; Lado and Wilson 1994, Wright et al. 1994).

The long-lasting life cycle of assets and constant change in users’ needs suggest that the concept of value and value management should be focused on users’ needs in addition to owners’ expectations in order to maximise the value creation and capture (Haddadi et al. 2015; Clarke, 2021). As a result of significant dependence on the type of assets and the specific business models, industries, or sectors they are part of, there is no single agreed definition of ‘value’ delivered by assets or asset management (El-Akruti et al., 2013). Hence, there is little theoretical and methodological consistency in understanding how to effectively integrate organisational value creation into the strategic management of assets (e.g., Wijnia, 2016; Lloyd, 2019; da Silva and de Souza, 2021; Maletič et al. 2019). This phenomenon has also led to the situation where asset performance measures are often not properly recorded and monitored against the overall organisational performance (Attwater et al., 2014; Shah et al. 2017).

Before the publication of the ISO standards, earlier asset management research had traditionally focused on the functional; aspects of managing assets such as reliability-centred

maintenance, condition monitoring and risk profiling with little or no reference to the holistic strategic aspects of realisation of organisational value. Indeed, after the release of the standards, concerns were raised by practitioners and academics regarding the potential ambiguity of the terms ‘*managing assets*’ and ‘*asset management*’ in practice. This led to ISO releasing a practice note in 2017 to explain the differences between ‘*managing assets*’ or what we “*do to*” assets and AM, which is what we “*do with*” assets that have a broader context of organisational purpose and strategy, which includes the value realisation for stakeholders (McKeown et al., 2017). These differences are summarised in Figure 3 below

Interested Parties	Managing Assets focus on:	Asset Management focus on:
Colleagues	- Asset data, location and condition assessment - Current KPIs - Department budget	- Information supported decisions (strategic context and related to customer needs) - Strategies to select and exploit assets over their lifecycles to support business aims - Collaboration across departments to optimise resources allocated and activities
Stakeholders	- Costs - Current performance - Response to failures / maintaining function	- Triple bottom line and value - Clarity of purpose of the organization - Focus on impact of activities
Top Management	- Short term gain / loss - Departmental / individual performance - Savings, especially OPEX	- Long term value for the organization - Developing competence and capability across workforce - Business risks understood and mitigated
Suppliers	- Short term contracts and performance - Service level agreements	- Long term contracts and/or partnering relationships in support of client value and objectives - Understanding client strategy and needs in 5-10 years

Figure 3 - Differences between ‘Asset Management’ and ‘Managing Assets’

Capabilities of AM in Practice

ISO acknowledged that not all aspects could be achieved within the AM system, such as leadership, culture, motivation, and behaviour. A key contributor to the standards, the Global Forum of Maintenance and Asset Management published the Asset Management Landscape document that outlined 39 knowledge areas or AM capabilities grouped under six groups for the purposes of gaining academic and professional certifications: (i) Strategy and Planning, (ii) AM Decision-making, (iii) Lifecycle Delivery, (iv) Asset Information Strategy, (v) Organisation & People, and (vi) Risk and Review as summarised in Figure 4. (GFMAM, 2014)

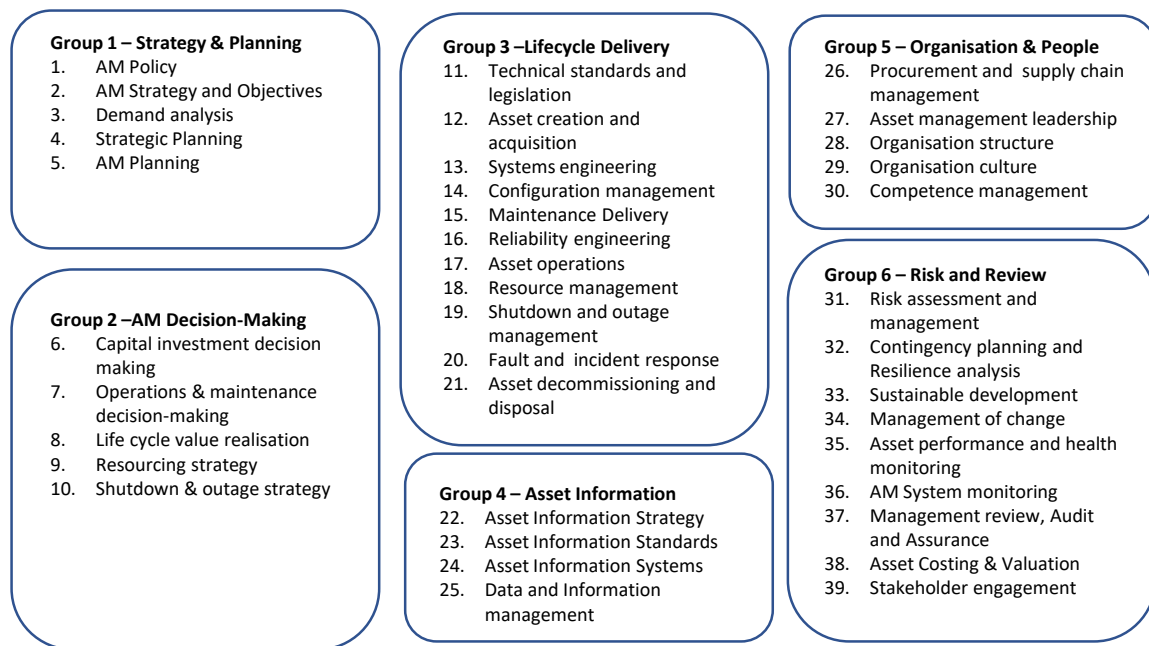


Figure 4 -GFMAM Asset Management subjects (2014)

These multidisciplinary subject areas provide the ontologies for AM that are well referenced in various international standards and technical publications and commonly used to develop delivery/operating models, AM frameworks and policies available published by government agencies and professional organisations. In essence, they provide the *‘how’* for the AM discipline while the ISO standards provide the *‘what’*. This study intends to address the *‘why’* that underpins most of these ontologies that have often been excluded.

The Systems Perspectives

Background

This paper is only focused on artificial man-made systems designed and built by people or organisations for a variety of purposes. Environmental systems that may occur naturally or spontaneously are outside its scope. There are many definitions of the term ‘built environment’ and associated physical assets, but for the purposes of our discussion, the term ‘built environment’ refers to man-made surroundings or facilities such as buildings, parks and open spaces supported by infrastructure that includes transport, water, and energy networks (Then and Tan, 2013). As a foundation of terminologies and theoretical concepts included in the discussions, the terms physical assets, facilities and infrastructure are used interchangeably, as shown in figure 5.

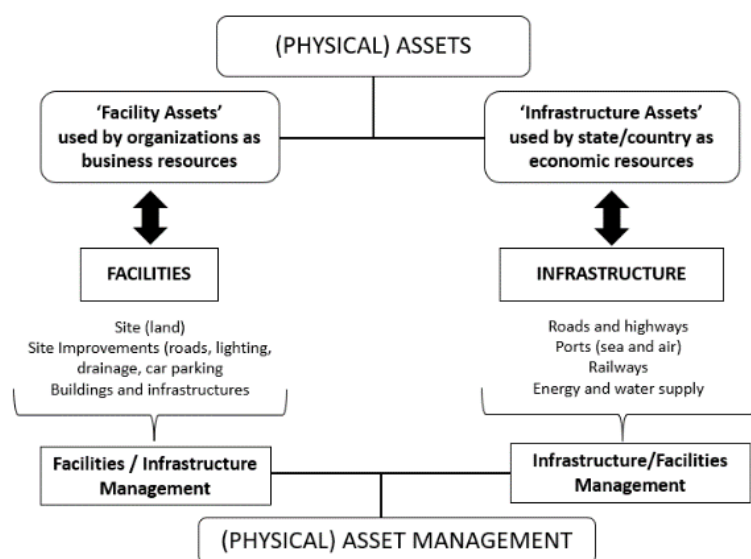


Figure 5 - Facilities and Infrastructure (adapted from Then and Tan, 2013)

While made up of individual physical assets, the built environment, when studied, highlights the systemic relationship between the enabling environment-assets and the sustainable use of resources or capital employed (social, financial, human, natural). Roof and Oleru (2008) consider the built environment holistically as *‘the material (e.g., physical assets), spatial and cultural products (e.g., placemaking) of the human labour force that reflects the people’s thoughts, aspirations, values, and goals which aim to serve human need’*. The management of the built environment must consider the attributes of a complex system with multiple layers, networks within and between organisations, external institutions, and users that collectively create value for all parties involved as Te Waihanga - New Zealand Infrastructure Commission (2021) defines infrastructure as *‘a system of interconnected physical structures that employ capital to provide shared services to enhance wellbeing’*, illustrates their view of how wellbeing benefits are delivered through these systems.

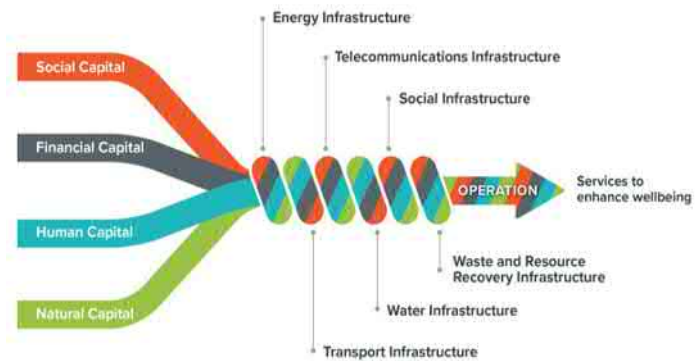


Figure 6 - Te Waihanga Definition of Infrastructure

Socio-Technical Systems

The provisions of the AM standards enforce the notion that ‘asset management systems are not just about the reliability and maintainability of assets but involve a larger array of processes that govern the life and use of an asset that encompasses elements of financial, economic, social and environmental requirements.’ Similarly, systems theory views organisations as social systems where elements must inter-relate in a congruent manner to be effective (Churchman, 1964). Taken together, an organisation and its built environment can be viewed as a structured sociotechnical system that involves the structuring and integration of human activities around various technologies, processes, and systems. In other words, in an imperfectly organised system, even if every part performs well relative to its own objectives, the total system may still not be optimal relative to its objectives. This is certainly the case in the built environment, as one would argue that while technologies affect the types of input and outputs from the system, it is the social aspect that determines the effectiveness of the technology introduced. Various studies have stressed the reciprocal interrelationship between humans and machines to foster the effective shaping of both the technical and social conditions of work in the industrial environment. However, as Green (1999) noted that while the present organisational structure and the built environment provides the formalisation of relationships between the technical and the psycho-social subsystems, these linkages are by no means complete and that many interactions and relationships occur between subsystems bypassing any formal structures which forms the second motivation of this study.

Systems Life cycle

According to ISO 15288 (2015), every system has a life cycle that can be described using ‘an abstract functional model that represents: *‘the conceptualisation its need, realisation, utilisation, evolution and disposal’*. The standard does not prescribe to any specific life cycle model, sequence of processes, relationships or outcomes but instead provides guidance on how decision gates can be used at different life cycle phases for organisations to understand and manage uncertainties and risks when creating or utilising a system that is fit-for-purpose. Instead, it provides a common framework of process descriptions for describing the life cycle of systems created by humans from a system engineering viewpoint that begins with defining

stakeholder needs and required functionality early in the development cycle, followed by documenting requirements before proceeding with design synthesis and system validation while focusing on the overall solution/s for the complete problem. The approach considers both technical and business needs by integrating all disciplines in a structured development process. Similarly, ISO 55000 do not prescribe any definitions of both the asset system and the asset management cycle, citing variations in different sectors and should be determined by the organisation. For an AM life cycle, the standard outlines seven phases (ISO, 2019): (i) requirements definition, (ii) asset planning, (iii) asset creation, (iv) operational and maintenance, (v) asset monitoring, (vi) renewal/rehabilitation, and (vii) disposal. For the life cycle of buildings, Joshi et al. (2010) describe four phases in the order of (i) material manufacturing, (ii) construction, (iii) use and maintenance and (iv) end of life. Recognising the cyclical nature of managing the built environment and a facilities management process viewpoint, Madritsch and Ebinger (2011) describe a lifecycle of (i) strategic planning, (ii) capital planning, (iii) design, (iv) construction, (v) commissioning, services, (vi) maintenance, and operations.

Research Methodology

As highlighted earlier that AM is an evolving concept, and because of its dynamic, contextually driven and multidisciplinary nature, few attempts have been made to develop a multifaceted and multidimensional model incorporating social, business and technical perspectives. Therefore, the intention of this study is exploratory in nature and based on the realist qualitative approach that accepts much of the conventional positivistic positions of mainstream managerial and organisational theories in the literature despite some differences between the classical and contemporary perspectives. The approach builds on the works of Simon (2002) and Schon (2017) that argues that additional focus on discovery and problem-solving in the research will be useful for both theory and research (Lawler et al., 1999). The lack of substantial literature on both the strategic and theoretical aspects of the AM discipline has led to the interpretive approach in this exploratory study as it attempts to discern multiple layers of intersubjective meaning that underlie the practice. Hence, the ISO 55000 suite of AM standards and guidance will be used as *a priori* in this study. The codes and themes are aligned to the various clauses within the ISO AM and other technical standards and AM capabilities/competencies recognised by the professional organisations, certification bodies and communities of practice. As the study is concerned with ‘discovering’ underlying theoretical meaning within the standards as well as causes of actions in practice, it relies on the reflexivity of the author and what Madill et al. (2000) described as the ‘contextual constructivist position’ of the discussion topics from different perspectives. Taking into account the complexity of AM practice and the built environment, the study aims to collect what is meaningful to the participants in the ongoing research that follows this paper.

This paper has utilised a systematic literature review for AM publications between 2014-2021 after the ISO AM standards were published. The initial stage of the approach involves an iterative scoping process of definition, clarification, and refinement to assess the relevance and size of the literature related to study aims. In the interest of brevity, we generally limit our references to review articles and viewpoints directly aligned to the ISO standards. However, studies prior to 2014 were later included when there was an obvious fit. Triangulation between the standards, theories and published events was carried out using the deductive logic of inquiry (Yin, 2016). Keywords used for the initial stage and the results are summarised below (Figure 7):

Words Selected	Articles Discovered	Final Selection
"strategic management" & facility*	1,446	28
"strategic management" & asset*	1239	
"strategic management" & infrastructure*	532	
"asset management" & strategy*	764	
"asset management" & ISO 55*	40	
"strategic asset management"	37	
"strategic asset management" & ISO 55*	3	
Note: * denotes search wildcard was used		

Figure 7 - Results of relevant SAM literature search

After excluding articles that mainly focused on specific non-physical assets related, non-functional and non-strategic considerations, twenty-eight AM base articles were selected. From the base list, the snowballing technique was used to consider any theoretical, practical or methodological debates surrounding the field and sub-fields of AM that included references to managerial and organisational theoretical frameworks in non-AM literature, in particular, related to the systems approach, dynamic capabilities and business model concept. A saturation point of repeated citations and references was made after a review of around 140 pieces of articles section sourced from conference proceedings, professional journals, standards, eBooks, Local and central government publications included in the references section (Figure 8).

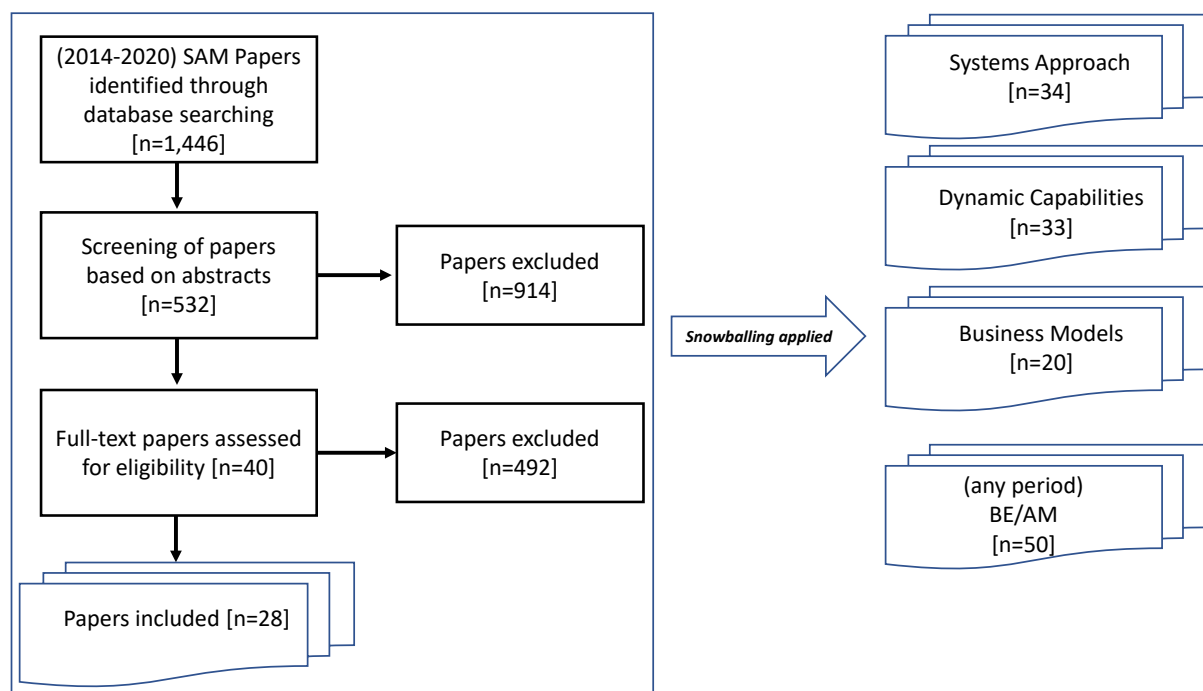


Figure 8 - Summary of subject/article selection

A code represents and captures the datum's primary context, meaning and quintessence. According to Basit (2003), coding is a key part of the analysis but not synonymous but as the initial step toward an even more rigorous process of linking data to an idea, and from all data pertaining to that idea (Richards & Morse, 2007). Data was coded both during and after collection based on the, *a priori* established for the overall research focused on ISO standards, AM practices, the AM System and its key elements, their relationships and constructs (refer to Figure 1, Figure 2). The discussion that follows this section is a result of several cycles of coding, re-coding and filtering to highlight relevant thoughts and ideas contained within the literature for the purpose of this study that could be later used to generate categories, concepts, themes in the future for building theory and a new business model creation.

Findings and Discussion

Systems Thinking

Previous research has found that systems thinking has been an established management practice since the 1960s, which supported the unification of many fields of knowledge of management and behavioural sciences to deal with problems in organisations (Kast & Rosenberg 1972). With Aristotle's statement that the "*whole is greater than the sum of its parts*", some researchers have argued that current practices are simply additions of new content to an ancient concept, for example, in Chinese traditional medicine (e.g., acupuncture) that treated each human body as a whole system more than 5,000 years ago (Forrest, 2018). Throughout history, as Teece (2018) noted, there were many definitions for the concept of systems that resulted from separate research streams in biology (von Bertalanffy), cybernetics (Wiener), economics (Boulding), and mathematics (Rapaport). All of which led to a common basis for communication between scientists, researchers and practitioners from various disciplines. The thinking resulted in wide application either implicitly or explicitly by management scientists in various fields and disciplines, including engineering, social science and asset management (Jackson 2009). Forest (2018) argues that philosophically, the systems approach is concerned with the concepts of the relationship of "*wholes*" and "*parts*" and focuses on the unified laws that govern the forms of existence of structures and forms of interactions within and between structures of various characteristics and behaviours that change over time and space. Such an approach is concerned with whole system performance, not on their parts taken separately that can only be treated adequately from a holistic point of view based on the relationships between parts of the systems, their interactions, and interdependencies.

Complexity and Behaviour

Ackoff (1971) describes four characteristics of an organisation to be considered a system: (i) containing at least two purposeful elements with a common purpose, (ii) a functional division of labour in pursuit of the common purpose(s) of its elements that define it, (iii) the functionally distinct parts of the system (by function, space, or time) can respond to each other's behaviour through observation or communication, and (iv) at least one subset of the system has a system control function. Boulding (1956) describes the behaviour of the different systems according to an intuitive nine-level hierarchy of real-world complexity ranging from structures and frameworks at the simplest level to transcendental systems at the most complex. The first three levels in the hierarchy can be classified as physical or mechanistic systems; the fourth, fifth and sixth levels are involved with biological, natural, or ecological systems, the last three are concerned with human and society (social systems). Organisations, according to Boulding's 9-level scale of system complexity, are characteristics typical of level 8 that are generally vast,

fragmented, and multidimensional. This complexity is even more pronounced in the built environment with the rapid expansion of knowledge and advances in technology that has led to various highly differentiated and specialised scientific fields focused on analytical, fact-finding, and experiential approaches in specific fields. According to ISO 42010:2011, “there is no single characterisation of what is essential or fundamental to a system; that could pertain to any or all of the following (ISO, 2011, p. 4):

- system constituents or elements
- how system elements are arranged or interrelated
- principles of the system’s organisation or design; and
- principles governing the evolution of the system over its life cycle.

Figure 9 provides an ontology for the description of a generic complex system’s architecture to assist in the understanding of its essence and key attributes (e.g., stakeholders, purpose/system concerns, environment) pertaining to its behaviour, composition and evolution.

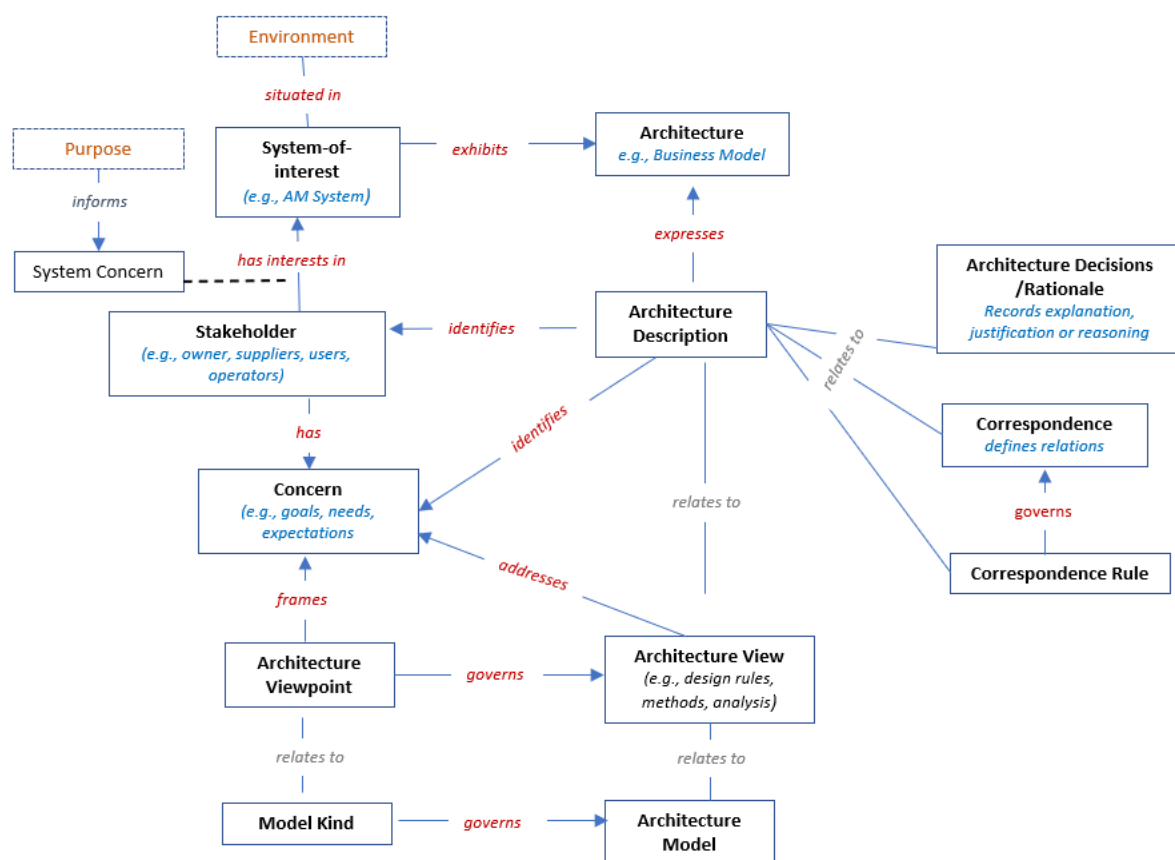


Figure 9-Conceptual model of an architect description (adapted from ISO 42010:2011)

Systems Dynamics

In the traditional analytical approach to planning and management, organisations start with today’s problems, break them into management parts, analyse and resolve one area at a time before addressing the next. The ISO AM standards appear to reflect the systems dynamics approach (Duggan, 2016), that emphasises (i) stocks (levels) and flows (rates) dimensions, (ii) strategic decision making, and (iii) the role of feedback in complex systems with an overall “endogenous point of view”. First presented in Forrester’s (1958) seminal article, his original four foundations of a slightly modified “industrial dynamics” (1961) include: (i) the theory of information feedback systems, (ii) knowledge of decision-making processes, (iii) the

experimental model approach to complex systems, and (iv) realistic mathematical model simulations. These later changed to a four-tiered structural hierarchy under “urban dynamics” (1969) that aligns with the philosophy in the AM standards:

- The closed boundary around the system
 - Feedback loops as the primary structural elements within the boundary
- Level (state) variables representing accumulations within the feedback loops
- Rate (flow) variables representing activity within the feedback loops
 - Goal
 - Observed condition
 - Detection of discrepancy
 - Action-based on discrepancy

Haines (2000) suggested the first step of the process is to determine the future of the organisation as a whole and works backward guided by what he calls the ABCDE guideposts or phases. Five critical questions guide the thought processes at each phase (p.35):

- *Phase A:* Where do we want to be? (i.e., our ends, outcomes, purposes, goals, holistic vision)
- *Phase B:* How will we know when we get there? (i.e., the customers’ needs and wants to be connected to a quantifiable feedback system)
- *Phase C:* Where are we now? (i.e., today’s issues and problems)
- *Phase D:* How do we get there? (i.e., close the gap from C→A in a complete, holistic way)
- *Phase E:* What will/ change in our environment in the future? (This is an ongoing question.)

A variation of this perspective is also evident in the strategic asset management planning process described in ISO 55002 (ISO, 2018), as illustrated in figure 2. The SAMP, as a key artefact of the AM System, requires inputs from stakeholder requirements, organisational objectives and plans, internal and external issues. The outputs of the SAMP will inform the tactical AM plans, and through a feedback mechanism, highlight what capabilities are needed for AM System, as shown in Figure 10.

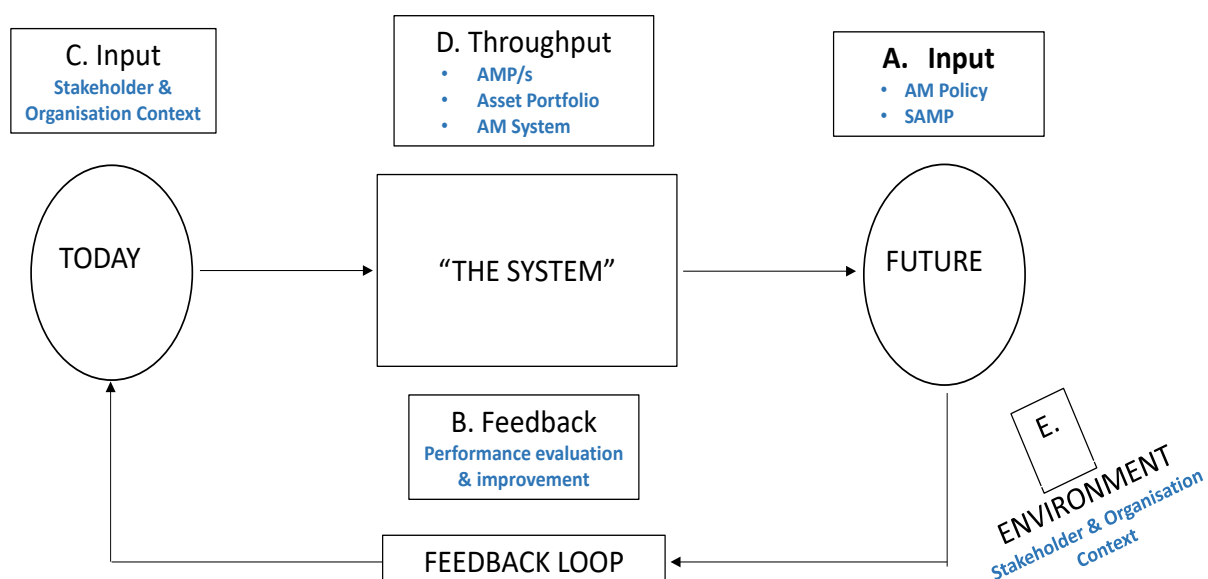


Figure 10- AM System Elements against ABCDE guideposts (adapted from Haines, 2000)

Dynamic Capabilities and Resilience

Resilience and Adaptability

The challenges of the built environment previously identified can be considered as critical drivers for the significant amount of research interest on the strategic aspects of AM (Gavrikova et al. 2020). Considering the long-term sustainable realisation of value across the organisation with the assets (Maletić et al. 2018, 2020, El-Akruti et al. 2018), sustainability and resilience issues due to inadequate funding to address ageing infrastructure, rising demand, adapting to climate change, short-term focus of political processes have led to researchers and practitioners contending that traditional mechanistic approaches to managing assets are no longer practical (Godau, 2004). The dynamic nature of these issues makes it crucial for organisations to better understand their potential impact but, more importantly, how to respond when they become a reality (Weick & Sutcliffe, 2001; Vogus et al. 2014; Ihemegbulem et al. 2017; Vonk et al. 2020).

Although the term ‘*resilience*’ is a growing theme in business and asset management research, its conceptualisation has been quite varied across studies, mainly because the concept itself is prodigious and fragmented within the academic silos of psychology, ecology, engineering, and management science (Annarelli et al. 2016). Fundamentally, the concept of resilience in the built environment domain applies to agile asset systems and the agility of the people that manage them, where the expectation is the overall functionality remain viable over time regardless of any expected or unexpected disruptions. Marsden and Dawson (2017) noted that organisations governed by complex systems could not operate in traditional ways to cope with the uncertain situations pertaining to internal or external permutations; they need to portray resilience characteristics of both flexibility and adaptability that describe either temporary or permanent changes. For the built environment, both artificial and natural hazards have led to organisations incorporating a sense of resilience at the strategic, tactical and operational levels in the long-, medium- and short-term timeframes (Annarelli et al. 2016; García-Gómez et al. 2021). In resilience engineering, Woods (2015) describes the system’s ability to retain or regain normal functions within acceptable thresholds (e.g., quality, capacity) and under a range of conditions. Asset resilience is often measured by the speed at which the system returns to equilibrium (Gunderson, 2000), while Walker et al. (2004) refer to resilience as the capacity to absorb disturbances while maintaining the same functionality. Hémond and Robert (2012) presented three essential components from the conceptualisation of resilience: (i) the required ‘*knowledge for understanding*’, (ii) the level of ‘*acceptability or threshold*’, and (iii) the level of ‘*adaptability*’.

Some researchers view organisational resilience as a positive adjustment to challenging conditions; for example, Pavlou and EL Sawy (2013), in their studies, identified examples of instances of technological breakthroughs, business model innovations, intelligent infrastructure development and others. Similarly, Dalziell and McManus (2004) posit that proactive, complex organisations need to be truthful or account for their vulnerabilities and be able to self-organise or alter their management infrastructure and practices when change is required. It is important to note that the challenge for asset managers is not to find a solution for every problem that an organisation faces but to have a clearly defined process of resilience management embedded within its strategic management framework. The failure to understand the importance of such methods leads organisations in an undesirable “firefighting” mode when a crisis occurs (McDonald, 2017).

From an AM System viewpoint, GFMAM (2021) describes an ‘*adaptable*’ AM organisation as “having the ability to sense and respond to changes in the organisation’s context and stakeholders’ expectations and refinement of decision-making tools for industries faster than the rate and magnitude of changes over time”. In short, it emphasises being proactive rather

than reactive to adverse situations that allow system changes to align to different conditions (Woods & Hollnagel, 2017), consistent with the ISO 55000 requirements of continuous improvement and forward-thinking approach to the strategic AM planning process.

Ordinary vs Dynamic Capabilities

Since resilience scholarship is primarily concerned with the development of organisational adaptability to adverse environmental conditions, Stephenson (2010) argues that it is logical to incorporate resilience capabilities as part of the dynamic capabilities (DC) that take into consideration a holistic view of the potential impact of both ‘adverse’ as well as ‘promising’ situations. In the seminal works of Teece et al. (1997), they defined the DC of an organisation as the ability to integrate, build and reconfigure internal and external competencies to address rapidly changing environments. They describe the organisation’s ability to change its resource configuration through strategic adjustments referred to as “*processes, positions and paths*” to the changing environmental conditions. It is essential to note the differences between ordinary (or operational) and dynamic capability. Operational capability, unlike DC, enables an organisation to perform highly technical, business-as-usual or day-to-day activities using more or less the same techniques and tools maintaining the status quo where Winter (2003) and Collis (1994) refer to as ‘zero-order’ capabilities. DC, on the other hand, are higher-order capabilities for sustained performance, directing ordinary powers towards high pay-off endeavours such as orchestrating available resources to address and shape the changing business environments (Teece 2014). DC involve a combination of organisational routines and entrepreneurial leadership/management and can be assigned to three clusters for application (Teece 2007):

- i. ‘*sensing*’ – identification, development, co-development, and assessment of technological opportunities
- ii. ‘*seizing*’ – mobilisation of resources to address needs and opportunities and to capture value from doing so
- iii. ‘*transforming*’ – continued renewal

Their efforts over the years had led to DC evolving into a distinct research topic that was based on earlier works such as strategic management (Mintzberg, 1994), patterned behaviour and stored knowledge (Nelson & Winter, 1982), core competency (Prahalad and Hamel, 1993) and the resource-based view (Barney, 1991; Wernerfelt, 1984). Other management scholars have also adapted DC with slightly different viewpoints (e.g., Eisenhardt and Martin, 2000; Helfat and Winter, 2011; Helfat and Peteraf, 2015; Arndt and Pierce, 2018) that emphasises behavioural (e.g., best practices, benchmarking) vs evolutionary (e.g., innovation) theories.

The term “dynamic” in DC implies the alignment to the dynamism of the business environment involving emergence and evolvability characteristics. While not explicit, DC principles are deeply enshrined in the ISO 55000 suite of standards, notably in the ‘leadership’ fundamental, vital elements of an AM system, the strategic AM planning and continual improvement processes where management and/or governance can ‘*sense*’, ‘*seize*’ and ‘*transform*’ opportunities by using internal resources effectively and efficiently for adaptation to the business environment as changes occur (Anand et al. 2009; Helfat and Winter, 2011). This thinking differs slightly from Teece’s (2018) response to risk and uncertainty where there is an emphasis on newer technologies, a changing mindset and culture involving the broader value change is required that extends beyond the AM Philosophy contained in the ISO 55000 standards as depicted in Figure 11.

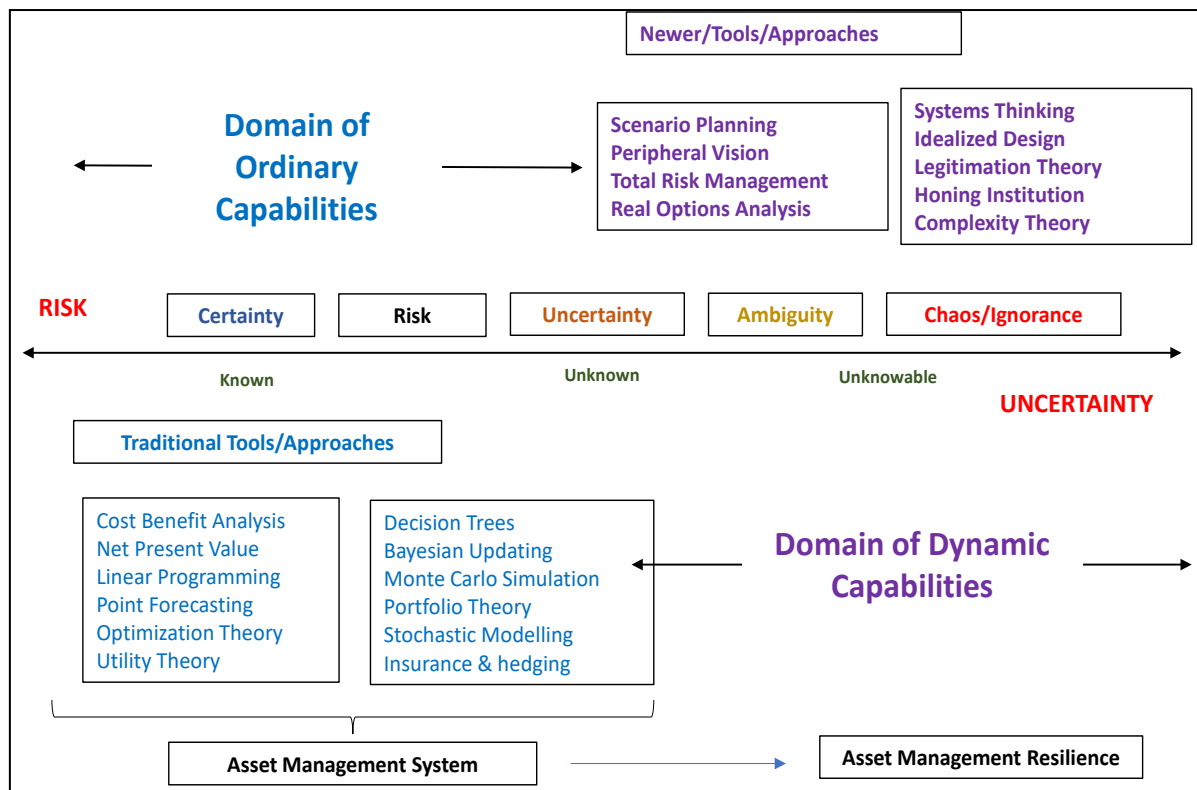


Figure 11 - Ordinary vs Dynamic Capabilities (adapted from Teece, 2021)

Business Model Concept

Business models (BM) can be considered cognitive models (Demil & Lecoq, 2019) used to describe activities or business processes and/or to describe taxonomies and typologies of how organisations can create and capture value (Baden-Fuller & Morgan, 2010). The typical AM models mentioned earlier could act as mediators between theory and practice, enabling scholars and practitioners to inquire about abstract concepts and infer them to reality and operationalised (Baden-Fuller & Morgan, 2012). According to Zott et al. (2011), the BM concept gained currency in academic articles in the late 1990s and by 2010 as it was considered more than a statement of “*how value is created and captured*”. Like any model, BM can “*appear in many guises and serve any purpose*” (Baden-Fuller & Mangematin, 2015). From a critical assessment of prior BM research, Massa et al. (2017) provided three viewpoints on what constitutes a BM: (i) mutual understanding of cognitive/linguistic schemas describing the purpose of the business, (ii) formal representations/descriptions of generic components of a business model, and (iii) as a focus on specific attributes that give organisations competitive advantage and superior performance. They reflected on why there might be multiple perspectives on the relationship between business models and strategy, noting that value creation and capture can come from both supply and demand sides of the value chain.

From the practitioner’s perspective, Mitchell and Coles (2003) conclude that a BM is simply the combined elements of ‘*who*’, ‘*what*’, ‘*when*’, ‘*why*’, ‘*where*’, ‘*how*’, and ‘*how much*’ is involved in providing services or product to customers or end-users. The socio-material perspective (e.g., Orlikowski & Scott, 2008; Kaplan, 2011) applied in the ISO 55001 certification process assumes that (i) the material dimension of reality (i.e., document evidence and other artefacts), (ii) the social dimensions (i.e., actions, practices and interactions that take place around artefacts) must be considered jointly within an AM system, and (iii) the broader

organisational system which it is part of; and to be measured using financial and non-financial indicators (IEC 62775:2016).

In the context of business structures and alignment, Beckett and Dalrymple (2019) claim that the design of a suitable business model is influenced by five elements of context: (i) business establishment & goals (e.g., Teece, 2010; Zott & Amit, 2015), (ii) business opportunities & stakeholders (e.g., George & Bock, 2011), (iii) dynamic capabilities (e.g., Teece, 2017; Da Silva & Trkman, 2013), (iv) organisational structure and activity systems (Morris et al., 2005; Zott et al., 2011; George & Bock, 2011), and (v) value architecture (e.g. Allee, 2000; Teece, 2010; Wirtz et al, 2016a, 2016b). These five elements can be further grouped into three separate activity groups: (i) business model antecedents, (ii) business model selection, and (iii) business model implementation. Figure 12 is an adaptation of their model for the AM function based on the systems approach, value management, dynamic capabilities and environmental contingencies.

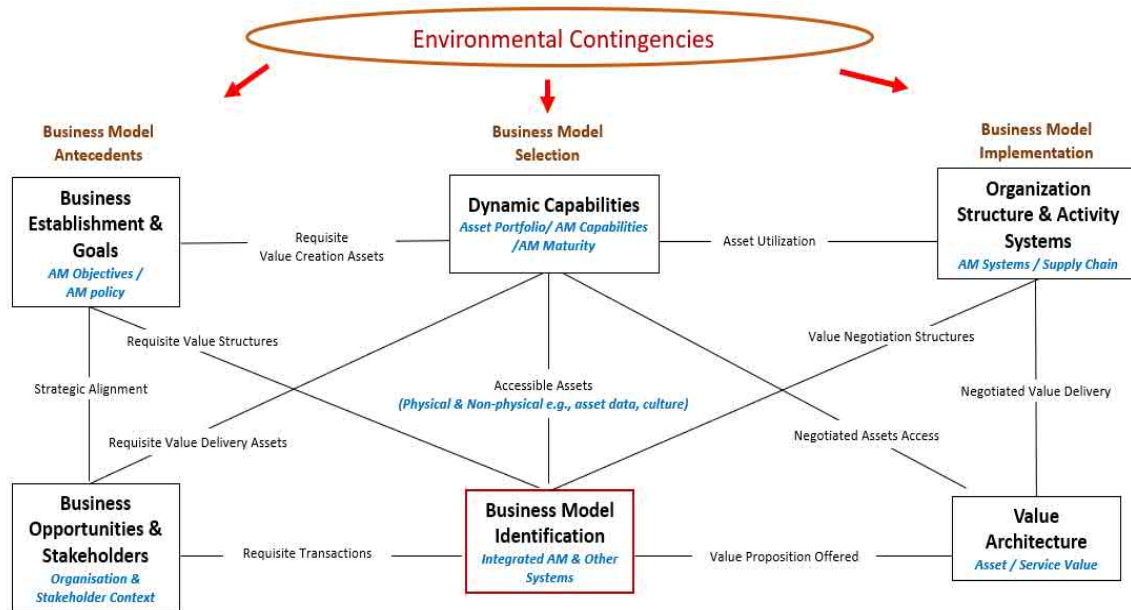


Figure 12 -AM System Elements / Contextual factors of a suitable business model concept (adapted from Beckett & Dalrymple, 2019)

AM in the Built Environment – A Synopsis

The point of departure of this article is the observation that the AM practice in the built environment sector is highly regulated and framed by many international standards, institutional policies and legislation during the different life cycle phases. Typically, there are multiple ways to frame any given problem and considering what has been discussed thus far may only be the symptoms, and symptoms do not always equal issues. Although the asset management in the built environment subject is now recognised and broadly accepted as distinct fields of multidisciplinary studies, their identities are often defined (in silos) in terms of the construction, architecture, engineering, property or facility management or other technical disciplines. Studies of this multidisciplinary field are few (Temple 2004) and often lack a theoretical disciplinary base (Betts and Lansley, 1993; Loosemore, 1997; Lombardi & Brandon, 2002) that can be used to benchmark organisational performance or support decision making (Madritsch and Ebinger, 2011). More recently, the subject has embraced the cultural and behavioural aspects when regarded as a management system for sociotechnical systems.

The systems approach is pronounced in the ISO standards, where guidelines for applying ISO 55001 emphasised the need for synergies among elements of the AM Systems, their integration, and the alignment of values or outcomes resulting from their interactions within primarily a closed system. However, many case studies have shown that systems engineering techniques alone are insufficient to deal with real-world problems as the existing management systems are too complex for the straightforward application of any tools or technology. The built environment as a sociotechnical system is subjected to changes in boundaries, functions, and structure over the period during its lifecycle, which will be recognised differently from various perspectives. It can also contain several closed systems or subsystems (e.g., automated or self-contained building systems, asset management systems) that exhibits the same characteristics but interact in a non-linear fashion evolving new networks constantly that gives organisations their identity at a given point in time (Millet, 1998). Moreover, the elements that form the environment of a system and the environment itself may be conceptualised as systems when they become the focus of attention. Every system can also be conceptualised as part of another more extensive system. For example, in the built environment, the architect may consider a house with its electrical, heating, and plumbing systems as one large system. But an electrical engineer may consider the electrical system as a system and the house as its environment. To a social psychologist, a home may be an environment of its occupants, the system with which he or she is concerned with the other physical elements irrelevant. While this phenomenon has been useful in developing knowledge quickly in the past, there is now a greater need for unification of these analytical and fact-finding elements into a broader, multidimensional, multidisciplinary capability that provides detailed attention to technological and social components to better understand and address the highlighted issues.

As Bosch et al. (2013) noted for complex problems, treating symptoms with band-aid solutions via linear thinking has not always been helpful as there is no one solution to a complex problem. In the past, business model innovation in the strategy literature tend to focus on the ability of the organisation to create and capture value by modifying or introducing new critical elements (e.g., resources, capabilities) while engaging externally (Hartmann et al., 2013). This phenomenon, according to some researchers, has led to organisational inertia (Sosna et al., 2010), leadership/management inertia (Chesbrough & Rosenbloom, 2002; Tripsas & Gavetti, 2000). Similarly, in recent AM literature, there is also the concern that was focusing solely on the alignment and assurance requirements of the standards may suppress the higher potential for AM to add more excellent organisational value (Hodkiewicz, 2015a; Abe & Mizutani, 2016; Llyod & Pilling, 2019). This view is supported by Mo and Beckett (2019), who claim that the mechanistic (deterministic) systems view of the built environment, the organisation and its management systems have since evolved into a wider sociotechnical system governed by different sets of rules and structures. These parameters are highly dependent on the dynamic nature of connectivity and interactions of the individual elements often constrained differently by regulatory and institutional requirements at various stages of a systems lifecycle. While complex systems are fundamentally deterministic, successful organisations have created complex adaptive systems that exhibit flexibility and resilience in challenging situations. However, dynamically re-inventing business models and strategies as circumstances change may sound straightforward, but such re-invention is not always possible as organisations are constantly faced with other competing priorities as demanded by stakeholders. Incorporating these forces in a climate of uncertainty requires more than just a desire for change; it requires dynamic capabilities executed at a systems-level utilising both internal and external resources.

Employing existing theories to define the dimensions of a workable AM business model is an acceptable practice when theorists and practice are in general agreement, but that does not

appear to be the case here. In general, this study has found that academic literature on the Systems, DC and BM perspectives often focus on the ‘*why*’ or better understanding of their triggers, drivers and enablers. In contrast, the AM literature, including the ISO standards, tends to emphasise the ‘*how*’ the different models should be adopted/implemented based on anecdotal knowledge and often without empirical scientific evidence. For example, AM success stories from technological innovations are often highlighted separately from the social/human aspect in terms of changes in culture, behaviour and leadership through business model innovation.

Conclusion

An awareness of inter-related or interdependent elements is of limited use unless managers can ascertain which relationships or competencies are most critical at a particular juncture (Blanchard & Fabrycky, 2011). Successful system interventions would require the ability to identify leverage points where remedies are most effective. Hence, this study has highlighted several limitations that warrant further research, including: (i) whether the concept of the closed system is still valid in the built environment setting, (ii) if there is any need to differentiate between standard and dynamic capabilities or should all capabilities have the ability to be dynamic when the need arises, (iii) whether the ambiguity of asset value and organisational value should be the main focus of asset management strategies, and lastly, (iv) further clarification of what is the balance between ‘value’, ‘risk’, cost and ‘performance’ is warranted and ‘trade-offs’ to have a holistic view. For instance, rather than a purely reactive stance, perhaps fully integrating AM in the onset into the broader organisational value creation strategies could better address some of the highlighted challenges

It is the ambiguity and variety in the existing literature discussed so far that has driven us to propose an exploratory approach in the research framework for the ongoing more exhaustive study using a case study approach to capture multiple viewpoints of different stakeholders (e.g., asset owners, asset users, service providers and regulators). The proposed research framework will focus on four components of what constitutes good AM practices: (i) definitions of factors or variables for delivering value based on the theories highlighted in this paper (ii) a comprehensive study of the domains or settings for their applications, (iii) a better understanding of the relationships of these variables and lastly, (iv) how they can be applied in practice with potentially specific predictions of outcomes within an organisational setting. It is hoped that the research findings will inform the new AM business model for effective enablement of different tangible and intangible resources (assets) not only owned or controlled by an organisation but also those in the wider networked environment.

Acknowledgement

This is an aspect of a PhD research study by the corresponding author. The authors wish to acknowledge the School of Built Environment, Massey University for providing a fee scholarship for this research.

References

- Abe, Y., & Mizutani, T. (2016). Internal audit, certification and maturity assessment based on ISO55001 in Sendai wastewater utility, Japan. *Water Practice and Technology*, 11(4), 822-828.
- Ackoff, R. L. (1971). Towards a system of systems concepts. *Management science*, 17(11), 661-671.

- Ali, H. (2021). The Strategic Implementation Asset Management System Basis ISO 55000: A Case Study On Indonesian Railways Company. *Journal of Business and Management Review*, 2(3), 226-244.
- Allee, V. (2000). Reconfiguring the value network. *Journal of Business strategy*, 21(4), 36-39.
- Alsyouf, I., Alsuwaidi, M., Hamdan, S., & Shamsuzzaman, M. (2021). Impact of ISO 55000 on organisational performance: evidence from certified UAE firms. *Total Quality Management & Business Excellence*, 32(1-2), 134-152.
- Amit, R., & Schoemaker, P. J. (1993). Strategic assets and organisational rent. *Strategic management journal*, 14(1), 33-46.
- Anand, G., Ward, P. T., Tatikonda, M. V., & Schilling, D. A. (2009). Dynamic capabilities through continuous improvement infrastructure. *Journal of Operations Management*, 27(6), 444-461.
- Annarelli, A., Battistella, C., & Nonino, F. (2016). Product service system: A conceptual framework from a systematic review. *Journal of Cleaner Production*, 139, 1011-1032.
- Arndt, F., & Pierce, L. (2018). The behavioral and evolutionary roots of dynamic capabilities. *Industrial and Corporate Change*, 27(2), 413-424.
- Attwater, A., Wang, J., Parlikad, A., & Russel, P. (2014). Measuring the performance of asset management systems. *Asset Management Conference 2014*,
- Audit New Zealand (2010) *Asset Management for Public Entities: Learning from Local Government Examples*, Wellington, New Zealand, National Office.
- Baden-Fuller, C., & Mangematin, V. (2013). Business models: A Challenging agenda [research-article]. *Strategic Organization*, 11(4), 418-427.
- Baden-Fuller, C., & Morgan, M. S. (2010). Business models as models. *Long Range Planning*, 43(2-3), 156-171.
- Barney, J. B. (1991). Firm resources and sustained competitive advantage. *Journal of Management*, 17(1), 99-120.
- Basit, T. (2003). Manual or electronic? The role of coding in qualitative data analysis. *Educational research*, 45(2), 143-154.
- Beckett, R. C., & Dalrymple, J. (2019). Business Model Architecture by Design. *Technology Innovation Management Review*, 9(7).
- Betts, M., & Lansley, P. (1993). Construction Management and Economics: A review of the first ten years. *Construction Management and Economics*, 11(4), 221-245.
- Blanchard, B., & Fabrycky, W. (2011). Chapter 17: Design for affordability (life cycle costing). *Systems engineering and analysis*, 5th edn. Prentice Hall, Upper Saddle River, 566.
- Bosch, O. J., Nguyen, N. C., Maeno, T., & Yasui, T. (2013). Managing complex issues through evolutionary learning laboratories. *Systems research and behavioral science*, 30(2), 116-135.
- Boulding, K. E. (1956). General systems theory—the skeleton of science. *Management science*, 2(3), 197-208.
- Bradley, C., & Main, K. (2015). ISO 55000: Creating an asset management system. *Health estate*, 69(2), 64-66.
- Capela, M., Santos, A., & Luís, A. (2020). ISO 55001 Certification at EPAL-the pains and the gains. *Water Practice and Technology*, 15(2), 321-326.
- Chesbrough, H., & Rosenbloom, R. S. (2002). The role of the business model in capturing value from innovation: Evidence from Xerox Corporation's technology spin-off companies. *Industrial and Corporate Change*, 11(3), 529-555.
- Clarke, R. (2021). Asset stewardship: delivering sustainable sewer rehabilitation across Ireland. *Proceedings of the Institution of Civil Engineers-Civil Engineering*,
- Collis, D. J. (1994). Research note: how valuable are organisational capabilities? *Strategic management journal*, 15(S1), 143-152.
- Churchman, C. W. (1964). An approach to general systems theory. Views on general systems theory: *Proceedings of the Second Systems Symposium at Case Institute of Technology*,
- da Silva, R. F., & de Souza, G. F. M. (2021). Mapping the Literature on Asset Management: A Bibliometric Analysis. *Journal of Scientometric Research*, 10(1), 27-36.
- DaSilva, C. M., & Trkman, P. (2014). Business model: What it is and what it is not. *Long range planning*, 47(6), 379-389.
- Dalziell, E. P., & McManus, S. T. (2004). Resilience, vulnerability, and adaptive capacity: implications for system performance.
- de Almeida Pais, J. E., Raposo, H. D., Farinha, J. T., Cardoso, A. J. M., & Marques, P. A. (2021). Optimising the Life Cycle of Physical Assets through an Integrated Life Cycle Assessment Method. *Energies*, 14(19), 6128.
- Demil, B., & Lecocq, X. (2015). Crafting an innovative business model in an established company: The role of artifacts (Vol. 33) [Article]. Emerald Group Publishing Ltd. <https://doi.org/10.1108/S0742-332220150000033003>
- Dobbs, R., Pohl, H., Lin, D.-Y., Mischke, J., Garemo, N., Hexter, J., Nanavatty, R. (2013). *Infrastructure productivity: How to save \$1 trillion a year: McKinsey Global Institute*.

- Duggan, J. (2008). Using system dynamics and multiple objective optimisation to support policy analysis for complex systems. In *Complex decision making* (pp. 59-81). Springer.
- El-Akruti, K., Dwight, R., & Zhang, T. (2013). The strategic role of Engineering Asset Management [Article]. *International Journal of Production Economics*, 146(1), 227-239. <https://doi.org/10.1016/j.ijpe.2013.07.002>
- El-Akruti, K., Kiridena, S., & Dwight, R. (2018, 12/10 /). Contextualist-retroductive case study design for strategic asset management research [Article]. *Production Planning and Control*, 29(16), 1332-1342.
- Eisenhardt, K. M., & Martin, J. A. (2000). Dynamic capabilities: what are they? *Strategic management journal*, 21(10-11), 1105-1121.
- Flyvbjerg, B. (2009). Survival of the unfittest: why the worst infrastructure gets built—and what we can do about it. *Oxford review of economic policy*, 25(3), 344-367.
- Forrest, J. Y.-L. (2018). *General systems theory: Foundation, intuition and applications in business decision making* (Vol. 32). Springer.
- Forrester, J.W., 1958. Industrial dynamics: A major breakthrough for decision makers. *Harvard Business Review* 36 (4), 37±66.
- Forrester, J. W. (1961) *Industrial Dynamics*. Cambridge: MIT Press; Currently available from Pegasus Communications: Waltham, MA.
- Forrester, J.W., 1969. *Urban Dynamics*. MIT Press, Cambridge, MA.
- Frolov, V., Ma, L., Sun, Y., & Bandara, W. (2010). Identifying core functions of asset management. In *Definitions, concepts and scope of engineering asset management* (pp. 19-30). Springer.
- García-Gómez, F., Rosales-Prieto, V. F., Sánchez-Lite, A., Fuentes-Bargues, J. L., & González-Gaya, C. (2021). An Approach to Sustainability Risk Assessment in Industrial Assets. *Sustainability*, 13(12), 6538.
- Gavrikova, E., Volkova, I., & Burda, Y. (2020). Strategic aspects of asset management: An overview of current research [Article]. *Sustainability (Switzerland)*, 12(15), <https://doi.org/10.3390/su12155955>
- George, G., & Bock, A. J. (2011). The business model in practice and its implications for entrepreneurship research. *Entrepreneurship Theory and Practice*, 35(1), 83-111.
- GFAM. (2014). *The asset management landscape*. In: *Global Forum Maintenance and Asset Management Zürich*.
- GFAM. (2021). *Asset Management Maturity - A Position Statement - Second Edition* Global Forum Maintenance and Asset Management Zürich.
- Godau, R. I., 2004, "Infrastructure Systems Engineering," *INCOSE Insight*, 7(1), 7-11.
- Godau, R. (2008). Why asset management should be a corporate function. *Journal of Public Works & Infrastructure*, 1(2), 171-184.
- Gómez, J. F., Fernández, P. M.-G., Guillén, A. J., & Márquez, A. C. (2019). Risk-based criticality for network utilities asset management. *IEEE Transactions on Network and Service Management*, 16(2), 755-768.
- Green, S. D. (1999). The missing arguments of lean construction. *Construction Management & Economics*, 17(2), 133-137.
- Grösser, S. N., Reyes-Lecuona, A., & Granholm, G. (2017). *Dynamics of long-life assets: from technology adaptation to upgrading the business model*. Springer Nature.
- Gunderson, L. H. (2000). Ecological resilience—in theory and application. *Annual review of ecology and systematics*, 31(1), 425-439.
- Haddadi, A., Temeljotov-Salaj, A., Foss, M., & Klakegg, O. J. (2016). The Concept of Value for Owners and Users of Buildings – A Literature Study of Value in Different Contexts [Article]. *Procedia - Social and Behavioral Sciences*, 226, 381-389.
- Haines, S. (2000). *The systems thinking approach to strategic planning and management*. CRC Press.
- Hanski, J., & Ojanen, V. (2020). Sustainability in strategic asset management frameworks: a systematic literature review. *International Journal of Strategic Engineering Asset Management*, 3(4), 263-294.
- Hartmann, M., Oriani, R., & Bateman, H. (2013). Exploring the antecedents to business model innovation: An empirical analysis of pension funds. *The Vienna Conference on Strategy, Organizational Design, and Innovation*, Vienna.
- Hémond, Y., & Robert, B. (2012). Preparedness: the state of the art and future prospects. *Disaster Prevention and Management: An International Journal*.
- Helfat, C. E., & Peteraf, M. A. (2015). Managerial cognitive capabilities and the microfoundations of dynamic capabilities. *Strategic management journal*, 36(6), 831-850.
- Helfat, C. E., & Winter, S. G. (2011). Untangling dynamic and operational capabilities: Strategy for the (N) ever-changing world. *Strategic management journal*, 32(11), 1243-1250.
- Hjelmbrekke, H., & Klakegg, O. J. (2013). The new common ground: Understanding value. *7th Nordic Conference on Construction Economics and Organization*,
- Hodkiewicz, M. (2015). Designing snakes and ladders: An analogy for asset management strategy development. *Simulation & Gaming*, 46(5), 455-470.

- Hodkiewicz, M. (2015a). Asset management-quo vadis (where are you going)? *International Journal of Strategic Engineering Asset Management*, 2(4), 313-327.
- IEC (2016). IEC 62775: Application guidelines - Technical and financial processes for implementing asset management systems, (International Electrotechnical Commission
- Ihemegbulem, I., Baglee, D., Wheatley, A., & Marttonen-Arola, S. (2017). The role of ISO 55000 Standard in asset integrity. *Proceedings of the 30th International Congress & Exhibition on Condition Monitoring and Diagnostic Engineering Management Comadem*, Preston, UK,
- Infrastructure New Zealand (2021). *Infrastructure as Strategy: Delivering Outcomes in a post-RMA Environment* [Electronic document], <https://www.infrastructure.org.nz/resources/Documents/Reports/Infrastructure Strategy Report.pdf>
- ISO (2011). ISO 42010:2011: Systems and software engineering — Architecture description, International Standards Organization
- ISO (2014a). ISO 55001:2014: Asset management—Overview, principles and terminology International Standards Organization, International Standards Organization
- ISO (2014b). ISO 55001:2014: Asset management – Management systems – Requirements, International Standards Organization.
- ISO (2015). ISO/IEC 15288: 2002, Systems Engineering-System Life-Cycle Processes, International Standards Organization.
- ISO (2018). ISO 55002:2018: Asset management — Management systems — Guidelines for the application of ISO 55001, International Standards Organization
- ISO (2019). ISO 55010:2019: Asset management — Guidance on the alignment of financial and non-financial functions in asset management, International Standards Organization
- Jackson, M. C. (2009). Fifty years of systems thinking for management. *Journal of the Operational Research Society*, 60(1), S24-S32.
- Joshi, S., Bayer, C., Gamble, M., & Gentry, R. (2010). *AIA Guide to Building Life Cycle Assessment in Practice*. The American Institute of Architects, 14.
- Kaplan, S. (2011). Strategy and PowerPoint: An inquiry into the epistemic culture and machinery of strategy making. *Organisation Science*, 22, 320-346.
- Kast, F. E., & Rosenzweig, J. E. (1972). General systems theory: Applications for organisation and management. *Academy of Management journal*, 15(4), 447-465.
- Kelly, J. & Hardy, M. (2018). Asset management in High Performance organisations. [Electronic document] White paper published by the Asset Leadership Network www.assetleadership.net
- Konstantakos, P. C., Chountalas, P. T., & Magoutas, A. I. (2019). The contemporary landscape of asset management systems Article]. *Quality - Access to Success*, 20(169), 10-17.
- Lado, A. A., & Wilson, M. C. (1994). Human resource systems and sustained competitive advantage: A competency-based perspective [Article]. *Academy of Management Review*, 19(4), 699-727.
- Lima, E. S., & Costa, A. P. C. S. (2019). Improving Asset Management under a regulatory view. *Reliability Engineering & System Safety*, 190, 106523.
- Lawler, E. E., Mohrman, A. M., Mohrman, S. A., Ledford, G., & Cummings, T. G. (1999). *Doing research that is useful for theory and practice*. Lexington Books.
- Lima, E. S., & Costa, A. P. C. S. (2019). Improving Asset Management under a regulatory view. *Reliability Engineering & System Safety*, 190, 106523.
- Lloyd, C. (2019). Introduction. One name for many things. In *Asset Management: Adding value to asset dependent businesses* (pp. 1-7). ICE Publishing.
- Lloyd, C., Corcoran, M., & Pilling, M. (2019). Asset management maturity and the pursuit of value. In *Asset Management: Adding value to asset dependent businesses* (pp. 29-43). ICE Publishing.
- Lombardi, P., & Brandon, P. (2002). Sustainability in the built environment: a new holistic taxonomy of aspects for decision making. *International journal of environmental technology and management*, 2(1-3), 22-37.
- Loosemore, M. (1997). Construction crises as periods of social adjustment. *Journal of Management in Engineering*, 13(4), 30-37.
- Madill, A., Jordan, A. and Shirley, C. (2000) 'Objectivity and reliability in qualitative analysis: realist, contextualist and radical constructionist epistemologies', *British Journal of Psychology*, 91: 1–20.
- Madritsch, T., & Ebinger, M. (2011). A management framework for the built environment: BEM2/BEM3. *Built Environment Project and Asset Management*.
- Maletić, D., Maletić, M., Al-Najjar, B., & Gomišček, B. (2018). Development of a model linking physical asset management to sustainability performance: An empirical research. *Sustainability*, 10(12), 4759.
- Maletić, D., Maletić, M., Al-Najjar, B., & Gomišček, B. (2019). Examination of the mediating effects of physical asset management on the relationship between sustainability and operational performance. *International Scientific-Technical Conference MANUFACTURING*,

- Maletič, D., Pačaiová, H., Nagyová, A., & Maletič, M. (2020). The link between asset risk management and maintenance performance: A study of industrial manufacturing companies. *Quality Innovation Prosperity*, 24(3), 50-69.
- Marsden, G., & Dawson, D. (2017). Disruption & Resilience–New Realities? Transportation Research Board 96th Annual Meeting, Location: Washington DC, United States Date: 2017-1-8 to 2017-1-12
- Massa, L., Tucci, C. L., & Afuah, A. (2017). A critical assessment of business model research. *Academy of Management Annals*, 11(1), 73-104.
- McDonald, N. (2017). Organisational Resilience and Industrial Risk. In E. Hollnagel, D. Woods & N. Leveson (Eds.), *Resilience Engineering* (pp. 155–180). London, UK: CRC Press.
- McKeown, D., O’Hanlon, T., & Smith, T., (2017). Managing Assets in the context of Asset Management (1st Edition), ISO/TC251, International Standards Organization
- Milina, J., Kristiansen, P., Jacobsen, A., & Sundve, A. (2017). Moulding the asset management system to PAS 55-1/ISO 55001 in one Scandinavian water and wastewater works. *Water Practice and Technology*, 12(1), 234-239.
- Millet, I. (1998). Ethical decision making using the analytic hierarchy process. *Journal of business ethics*, 17(11), 1197-1204
- Mitchell, D., & Coles, C. (2003). The ultimate competitive advantage of continuing business model innovation. *Journal of Business strategy*, 24(5), 15-21. <https://doi.org/10.1108/02756660310504924>
- Mintzberg, H. (1994). Rethinking Strategic Planning Part I: Pitfalls and Fallacies [Article]. *Long range planning*, 27(3), 12-21
- Mo, J., & Beckett, R. (2018). *Engineering and Operations of System of Systems*. CRC Press.
- Morris, M., Schindehutte, M., and Allen, J. (2005). The entrepreneurs’ business model: Toward a unified perspective. *Journal of Business Research*, Vol. 58, pp. 726–735.
- Nelson, R. R., & Winter, S. G. (1982). The Schumpeterian tradeoff revisited. *The American Economic Review*, 72(1), 114-132.
- OAG (2017). Reflections from our audits: Investment and asset management. [Electronic document]. Controller and Auditor-General, <http://www.oag.govt.nz/2017/asset-reflections/docs/asset-reflections.pdf>
- Orlikowski, W. J., & Scott, S. V. (2008). Sociomateriality: Challenging the separation of technology, work and organisation. *The Academy of Management Annals*, 2(1), 433-474.
- Pavlou, P. A., & El Sawy, O. A. (2013). Searching for a simple model of dynamic capabilities. Available at SSRN 2369378.
- Hamel, G., & Prahalad, C. K. (1993). Strategy as stretch and leverage [Article]. *Harvard business review*, 71(2), 75-84.
- Penrose, E. G. *The Theory of the Growth of the Firm*, Wiley, New York, 1959.
- Petchrompo, S., & Parlikad, A. K. (2019). A review of asset management literature on multi-asset systems [Review article]. *Reliability Engineering and System Safety*, 181, 181-201. <https://doi.org/10.1016/j.res.2018.09.009>
- Richards, L., & Morse, J. M. (2012). *Readme first for a user's guide to qualitative methods*. Sage.
- Roda, I., Parlikad, A. K., Macchi, M., & Garetti, M. (2016). A framework for implementing value-based approach in asset management. In *Lecture Notes in Mechanical Engineering* (Vol. PartF4, pp. 487-495).
- Roof, K., & Oleru, N. (2008). Public health: Seattle and King County’s push for the built environment. *Journal of environmental health*, 71(1), 24-27.
- Rumelt, R.P (1984) - *Competitive strategic management*, 1984 - Prentice-Hall, Englewood Cliffs, NJ
- Schön, D. A. (2017). *The reflective practitioner: How professionals think in action*. Routledge.
- Shah, R., McMann, O., & Borthwick, F. (2017). Challenges and prospects of applying asset management principles to highway maintenance: A case study of the UK. *Transportation Research Part A: Policy and Practice*, 97, 231-243.
- Simon, H. A. (2002). Forecasting the future or shaping it? *Industrial and Corporate Change*, 11(3), 601–605.
- Sosna, M., Treviño-Rodríguez, R. N., & Velamuri, S. R. (2010). Business model innovation through trial-and-error learning: The Naturhouse case. *Long Range Planning*, 43(2-3), 383-407.
- Srinivasan, R., & Parlikad, A. K. (2020). An approach to value-based infrastructure asset management. In *Value Based and Intelligent Asset Management* (pp. 123-138). Springer.
- Stephenson, A. V. (2010). Benchmarking the resilience of organisations.
- Teece, D. J. (2010). Business models, business strategy and innovation. *Long range planning*, 43(2-3), 172-194.
- Teece, D. J., Pisano, G., & Shuen, A. (1997). Dynamic capabilities and strategic management. *Strategic management journal*, 18(7), 509-533.
- Teece, D. J. (2007). Explicating dynamic capabilities: the nature and microfoundations of (sustainable) enterprise performance. *Strategic management journal*, 28(13), 1319-1350.
- Teece, D. J. (2014). The foundations of enterprise performance: Dynamic and ordinary capabilities in an (economic) theory of firms. *Academy of management perspectives*, 28(4), 328-352.

- Teece, D. J. (2017). Towards a capability theory of (innovating) firms: implications for management and policy. *Cambridge Journal of Economics*, 41(3), 693-720.
- Teece, D. J. (2018). Dynamic capabilities as (workable) management systems theory. *Journal of Management & Organization*, 24(3), 359-368.
- Temple, M. (2004). *Studying the built environment*. Macmillan International Higher Education.
- Then, D. S.-S., & Hee, T. T. (2013). *Facilities management and the business of managing assets* [Bibliographies Online Non-fiction Electronic document]. Routledge. <https://www.taylorfrancis.com/books/9780203497098>
- Tholana, T., & Neingo, P. (2016). Extending the application of PAS 55/ISO 55 000 to mineral asset management. *Journal of the Southern African Institute of Mining and Metallurgy*, 116(11), 1043-1050.
- Tranfield, D., Denyer, D., & Burr, M. (2004). A framework for the strategic management of long-term assets (SMoLTA). *Management decision*.
- Treasury (2007). <https://www.treasury.govt.nz/information-and-services/state-sector-leadership/investment-management/review-investment-reviews/investor-confidence-rating-icr/investor-confidence-rating-asset-management-maturity>
- Tripsas, M., & Gavetti, G. (2000). Capabilities, cognition, and inertia: Evidence from digital imaging. *Strategic Management Journal*, 21(10-11), 1147-1161.
- Valencia, V. V., Colombi, J. M., Thal Jr, A. E., & Sitzabee, W. E. (2011). Asset management: a systems perspective. IIE Annual Conference. Proceedings,
- Vogus, T. J., Rothman, N. B., Sutcliffe, K. M., & Weick, K. E. (2014). The affective foundations of high reliability organising. *Journal of Organizational Behavior*, 35(4), 592-596.
- Vonk, B., Klerk, W. J., Fröhle, P., Gersonius, B., Den Heijer, F., Jordan, P., Radu Ciocan, U., Rijke, J., Sayers, P., & Ashley, R. (2020). Adaptive asset management for flood protection: The FAIR framework in action. *Infrastructures*, 5(12), 109.
- Walker, B., Holling, C. S., Carpenter, S. R., & Kinzig, A. (2004). Resilience, adaptability and transformability in social-ecological systems. *Ecology and society*, 9(2).
- Weick, K. E., & Sutcliffe, K. M. (2001). *Managing the unexpected* (Vol. 9). San Francisco: Jossey-Bass.
- Wernerfelt, B. (1984). A resource-based view of the firm. *Strategic Management Journal*, 5(2), 171-180.
- White, E. (1975). Terotechnology (physical asset management). *Mining Technology*, 57(5), 293-297.
- Wijnia, Y. (2016). Towards quantification of asset management optimality. *Proceedings of the 10th World Congress on Engineering Asset Management (WCEAM 2015)*,
- Winter, S. G. (2003). Understanding dynamic capabilities. *Strategic management journal*, 24(10), 991-995.
- Wirtz, B.W., Göttel, V., and Daiser, P. (2016a). Business model innovation: Development, concept and future research directions. *Journal of Business Models*, Vol. 4, No. 2, pp. 1-28.
- Wirtz, B.W., Pistoia, A., Ullrich, S., and Göttel, V. (2016b). Business models: Origin, development and future research perspectives. *Long Range Planning*, Vol. 49, No. 1, pp. 36-54.
- Woetzel, J., Garemo, N., Mischke, J., Hjerpe, M., Palter, R. (2016). *Bridging Global Infrastructure Gaps*: McKinsey Global Institute.
- Woods, D. D. (2015). Four concepts for resilience and the implications for the future of resilience engineering. *Reliability Engineering & System Safety*, 141, 5-9.
- Woods, D. D., & Hollnagel, E. (2017). Prologue: Resilience engineering concepts. In *Resilience engineering* (pp. 1-6). CRC Press.
- Wright, P. M., McMahan, G. C., & McWilliams, A. (1994). Human resources and sustained competitive advantage: a resource-based perspective [Article]. *International Journal of Human Resource Management*, 5(2), 301-326.
- Yates, K., Lima, J. B., Sapountzis, S., Tzortzopoulos, P., & Kagioglou, M. (2009). BeReal benefits realisation model integrated approach: The built environment lifecycle and organisational views. 2nd HaCIRIC Symposium,
- Yin, R. K. (2016). *Qualitative research from start to finish* (Second edition ed.)
- Zott, C., Amit, R., & Massa, L. (2011). The business model: recent developments and future research. *Journal of Management*, 37(4), 1019-1042.
- Zott, C., & Amit, R. (2015). Business model innovation: Toward a process perspective. *The Oxford handbook of creativity, innovation, and entrepreneurship*, 395.

In the Middle of the Pandemic: Experiences for Built Environment Education

Ayobami Popoola^{1*}, Ockert Pretorius², Nunyi Blamah³, Lovemore Chipungu¹. And Hangwelani Magidimisha-Chipungu¹

¹SARChI Chair for Inclusive Cities, University of KwaZulu-Natal, South Africa.

²Department of Urban and Regional Planning, University of Johannesburg, South Africa.

*Corresponding author: PopoolaA@ukzn.ac.za

Abstract

The global pandemic through COVID-19 continues to leave a footprint in all areas of human endeavour. Livelihood experiences continues to be changed and characterised by shocks and vulnerabilities. One of such shock is the way academia responds to the education and training needs of built-environment students in tertiary institutions. Built-environment education, as a 'hands-on-deck' learning experience has been subjected to changes away from the physical studio contact, field trip and site-oriented experiences, to a 'less robust' but more 'home-based and arm-chair' defined teaching and learning approach.

Despite the outbreak of COVID-19, there remains a gap in literature argument and evidence on the relationship between built-environment education and the pandemic effect.

The study investigates the effect of the pandemic on education in the built-environment, with objectives that include determining the impact of the pandemic on teaching and learning and the nature of adaptation in response to the pandemic and its related disruption.

This study adopted a qualitative method through applying a thematic analysis of academic journal articles that spoke to issues related to two predetermined domains: 'COVID 19 shocks on education' and 'educational adaptation in the face of COVID 19'. The study, with the aid of NVivo 10, engaged in a close thematic coding of the articles to identify emerging themes under the two domains. The study findings point at the pedagogical change and transitioning to an online teaching environment during the pandemic. This study provides insights into the adaptation of built-environment education with reference to teaching and learning in response to the pandemic and its effect.

Keywords

Built-Environment, Education, 'Hand-on-deck' learning, Pandemic, Teaching and Learning.

Introduction

Since the outbreak of the coronavirus, the effect of the pandemic has been felt across all sectors of the economy. McKibbin & Fernando (2020) documented the morbidity, economic activities and mobility restrictions, and the disruption of demand and supply chains that are associated with the pandemic. The authors reported on the economies of scale that are associated with mobility, and the interaction between one country and another. The argument iterates the non-isolated state and flaws the preposition that developed countries are completely sustainable and independent without economic interaction between nations (developed and developing). Asserting that demand and supply (between producing and consuming regions) is negatively impacted by the pandemic, Siche (2020) reported the food security dependence that is

associated with cross-country interaction. In education sector, the hashtag #Reopenschools, educator impact, teaching approach transition, and loss of learning time are a few of the dimensions of the impact of the pandemic on teaching and learning. Emphasising the pandemic effect in education, UNICEF (2020) raised that 1 in every 3 children lack access to learning owing to lack of access to remote learning during the pandemic. It was reported that the educational crisis due to the pandemic has resulted into about 77 million children being out of school due to the lockdown restrictions.

With reference to the United Nations Educational, Scientific and Cultural Organisation report, the Global Campaign for Education (GCE) (18 March 2020) mentioned that about 800 million learners from around the world were affected, 1 in 5 learners could not attend school, 1 in 4 could not attend higher education classes, and over 102 countries had ordered nationwide school closures while 11 implemented localised school closure. Schleicher (2020) has spoken (via a query) on the instructional tool, procedure and process, education sector financing, instructors and educators' pandemic teaching preparedness, capacity, and adaptation, and issues around class size in the face of social distancing and digital learning. In this study, the teaching and learning preparedness, teaching adaptation to pandemic and e-learning are argued along the pedagogical teaching thinking within the built-environment cluster of disciplines. Luckan (2016), with focus on built environment (Architecture) has questioned the curriculum, approach, and process of teaching along the socio-economic redress and spatial transformation line. Components of this teaching approach remains unsustainable in the face of the change in global learning, with reference to online approaches, due to the pandemic resulting in physical restrictions. However, the peculiarity of the shocks (from pandemic) continues to question the sustainability of the teaching process, procedure, and approach beyond architecture. Beyond a single discipline, the question on the future of built-environment teaching and learning is subjected to numerous arguments.

In India, Dubey & Pandey (2020) raised the limitations to higher education along limited awareness and access and lack of adequate digital technology, eroded psychosocial learning setting, and preparedness of the online teaching. While this position remains almost global (Arora & Srinivasan, 2020; Murphy, 2020; Aristovnik et al., 2020), the gap is the 'technological-integration' of hands-on built environment demands such as field trips, designing, scenario modelling and community engagement in planning and plans preparedness into the 'cloud-room or e-room' setting. The limitation of adaptation of some learning symbols and system management has been raised by Irfan et al. (2020). This provokes the limitations of the learning setting and that e-learning and teaching does not always support built environment education.

Studies continue to report on the need for a sustainability oriented approach that mitigates against or enhances adaptation in the face of the pandemic, with limited current focus on sustainable learning, teaching and education pre- and post-pandemics. Forsyth (2020) raises the gap in planning research and practice with regards to its role in managing the pandemic. The author states that "for the past decades, those looking at the intersections of planning, design, and public health have focused less on infectious diseases and more on chronic disease, hazards and disasters, and the vulnerable. The current pandemic brings the question of designing for infectious diseases back to the forefront and raises important questions for future research and practice". The argument that emerges in the role that planning as well as built-environment education play in space design knowledge and practice. The preposition is the need for not just basic training and capacity development for the built environment professionals (graduate or in-training) (Popoola & Magidimisha, 2020), but rather education

that is conscious of potential future pandemics or shocks. Essential to this study is the experience and practice of the researchers as both academia and professionals in the built-environment cluster. Thus, some of the narratives may speak or reflect the ideology of experiences of the researchers towards a critical thinking for the generation of ideas or provoking of arguments (Beaufort, 2008; Irish, 2016).

While the effect of the pandemic on both learners and higher learning have been commonly conceptualized, the peculiarities of the impact of the pandemic externalities on built-environment education remains undocumented. This gap remains essential to effective and responsive adaptive mechanisms for sustainable education in built-environment disciplines. The justification of this study as in Schleicher (2020), is based on a reflective study on the educational approach during the pandemic towards a futuristic sustainable and resilient education and society. Therefore, this study incorporates a thematic analysis of related literature to understand built-environment education during the pandemic. In this analysis, key themes are identified to determine the impact of the pandemic on teaching and learning and the nature of subsequent adaptation in response to the related disruption.

Research Methodology

The research adopted a qualitative method. The question the study asked was related to the effect of the pandemic on education and adaptation to the pandemic in built-environment learning and training. The data was sourced from academic journal articles that spoke to issues related to two predetermined domains: ‘COVID-19 shocks on education’ and ‘educational adaptation in the face of COVID-19’. These phrases were used to search for relevant articles using the Google engine. Before downloading the articles, their abstracts were read to establish relevance to the domains. A total of 36 articles were downloaded, which were further reduced to 24 after going through the main bodies of the articles to determine their relevance to the objectives of this paper. However, 18 other relevant articles came up in the course of the analysis, thereby increasing the number to 42 articles. The study, with the aid of NVivo 10, engaged in a close thematic coding of the articles to identify emerging themes under the two domains. A review of literature was therefore carried out based on the identified themes from the articles.

According to Blamah *et al.* (2021), thematic analysis through NVivo allows for interpretive social construct of experiences. The social construct as Popoola (2021) renders it provided for an indepth understanding of the cause and effect of a study phenomenon. Thus, in the face of challenges in primary data collection owing to COVID-19 restrictions, existing literature provides a realist alternative to understanding COVID-19 realities on built-environment teaching and learning.

Findings and Discussion

This section provides an overview of the findings inherent to the thematic analysis using NVivo. In line with the discussion in the research methodology, this section is comprised of two parts, namely the COVID-19 shocks on education and the educational adaptation in the face of COVID-19. These represent the two bodies of knowledge utilised in the analysis. A total of nine themes were realised under the former and ten under the latter.

COVID-19 shocks on education

Literature have acknowledged that the campus shut down of the many universities globally is a major disruption of the learning process which called for a shift to online learning (Karadag et al., 2021; Ali & Kaur, 2020; Ali, 2020; Louis-Jean & Cenat, 2020; Flores et al., 2021). This came as an emergency and many institutions were not well equipped with requisite infrastructure and resources (including technological and human resources) for online teaching (Almutawa et al., 2021; Nuru et al., 2021; Vicente et al., 2020; Louis-Jean & Cenat, 2020; Huang et al., 2020). As a result, institutions (comprising academic and non-academic staff and students) were faced with a lot of uncertainties of the future due to the sudden shift to online learning (Alonso-García et al., 2021; Jia et al., 2021; Nuru et al., 2021; Kodancha et al., 2020). In Brazil, this uncertainty, led to the asking of questions such as: “Can we handle this pandemic and its consequences? What are we learning from this pandemic to improve our educational system and public health? Can we handle future outbreaks in a globalized world?” (Carvalho et al., 2020, p.1170). The uncertainty thus led to unclear plans for universities and individual students (Kodancha et al., 2020), whereby students resorted to self-regulated learning (Biwer et al., 2021; Harsel, 2021). It also made content of face-to-face teaching to be taught online - whereby using emergency remote teaching instead of conventional online teaching (Alonso-García et al., 2021). A condition associated with inequality was experienced among the disadvantaged students. Flores et al. (2021) likewise reported on the inapplicability of teaching pedagogy to fit holistically in an online format. This was reported to have led to higher workloads (Alonso-García, et al, 2021; Flores et al., 2021), education resources inaccessibility, (Nuru et al., 2021), and loss of practical operational experience (Gabara et al., 2020; Guraya, 2020) among students owing to the new online teaching alternative (Figure 1).

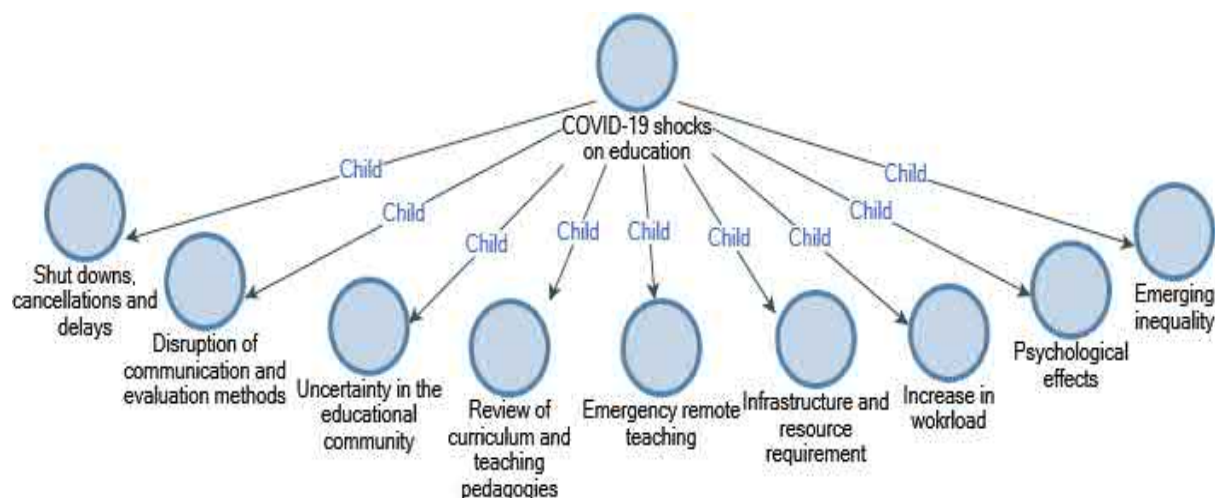


Figure 1: Emerging themes from the literature that describe COVID-19 shocks on education.

In Qatar, cross-border knowledge exchange was restricted due to the suspension of travel into the country which limited foreign experts and educators access to the country (Almutawa et al., 2021). Kodancha et al. (2020) have observed that, even school programs that had earlier adopted the online platform became slower than when it was face-to-face. In Ireland, Hill and Fitzgerald (2020) found that online learning could reduce students’ engagement. School closures were therefore accompanied by cancellations and delays (Alonso-García et al., 2021). This was considered worse in low and middle-income countries where access to internet services was below 50 percent and worse for first-year university students (Perez et al., 2021) who have little or no knowledge about online teaching and evaluation, especially those from public schools (Karadag et al., 2021).

Thematic evidence shows that school closure had a significant impact on education and evaluation due the communication gaps it caused in the university system. Alonso-García et al.

(2021) found that communication is worse during online education than face-to-face education. Weller (2020) opines that a relevance of face-to-face educational system is its immense organisation of students through timetables, venues on a physical campus location, and hands-on resources, which was interrupted due to moving online. According to Argenti (2020) and Gershman (2020), field work and other hands-on academic activities had been hampered with the shift to online teaching during the peak of the pandemic. They added that virtual teaching impairs attention and adds to mental stress. These factors, together with the urgent nature of online learning, could lead to major issues such as academic disruptions, time and financial loss and anxiety and frustration (Flores et al., 2021; Baloran, 2020; Wang et al., 2020). In respect to student evaluation, studies (Flores et al., 2021; Gonzalez et al., 2020; Guangul et al., 2020) identified possible examination malpractice to be most frequent during online evaluation due to reduced capacity to regulate students' actions. This according to Alonso-García, et al. (2021) is tantamount to unfair evaluation and dissatisfaction with the system (see Figure 1).

Educational adaptation in the face of COVID-19

Figure 2 shows the emerging themes from the literature that describe educational adaptation in the face of COVID-19. The major educational adaptation strategy applied in the face of the COVID-19 pandemic was engaging in online blended learning (Ali and Kaur, 2020; Ali, 2020). This included online flipped classroom, an active method used in face-to-face classes to make students more participatory (Fidalgo-Blanco et al., 2020). Studies (Jia et al., 2021; Chen et al., 2020) show that the online flipped classroom platform is as effective as the conventional flipped classroom in terms of impact. In the online transformation, pre-recorded video lecture are sent online to students followed up by an in-class or online lectures and group discussions (Guraya, 2020). Studies show that, with increased teacher-student interaction (synchronous or asynchronous), and extensive follow-up, the online platform can yield positive result (Chen et al., 2020; Flores et al., 2021).

This positive feedback can be achieved through effective long term planning and continuous improvement (Tamrat & Teferra, 2020). The suggested improvement was the need for incremental innovation - to learn on the go (Almutawa et al., 2021). This suggests the need for governments and school administrators to promote/invest in the development of online education infrastructure, and equip teachers and students with state-of-the-art ICT equipment and technical abilities in order to provide a seamless, acceptable and integrated online flipped classrooms (Williamson et al. 2020; Korkmaz and Toraman, 2020; Louis-Jean & Cenat, 2020; Chavarria-Bolaños, 2020). Louis-Jean & Cenat (2020) reported on software that made for easier and advanced online learning, including Zoom and WebEx for video conferencing, Canvas, ALEKS, Blackboard and Google classroom for learning management systems and Proctorio for online examination monitoring. The functionality of these depends on enhanced network capacity and internet speed (Korkmaz and Toraman, 2020, 2021).

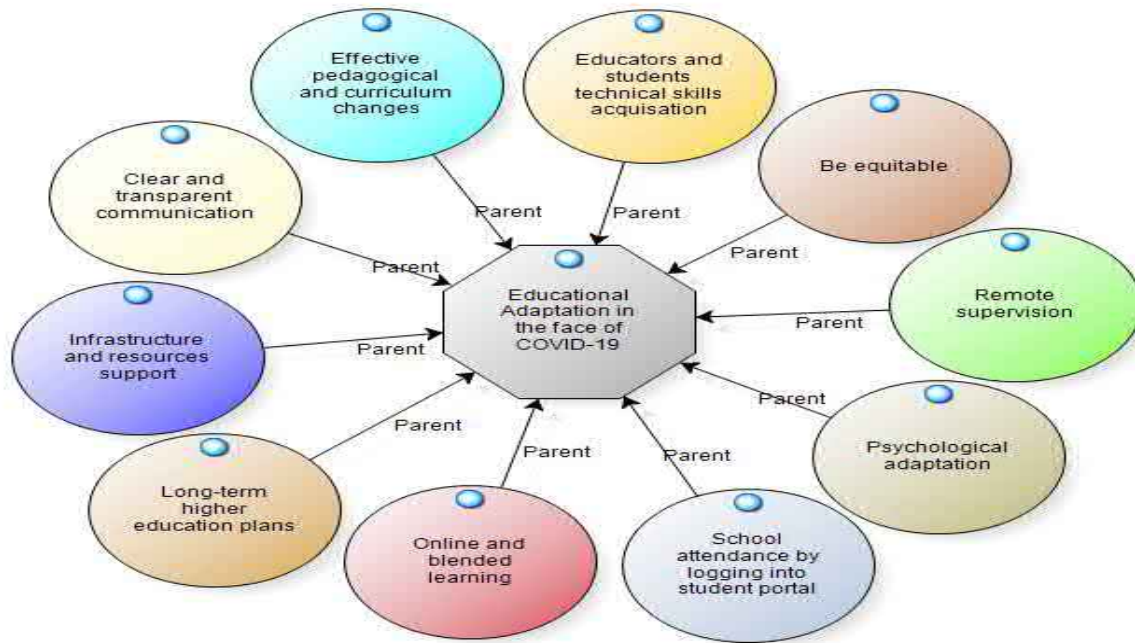


Figure 2: Theme map of educational adaptation in the face of COVID-19.

Owing to the impact of the transition to online learning on students' emotions and psychological well-being, there are suggestions that institutions, teachers and parents need to invest into students' socio-emotional competencies for better online learning conditions (Hadar et al., 2020). Research has it that an evaluation of the needs and situations faced by students (Chavarría-Bolaños, 2020) and their level of preparedness for online learning (Ali, 2020) need to be determined for appropriate support and motivation.

Adopting to online class is beyond handling just technical and psychological issues but also pedagogical issues. Adequate preparation in respect of teaching method and curriculum modification is vital to the adoption of an effective online class (Ali, 2020). Chavarría-Bolaños (2020) added that it is essential to have courses classified into different categories based on virtualisation possibility, then carry out curricula analysis to determine the level of impact and what is required to mitigate the negative effects of the changes on students learning process. Korkmaz & Toraman (2020, 2021) also opined that it is important not to overwhelm learners with too many courses and content, and that the curriculum should be meaningful - emphasising more on teaching real-life issues. Developing online pedagogy will minimize disruption of learning when shocks that restrict physical gathering occur in the future (Louis-Jean & Cenat, 2020). Carrillo & Flores (2020) suggested a total review of pedagogy for online education such that it uses technology to integrate teaching, learning, mentoring and monitoring.

The relevance of having effective student evaluation in online learning can also not be overemphasised. Rahim (2020) calls for a balance between different assessment methods, say, summative and formative assessment, in remote teaching, as there is feedback on students achievements by teachers based on learning objectives. When carrying out evaluation exercises for online education, emphasis should not be on control but on assistance and feedback to the student to consolidate knowledge (Perez et al., 2021). Thus, it was forwarded that an authentic assessment strategy "...must first be realistic, performance- based, and cognitively complex; Second, students must defend answers, products, and learn to work collaboratively. Third, the assessment must be formative. Finally, students should be informed about the grading criteria, which includes several indicators for assessment..." (Sutadji et al., 2021, p.1). He

acknowledged that authentic assessment enables assessment of students' higher-order thinking about the real world situations and not memory ability of what was learnt in class like is with the traditional assessments method.

Conclusion

A critical part of the built environment is the robustness, interwoven, multi-sectoral and multi-disciplinary tendencies of its education. The subjectivity of the built-environment ideologies owing to the roles of dynamic spaces in education and training calls for continued place-, school- and student-based responses to various spatial issues and literacy. While this is true, the global pandemic through COVID-19 continues to leave a footprint in all areas of human endeavour. Livelihood experiences continues to be changed and variants of shocks and vulnerabilities have emerged. One of such shocks is the way academia responds to the education and training needs of built-environment students in tertiary institutions.

The dimension of the effect of the pandemic on built-environment education ranges from classroom effect (studio and site work) and its limitations to practice. Built-environment education, as a 'hands-on-deck' learning experience has been subjected to changes away from the physical studio contact, field trip and site-oriented experiences, to a 'less robust' but more 'home-based and arm-chair' defined teaching and learning approach. Due to the pandemic effect, Milovanović *et al.* (2020, p.1) calls for a shift in architectural education through the development of new approaches in teaching methodology, improving curricula, and making advancements in new learning arenas and digital environments. The authors posited the shock from the pandemic on learning setting from real-life experience as embedded in site visits to virtual learning. It was mentioned that COVID-19 pandemic directly affected the transformation of the learning environment in architecture, resulting in distance learning through various online applications and platforms as a part of imposed epidemiological measures (Milovanović *et al.*, 2020, p.9). This development is envisaged to have a limitation and impact on learning perspectives and profiles of built-environment graduates and future practitioners.

Drawing from experiences of studio-oriented discipline such as planning, architecture, housing, civil engineering, and quantity surveying in Egypt, Elrawy & Abouelmagd (2021) reported on the psychological effect of architectural work and education isolation due to the pandemic on students. It was reported that pandemic raises the question of the urban management education sustainability. The argument was along the shocks on studio works due to the pandemic. The pandemic was reported to have limited collective learning and development that the studio and site training and learning offers to both the students and educators. Studies (Seniz, 2009; Kurt, 2009; Dizdar, 2015; Yıldırım, Yavuz & Kirci, 2012) alluded that hands-on and studio related disciplines are traditionally developed and designed along the physical setting engagement that supports interaction, student-teacher discussions and (towards on-the-spot feedbacks), physical engagements (which is often a room for free thoughts and ideas birth, development and branding). Traditional urban discipline education also allows for group tasking, on-the-spot assessment and evaluation of physical designs, and community and spatial evaluation of learners' class knowledge through site experiences, designs, built-environment life-skills applications, and scenario constructions. Many of these have been restricted, distorted and limited due to the enforced physical school closures, restricted studio activities and site visits during the pandemic. The ideology of physical interaction is embedded in the ideas that the discipline calls for, including designing (as an

iterative decision-making process for plan making) and the production of outputs in plans to improve human life or solve planning and societal problems.

Shah (2020) posited that the design studio has always been a space that allowed for experimentation and exploration to facilitate learning that goes well beyond a lesson plan. The view was the intimacy with space (whether in class or on site) remains a key part of design disciplines (many of which are within the built environment). Field studies and site visits are an integral methodology of design and built space academia, which leads itself to a more holistic understanding of design and spatial problems (Shah, 2020). This, the author argued, has been distorted owing to off-campus ‘forced’ learning due to the pandemic. Allam, Siew & Fokoua (12 May 2021) mentioned that disruption in course content and training in architecture and built-environment education and training. The authors forwarded that there is a need for syllabus and curriculum adaptation of studio and modern teaching dimensions. This, Maturana, Salama & McInnery (2021, p.1) buttressed, that the diversity alternative in urbanity and society and the associated education and practice of future built environment professions needs to be revisited.

To this end, the authors suggest further study to examine the effect of COVID-19 on built environment research. This can be achieved through bibliographic analysis. Likewise, there is a need to further examine the built-environment education impact from COVID-19 using primarily generated data. Such study will further promote the understanding of the nexus between COVID-19 impact on learning and training viz-a-viz built-environment practice.

Acknowledgement

Some of the authors would like to acknowledge the funding and support received from the National Research Foundation (NRF) of South Africa and the South African Research Chair of Inclusive Cities (SARChI), within School of Built Environment and Development Studies, University of KwaZulu-Natal, South Africa.

References

- Allam Z., Siew, G., and Fokoua, F. 12 May 2021. How COVID-19 Will Shape Architectural Education. ArchDaily. Available from: <https://www.archdaily.com/939423/how-covid-19-will-shape-architectural-education> ISSN 0719-8884
- Ali, W. (2020). Online and remote learning in higher education institutes: A necessity in light of COVID-19 pandemic. *Higher education studies*, 10(3), 16-25.
- Ali, W., & Kaur, M. (2020). Mediating educational challenges amidst COVID-19 pandemic. *Asia Pacific Institute of Advanced Research (APJCECT)*, 6(2), 40-57.
- Almutawa, N., Mahmoud, M., Rao, C., & Main, M. (2021). Continuing Professional Development: Provision and Adaptation of Clinical Education within the Primary Health Care Setting in Qatar during the COVID-19 Pandemic. *Principles and Practice of Clinical Research*, 7(1), 40-45.
- Alonso-García, M., Garrido-Letrán, T. M., & Sánchez-Alzola, A. (2021). Impact of COVID-19 on Educational Sustainability. Initial Perceptions of the University Community of the University of Cádiz. *Sustainability*, 13(11), 5938.
- Argenti, P. (2020). Communicating Through the Coronavirus Crisis. Harvard Business Review. Available from: <https://hbr.org/2020/03/communicating-through-the-coronavirus-crisis>
- Aristovnik, A., Keržič, D., Ravšelj, D., Tomaževič, N. and Umek, L. (2020). Impacts of the COVID-19 pandemic on life of higher education students: A global perspective. *Sustainability*, 12(20), p.8438.
- Arora, A.K. and Srinivasan, R. (2020). Impact of pandemic COVID-19 on the teaching–learning process: A study of higher education teachers. *Prabandhan: Indian journal of management*, 13(4), pp.43-56.
- Baloran, E. (2020). Knowledge, attitudes, anxiety, and coping strategies of students during COVID-19 pandemic. *Journal of Loss and Trauma*, 25(8), 635–642. <https://doi.org/10.1080/15325024.2020.1769300>

- Beaufort, A., 2008. *College writing and beyond: A new framework for university writing instruction*. University Press of Colorado.
- Biwer, F., Wiradhany, W., Oude Egbrink, M., Hospers, H., Wasenitz, S., Jansen, W., & de Bruin, A. (2021). Changes and Adaptations: How University Students Self-Regulate Their Online Learning During the COVID-19 Pandemic. *Frontiers in psychology*, 12, 642593. [10.3389/fpsyg.2021.642593](https://doi.org/10.3389/fpsyg.2021.642593)
- Blamah, N.V., Magidimisha-Chipungu, H., Dayomi, M. and Popoola, A.A. (2021). Intrinsic mode choice determinants based on a descriptive analysis of the perceptions of Abuja commuters: towards refocusing the societal mind-set on environmentally sustainable modes choice. *Smart and Sustainable Built Environment*, Vol. ahead-of-print No. ahead-of-print. <https://doi.org/10.1108/SASBE-03-2021-0041>
- Carrillo, C., & Flores, M. (2020). COVID-19 and teacher education: a literature review of online teaching and learning practices. *European Journal of Teacher Education*, 43(4), 466–487. <https://doi.org/10.1080/02619768.2020.1821184>
- Carvalho, V., Conceição, L. & Gois Jr. M. (2020). COVID-19 pandemic: Beyond medical education in Brazil, *J Card Surg*, 35, 1170–1171. DOI: 10.1111/jocs.14646
- Chavarria-Bolaños, D., Gómez-Fernández, A., Dittel-Jiménez, C., & Montero-Aguilar, M. (2020). E-Learning in Dental Schools in the Times of COVID-19: A Review and Analysis of an Educational Resource in Times of the COVID-19 Pandemic. *Odovtos International Journal of Dental Sciences*, 22(3), 69-86.
- Chen, E., Kaczmarek, K., & Ohshima, H. (2020). Student perceptions of distance learning strategies during Covid-19. *Journal of Dental Education*. Advance online publication. <https://doi.org/10.1002/jdd.12339>
- Dizdar, S. (2015). Architectural education, project design course and education process using examples. *Procedia-Social and Behavioral Sciences*, 176, pp.276-283.
- Dubey, P. & Pandey, D. (2020). Distance learning in higher education during pandemic: challenges and opportunities. *Int. J. Ind. Psychol*, 8(2), pp.43-46.
- Elrawy, S. & Abouelmagd, D. (2021). Architectural and Urban Education in Egypt in the Post COVID-19 Pandemic. *European Journal of Sustainable Development*, 10(2), pp. 91-112. <https://doi.org/10.14207/ejsd.2021.v10n2p91>
- Fidalgo-Blanco, Á., Sein-Echaluce, M. L., & García-Peñalvo, F. J. (2020, October). Hybrid Flipped Classroom: adaptation to the COVID situation. In *Eighth International Conference on Technological Ecosystems for Enhancing Multiculturality* (pp. 405-409).
- Flores, M., Brown, G., Pereira, D., Coutinho, C., Santos, P., & Pinheiro, C. (2020). Portuguese university students' conceptions of assessment: taking responsibility for achievement. *Higher Education*, 79, 377–394. <https://doi.org/10.1007/s10734-019-00415-2>
- Forsyth, A. March 19, 2020. What role do planning and design play in a pandemic? Ann Forsyth reflects on COVID-19's impact on the future of urban life. Available from: <https://www.gsd.harvard.edu/2020/03/what-role-do-planning-and-design-play-in-a-pandemic-ann-forsyth-reflects-on-covid-19s-impact-on-the-future-of-urban-life/>
- Gabara, A., Visram, K. & Leveridge, M. (2020). Early adaptation of urology residency educational programs during COVID-19 clinical and gathering restrictions, *Can Urol Assoc J* 2020;14(8):235-236. <http://dx.doi.org/10.5489/cuaj.6746>
- Gershman, S. (2020). Stop Zoning Out in Zoom Meetings. *Harvard Business Review*. <https://hbr.org/2020/05/stop-zoning-out-in-zoom-meetings>
- Gonzalez, T., de la Rubia, M. A., Hincz, K. P., Comas-Lopez, M., Subirats, L., & Fort, S. (2020). Influence of COVID-19 confinement on students' performance in higher education. *PLoS One*, 15(10), e0239490. <https://doi.org/10.1371/journal.pone.0239490>
- Guraya S. (2020). Combating the COVID-19 outbreak with a technology-driven e-flipped classroom model of educational transformation. *Journal of Taibah University Medical Sciences*, 15(4), pp. 253–254. <https://doi.org/10.1016/j.jtumed.2020.07.006>
- Guangul, F., Suhail, A., Khalit, M., & Khidhir, B. (2020). Challenges of remote assessment in higher education in the context of COVID-19: A case study of Middle East College. *Educational Assessment, Evaluation and Accountability*. Advance online publication. <https://doi.org/10.1007/s11092-020-09340-w>
- Hadar, L., Ergas, O., Alpert, B., & Ariav, T. (2020). Rethinking teacher education in a VUCA world: Student teachers' social-emotional competencies during the COVID-19 crisis. *European Journal of Teacher Education*, 43(4), 573–586. <https://doi.org/10.1080/02619768.2020.1807513>
- Harsel, M. V. (2021). *Acquiring problem-solving skills in higher education: Sequencing and self-regulated learning from examples and problems* (Doctoral dissertation, Utrecht University). ISBN: 978.94.641.9260.5 DOI: 10.33540/697
- Hew, K. F., Bai, S., & Huang, W. (2021). Adaptation of a conventional flipped course to an online flipped format during the COVID-19 pandemic: Student learning performance and engagement. *Journal of Research on Technology in Education*, 1-21.

- Hill, K., & Fitzgerald, R. (2020). Student perspectives on the impact of COVID-19 on learning. *AISHE-J*, 12(2), 1–9 retrieved from: <http://ojs.aishe.org/index.php/aishe-j/article/view/459>
- Huang, R., Tlili, A., Chang, T., Zhang, X., Nascimbeni, F. & Burgos, D, (2020). Disrupted classes, undisrupted learning during COVID-19 outbreak in China: application of open educational practices and resources, *Smart Learning Environments*, 7 (19). <https://doi.org/10.1186/s40561-020-00125-8>
- Irfan, M., Kusumaningrum, B., Yulia, Y. & Widodo, S.A. (2020). Challenges during the pandemic: use of e-learning in mathematics learning in higher education. *Infinity Journal*, 9(2), pp.147-158.
- Irish, R., 2016. Engineering Persuasion: Teaching Rhetorical Savvy for Engineering Leadership. *Proceedings of the Canadian Engineering Education Association (CEEA) Conference- Dalhousie University June 19-22, 2016*. <https://ojs.library.queensu.ca/index.php/PCEEA/article/view/6493>
- Izumi, T., Sukhwani, V., Surjan, A. & Shaw, R., 2021. Managing and responding to pandemics in higher educational institutions: initial learning from COVID-19. *International Journal of Disaster Resilience in the Built Environment*, 12(1), pp. 51-66
- Jia, C., Hew, K., Bai, S. & Huang, W. (2021). Adaptation of a conventional flipped course to an online flipped format during the COVID-19 pandemic: Student learning performance and engagement, *Journal of Research on Technology in Education*, DOI: 10.1080/15391523.2020.1847220
- Karadag, E., Su, A., & Ergin-Kocaturk, H. (2021). Multi-level analyses of distance education capacity, faculty members' adaptation, and indicators of student satisfaction in higher education during COVID-19 pandemic. *International Journal of Educational Technology in Higher Education*, 18(1), 1-20.
- Kodancha, P., Sajjani, K. S., Raut, A., & Baboo, S. (2020). Service-Learning in Indian Higher Education: Experiences of Adaptation to the COVID-19 Pandemic. *Journal Of Service-Learning In Higher Education*, 11(2), pp. 5-29.
- Korkmaz, G. & Toraman, Ç. (2020). Are we ready for the post-COVID-19 educational practice? An investigation into what educators think as to online learning. *International Journal of Technology in Education and Science (IJTES)*, 4(4), 293-309
- Korkmaz, G., & Toraman, C. (2021). Exploring Medical Students' Readiness for E-Learning and Knowledge Sharing Behaviors in Emergency Remote Learning Environments during COVID-19. *Journal of Education in Science, Environment and Health*, 7(3), 259-268.
- Kurt, S. (2009). An analytic study on the traditional studio environments and the use of the constructivist studio in the architectural design education. *Procedia-Social and Behavioral Sciences*, 1(1), pp.401-408.
- Louis-Jean, J., & Cenat, K. (2020). Beyond the Face-to-Face Learning: A Contextual Analysis. *Pedagogical Research*, 5(4): em0077. <https://doi.org/10.29333/pr/8466>
- Luckan, Y. (2016). The transformation of architectural pedagogy towards a new model for architectural education at universities of technology in South Africa. *PhD Thesis*. University of KwaZulu-Natal, South Africa.
- Maturana, B., Salama, A.M. and McInnery, A. (2021). Architecture, urbanism and health in a post-pandemic virtual world", *Archnet-IJAR*, 15(1), pp. 1-9.
- McKibbin, W. and Fernando, R. (2020). The economic impact of COVID-19. *Economics in the Time of COVID-19*, 45(10.1162).
- Milovanović, A., Kostić, M., Zorić, A., Đorđević, A., Pešić, M., Bugarski, J., Todorović, D., Sokolović, N. & Josifovski, A. (2020). Transferring Covid-19 challenges into learning potentials: Online workshops in architectural education. *Sustainability*, 12(17), p.7024.
- Murphy, M. (2020). COVID-19 and emergency eLearning: Consequences of the securitization of higher education for post-pandemic pedagogy. *Contemporary Security Policy*, 41(3), pp.492-505.
- Nuru, S., Fred, F., Oyekola, P. & Ngene, C. (2021). Resourcing as an Antecedent of Effective Online Learning Adaptation in the Face of COVID-19: The Case of Papua New Guinea University of Technology (PNGUoT). *Journal of Education, Society and Behavioural Science*, 34(2), pp. 80-89
- Perez, W., Arenas, A. & Cariapaza, D. (2021). The non-face-to-face assessment in basic mathematics in times of Covid: "we are prepared for this educational pandemic", IEEE World Conference on Engineering Education (UNINE). DOI: 10.1109/EDUNINE51952.2021.9429124
- Popoola, A., & Magidimisha, H. (2020). The Dilemma of Rural Planning and Planners in Oyo State, Nigeria. *Bulletin of Geography*, 47(47), pp. 75-93
- Popoola A.A. (2021) Rural Climate Change Experiences in Nigeria and Africa: Post-Millennia Methods and Findings. In: Leal Filho W., Luetz J., Ayala D. (eds) Handbook of Climate Change Management. Springer, Cham. https://doi.org/10.1007/978-3-030-22759-3_22-1
- Rahim, A. (2020). Guidelines for online assessment in emergency remote teaching during the COVID-19 pandemic. *Education in Medical Journal*, 12(2), 59–68. <https://doi.org/10.21315/eimj2020.12.2.6>
- Schleicher, A. (2020). The impact of COVID-19 on education insights from education at a glance 2020. Available from: <https://www.oecd.org/education/the-impact-of-covid-19-on-education-insights-education-at-a-glance-2020.pdf>.
- Seniz, C. (2009). Problematisation of assessment in the architectural design. *Procedia Social and behavior science*, 1(1), pp. 2103-2110.

- Shah, D. 29 May, 2020. Tracing the impact of COVID-19 on design education. Available from: <https://www.stirworld.com/think-opinions-tracing-the-impact-of-covid-19-on-design-education>
- Sia, J. and Adamu, A (2021). Facing the unknown: pandemic and higher education in Malaysia. *Asian Education and Development Studies*, 10(2), 263-275
- Siche, R. (2020). What is the impact of COVID-19 disease on agriculture?. *Scientia Agropecuaria*, 11(1), pp.3-6.
- Sutadji, E., Susilo, H., Wibawa, A. P., Jabari, N. A. M., & Rohmad, S. N. (2021, March). Adaptation strategy of authentic assessment in online learning during the covid-19 pandemic. In *Journal of Physics: Conference Series* (Vol. 1810, No. 1, p. 012059). IOP Publishing.
- Tamrat, W., & Teferra, D. (2020). COVID-19 Threat to higher education: Africa's challenges, responses, and apprehensions. *International Higher Education*, 102, 28–30.
- The Global Campaign for Education (GCE) (18 March 2020). #CoronaVirus: Don't Let Our Children Down! Available from: https://campaignforeducation.org/en/2020/03/18/coronavirus-dont-let-our-children-down/?gclid=Cj0KCQjwwY-LBhD6ARIsACvT72NmCTbNUoInKqnmzRNC0Nk_KfwsGilhGBRIZJiByCLgKC7m99p8nDMaAr72EALw_wcB
- UNICEF. (2020). #ReopenSchools. Available from: https://www.unicef.org/coronavirus/reopen-schools?gclid=Cj0KCQjwwY-LBhD6ARIsACvT72OdrbOcJ0Ybl8Iqsn7ZfQXILMn5X1JUzcqR9OIJraYk0-kunxTv0ZAaAiT5EALw_wcB
- Wang, C., Pan, R., Wan, X., Tan, Y., Xu, L., Ho, C., & Ho, R. (2020). Immediate Psychological Responses and Associated Factors during the Initial Stage of the 2019 Coronavirus Disease (COVID-19) Epidemic among the General Population in China. *International Journal of Environmental Research And Public Health*, 17(5), 1729. doi: <https://doi.org/10.3390/ijerph17051729>
- Weller, M. (2020). The COVID-19 online pivot: The student perspective, The London School of Economics and Political science. Available: <https://blogs.lse.ac.uk/impactofsocialsciences/2020/03/12/the-covid-19-online-pivot-adapting-university-teaching-to-social-distancing/>
- Williamson, B., Eynon, R., & Potter, J. (2020). Pandemic Politics, Pedagogies And Practices: Digital Technologies And Distance Education During The Coronavirus Emergency. *Learning, Media and Technology*, 45(2), 107–114.
- Yildirim, T., Yavuz, A. & Kirci, N. (2012). Experience of traditional teaching methods in architectural design education: “mimesis technique”. *Procedia-Social and Behavioral Sciences*, 51, pp.234-238.

Asset Classification for Roads – CONie, towards COBie-for-Roads

Fereshteh Banakar* and Robin Drogemuller, Sara Rashidian, Sara Omrani

School of Architecture and Built Environment, Queensland University of Technology, Australia.

*Corresponding author: f.banakar@qut.edu.au

Abstract

Building Information Modelling (BIM) implementation in the design and construction phases of road projects has increased significantly during the last decade, while the application of BIM for the operation and maintenance phase of roads is less developed. BIM can offer an integrated and unified asset management process based on all phases of a road project, leading to significant savings in time and cost. COBie (Construction Operation Building information exchange) is the data handover solution applicable for vertical infrastructure (buildings). Australian and New Zealand Road Authorities are working on an adaptation of COBie, called CONie (Construction Operation Network information exchange), that considers linear infrastructure requirements for asset management. One of the challenges required to support the development of this data handover framework is the lack of a harmonised data schema for asset management in terms of asset name, definition, and categorisation.

The purpose of this paper is to argue that developing and utilising a harmonised and synthesised object model of road assets will assist Australasian road organisations to increase efficiency in asset management, especially through collaboration. This paper describes the procedure followed to harmonise road asset databases that has been used as a basis for developing CONie. The described aim was achieved through collecting relevant data from Road Authorities and the developers of road standards in Australia and New Zealand. The collected data was harmonised and synthesised. The harmonised database was then mapped to the building Smart ifcRoads project.

Regarding the existing road assets, a categorisation system is suggested by authors. It introduces the main categories including relevant subcategories and asset types. The developed database of road assets provides a basis for asset management, operation and maintenance purposes by road organisations beside being used for CONie development.

Keywords

BIM, Classification, COBie, CONie, Road Asset management.

Introduction

According to the statistics released by Australian and New Zealand road authorities, the annual expenditure on roads in these two countries is approximately AU\$35 billion. Almost half of this total expenditure is allocated to the maintenance, operation, and renewal work category, which accounts for a large proportion of the overall spending (BITRE 2020, Infrastructure Australia 2020, WAKA KOTAHI - New Zealand transport agency 2020). The complexity of road infrastructure and the existence of various stakeholders and agencies involved in the design, construction, and operation phases, requires effective and cost-efficient asset management strategies (Nezamian 2018, Austroads 2019). Asset management assists in making the appropriate decisions related to maintenance, repair, and rehabilitation of road assets based on data concerning the existing condition, usage risk, life-cycle cost, and age of the assets. An optimal and comprehensive plan to manage road infrastructure assets can be

achieved through a structured framework using Building Information Modeling (BIM) (East *et al.* 2015, Kenley *et al.* 2015). One of the BIM tools used internationally for vertical infrastructure asset management is COBie (Construction Operation Building information exchange) (East 2007). The objective of COBie is to enhance how information is captured during the design and construction phases and then provided for operations, maintenance, and asset management functions (East 2007). The use of COBie provides information that will be stored in a reusable and interoperable format.

There is no COBie-like system that can be utilised for asset management of linear infrastructure. CONie (Construction Operation Network information exchange) has been introduced as an equivalent to COBie which works for linear infrastructure. The CONie specification makes use of BIM capabilities to link information flow from the design and construction phases of a road project to the maintenance phase and asset management. This tool is being developed to assist road stakeholders as an information exchange framework, for operation and maintenance, and asset management aiming to ease the process of data handover. (East *et al.* 2015, Kenley *et al.* 2015)

One of the fundamentals for developing CONie is a harmonised database of road assets that can be used by all road authorities and different parties involved in the several phases of a road project. This database includes asset naming, categorisation, asset type, and asset components (East *et al.* 2015, Kenley *et al.* 2015). Different parties involved in a road project have processed a specific database for themselves in line with their methods and regulations. The lack of a common database of assets causes inconsistency in road asset management. Thus, there is a need for agencies to harmonise their databases based on the commonly used standards. To fill these gaps, this study introduces an object model of road assets based on the databases of road authorities in Australasia and two road standard development, BuildingSMART and Austroads. The objectives of the research are as follows:

1. To recognise road assets and to categorise the assets based on their functions on road infrastructure.
2. To identify the asset types included in each category, as well as the harmonisation and synthesis of asset names based on an existing database of road organisations in Australia and New Zealand.

Literature Review

According to ISO 55000, Asset Management (AM) transforms the priorities of the organisation, using a risk-based strategy, into asset-related decisions, plans, and activities (ISO 2014). AM includes tasks such as acquisition, replacement, and amortization of assets in addition to the management of scheduled maintenance and defect repair (Boyes *et al.* 2017). Asset lifecycle management can reduce maintenance costs, improve asset performance, enhance decision making, and extend the useful life of assets. Austroads, the peak organisation of road transport in Australia and New Zealand highlights the purpose of asset management as:

“providing the required levels of service at the lowest life-cycle cost to present and future road users and customers, using a ‘whole-of-agency’ approach to the acquisition and management of physical assets (Austroads 2018b).”

This purpose is aligned with the goal of road organisations with respect to working cost-efficiently. As road authorities aim to work efficiently, implementing asset lifecycle management using an integrated and unified process that includes design, construction, and

operation phases in road infrastructure leads to significant time and cost savings (Austroads 2018b, Nezamian 2018, Austroads 2019). The majority of the data needed in the operations stage is created during the design and construction stages. This information must be adjusted during the operations stage (Smith and Tardif 2009, Bosch *et al.* 2015). An efficient asset management system including all the mentioned features can be developed using BIM. BIM is a shared digital representation based on open interoperability standards (NIBS 2012). BIM makes it possible to store information from all project phases in a single digital model and it enables effective data management, particularly in large-scale projects where there are many parties involved (Love *et al.* 2014, Love *et al.* 2015).

Many standards development organisations such as BuildingSMART have created information exchange standards for building design, construction, and operation phases for the creation, exchange, and use of data to manage their assets. Building asset management is often performed using a combination of two approaches; Industry Foundation Classes (IFC) and Construction Operation Building information exchange (COBie) (Niestroj *et al.* 2018, "BuildingSMART" 2019). COBie is one of the most highly developed information exchange standards for building assets. COBie supports the specification of the subset of digital information transmitted from the design and construction phases to the asset management databases (East 2007, Anderson *et al.* 2012). The ability of BIM to register and process large amounts of correlated detailed information helps to improve information and project management, as well as performance and resource monitoring. This has led to the development of COBie (East 2007, Lee *et al.* 2013).

Unlike buildings, where BIM-based asset management has been implemented, the capabilities of bridges, roads, and other linear infrastructure projects are much less well defined due to differences between vertical and horizontal infrastructure projects such as location referencing method and (Kenley *et al.* 2015, Niestroj *et al.* 2018, Perumpilly *et al.* 2019). Studying road projects in Australia and New Zealand shows that BIM has been successfully implemented in several road infrastructure projects resulting in savings in time and cost in the construction phase (Nezamian 2018, Aurecon 2021, MRWA 2021, RMS-NSW 2021, TMR-QLD 2021, Vicroads 2021b). But this implementation is mostly undertaken during the design and construction phases of a road project and has not been carried further into the asset management and operation phase (Love *et al.* 2013, Hampson *et al.* 2018, BITRE 2020, Infrastructure Australia 2020, Kelly 2020, Aurecon 2021, Vicroads 2021a).

Construction Operation Network information exchange (CONie) has been introduced as an extension of COBie to support linear infrastructure asset management. It aims to support the specification of the subset of digital information transmitted from the design and construction phases to the asset management databases in roads. This project is currently at the developing stage (East *et al.* 2015). Similarly to COBie, the CONie specification takes advantage of BIM capabilities to connect the information flow from the design and construction phase to asset management (Kenley *et al.* 2015). This digitalising process does not alter the current delivery of construction project information; rather, it ensures the long-term survival of road network construction information in an easily retrievable format (East *et al.* 2015). This offers the fundamental infrastructure to support effective asset management by providing a framework for information, covering the whole lifecycle of an asset such as product data, warranties, and preventative maintenance schedule (Drogemuller 2009, Martin 2011, East *et al.* 2015, Nezamian 2018).

As CONie can provide a performance-based specification for project information delivery, it can be used by road owners as an information exchange framework for operation and maintenance and asset management purposes (East *et al.* 2015, Kenley *et al.* 2015). The

development of CONie requires the gathering of different types of data, for example, the types of assets and their functions, location of each asset and location referencing of different types of assets, detailed information about the maintenance, guaranty and warranty, the authorised organisation for the maintenance of each asset, and also cost estimation of maintenance operations (Perumpilly *et al.* 2019). In the road industry in Australia and New Zealand, lead agencies are defined as authorities that develop road-related standards, guidelines, codes of practice, and regulations. They also are road owners and responsible for the maintenance and operation of the roads practically and financially (BITRE 2020, Kelly 2020, WAKA KOTAHU - New Zealand transport agency 2020). Figure 1 shows these sectors in Australia and New Zealand which collaborate with this research:

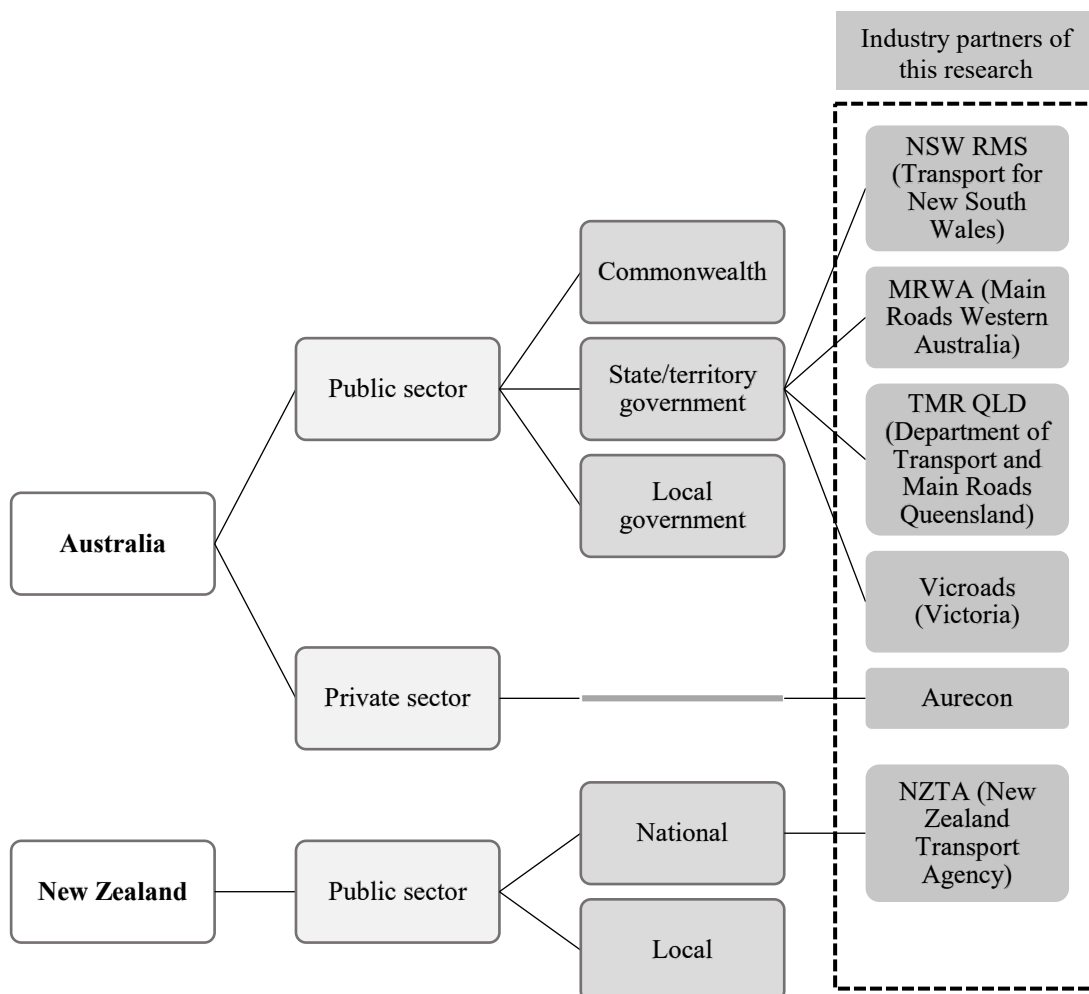


Figure 1. Lead agencies in Australia and New Zealand's road industry recognised by their collaboration with this research (Developed by the authors)

Having the appropriate information and data about the assets is the first step in creating a road infrastructure asset management system. This data should include the features listed below:

- **Availability:** data should be computer-readable and available for engineers.
- **Actuality:** data should contain the latest status of each asset.

- **Integrity:** data should be comprehensive and completely express all required features of each asset.
- **Diversity:** different data sources should be combined to make a comprehensive database (Godø *et al.* 2010).
- **Interoperability:** data should be easily shared between different parties involved in a project. It will save time and budget for asset management if data could be smoothly transferred between different parties and software systems in a project and between the project data and the organisation's asset management system (Kenley *et al.* 2016, Drogemuller *et al.* 2020).

Three stages must be followed in order to establish a BIM-based platform: Object-based modelling, shared-model collaboration, and network-based integration, in which all infrastructure-related information is fully integrated and managed in a single environment (Bosch *et al.* 2015). Interoperability is the key aspect that should be considered in this process. There should be a clear understanding of which information is or should be integrated, and no relevant data should be lost (Bosch *et al.* 2015, Kenley *et al.* 2016).

The targeted sectors are the decision-makers for the major national programs Based on the reports released by these authorised organisations, the national road maintenance strategy is identified as a high-priority initiative. It is also stated that “integrating road assessment and maintenance management (RAMM) data and improving its access” is economically in the high-priority programs (New Zealand Ministry of Transport 2019, Infrastructure Australia 2020)

Despite the fact that all these sectors have the same future plan targeting the improvement of efficiency in the maintenance phase of road projects, all of them are individually handling several projects with the aim of efficiency in asset management (Infrastructure Australia 2020). The effort is mostly on defining the scope of asset management, asset information and data, BIM implementation, contract framework and maintenance requirements, and Road Assessment and Maintenance Management (RAMM) database (Nezamian 2018, Aurecon 2021, MRWA 2021, RMS-NSW 2021, TMR-QLD 2021, Vicroads 2021b).

Reviewing the listed programs shows that the common feature of all programs is that they are developed based on Austroads data standards for road management. On the other hand, it indicates that each organisation follows its own path and has a separate asset management system that is not aligned and harmonised with other organisations' systems. To be specific, this issue is mainly about differences between asset naming and definition and the classification of those assets. The mentioned aspect are critical fundamentals of an asset management system. The existence of different systems and frameworks will cause inconsistency in the collaboration of road organisations with each other and with the third parties and contractors involved in projects.

Although much of the data required by different domains may be comparable, smooth and efficient collaboration requires that all data must be modelled similarly across all domains. The CONie specification can assist the road organisations by modeling the details of each element of the road infrastructure network in a way that professionals and practitioners can comprehend. Giving the best service to all road network stakeholders, asset managers, operations systems, maintenance work orders, and new capital works depends on reliable and useable data (East *et al.* 2015).

For a clear understanding of the undertaking programs aligned with the road organisations' asset management plan and the scope of this research, two standard developer organisation and their related projects are discussed.

Austroads

Austroads is the collective of the Australian and New Zealand transport agencies. All Australasian state road authorities are members of the Austroads and work collaboratively. The role of Austroads is to provide high-quality, practical and impartial advice, information, tools and services to help their members to deliver efficient, reliable and safe mobility to their customers. Austroads has several published road-related guidelines and standards and continually updates those guides that provide advice on the design, construction, and operation of the road network.

Austroads works on projects regarding road asset classification and data standards for road assets. The two Austroads' reports aligned with the aim of this research have been reviewed. One of them is "Data Standard for Road Management and Investment in Australia and New Zealand" which is the third version, released in 2019 (Austroads 2019). This data standard is a result of a review and comprehensive consultation across the road industry in Australia and New Zealand. It presents standardised and harmonised data sets that support common road management activities intended to help asset information management systems in collecting data, finance, risk, and information. The scope of this data standard includes improving information on road asset inventory data, addition of new items, and revising some data definitions (Austroads 2019).

Another review by Austroads is "Asset Data Harmonisation - BIM IFC Alignment Review", stage III of which was published in 2018 (Austroads 2018a). This review revealed the potential inconsistencies in the Data Standard with other available data standards, namely the UK Government's Uniclass 2015 and buildingSMART's IFC4. There has been indications that further effort will also be needed in the longer term to harmonise the Data Standard and align locational referencing and classification of the assets to international approaches (Austroads 2018a).

The asset data harmonisation is specifically designed to provide the basis for road asset data such as a common understanding of the meaning of the data, consistency in data definition and format, a list of data items that support road management activities, guidance for appropriate levels of sophistication in asset location referencing, and asset data description. 14 function groups are defined as the scope of data items that structure this standard. One of those is inventory or asset register, while the relevant sub-functions are the asset types.

The future work that is identified in these reviews emphasises the importance of the presented research and shows its alignment with the industry perspective. These reports and guidelines are also the resource for this research's data analysis stage as they provide asset inventory lists and corresponding information.

The Asset Inventory defined by Austroads as:

"A list of assets considered *worthy* of identification as discrete assets, with information such as location, design standard, construction date, maintenance history, configuration, condition, and technical details (Austroads 2015)."

The Austroads Asset Inventory list is presented in Figure 2.

Road asset inventory defined by Austroads		
Code	Data Specifications	
8.3.1	Amenities	
8.3.2	Bins	
8.3.3	Bridge / Major Culvert	
	Bridge / Major Culvert: Components	
8.3.4	Culverts (Minor)	
8.3.5	Fences	
8.3.6	ITS (Intelligent Traffic Systems) Assets	
	ITS Polyline	
	ITS Point	
	ITS Polygon	
8.3.7	Kerb and Channel	
8.3.8	Landscaping	
8.3.9	Lighting	
8.3.10	Line-Marking Assets	
	Line-Marking Polyline & polygons	
	Line-Marking Point	
8.3.11	Mechanical and Electrical Assets	
	M&E Polyline	
8.3.12	Parking	
8.3.13	Pathways	
8.3.14	Pavement	
	Pavement Layers	
	Pavement Surfacing	
	Pavement Surfacing detail	
8.3.15	Pavement Surfacing	
	Pavement Surfacing detail	
8.3.16	Pits	
8.3.17	Poles	
8.3.18	Public Art	
8.3.19	Public Toilets	
8.3.20	Retaining Walls	
8.3.21	Road Barriers	
8.3.22	Shelters	
8.3.23	Signs	
8.3.24	Slopes	
8.3.25	Structures	
8.3.26	Table Drains	
8.3.27	Tactile Paving	
8.3.28	Traffic Management Devices Point	
	Traffic Management Devices – Polygon	
8.3.29	Traffic Signals	
8.3.30	Trees	
8.3.31	Tunnels	
8.3.32	Vehicle Crossings	

Figure 2. Road asset inventory defined by Austroads (Austroads 2019)

IFCRoad

In 2019, it was acknowledged that there was an urgent need to harmonise the work across linear infrastructure domains at an international level. Since most infrastructure projects are inter-modal and have elements from all the infrastructure domains, the schemas must be consistent at the conceptual level (BuildingSMART 2020). As a result, the IFC Infrastructure Extensions project started with the scope of a harmonised approach to linear infrastructure assets incorporating Road, Rail, Bridge, Ports and Waterways. These individual projects are running across different time frames with different milestones. These domain projects address several common concepts. Thus, an additional project called "Common Schema" was established to detect and define common concepts (such as spatial structure, geotechnics and earthworks, utility networks, etc.) out of the mentioned domain projects. This project leads to a harmonised and consistent development of IFC Infrastructure Extension (BuildingSMART 2020).

The focus of this research is on road infrastructure, so the details related to this BuildingSMART domain have been used in this project. As all road authorities in Australia and New Zealand are working collaboratively with BuildingSMART in the development of a harmonised framework for asset management of road infrastructure in Australia and New Zealand. Besides the local road organisations database and Austroad standards, the IFCRoad project should be considered, and all databases should be aligned with the goals of IFC Extension Infrastructure project. This alignment is part of the road organizations' goal. The scope of IFCRoad has been defined with the consultation of road organisations worldwide to ensure that it is in line with the needs of the road industry (BuildingSMART 2020).

The following points provide a general indication based on the initial scope statement of a road project, showing in-scope and out-of-scope criteria (Figure 3) (BuildingSMART 2018). This scope definition helps narrow down the focus of developing the object model for road asset

management based on the defined road and path types, junction types, and road components and elements.

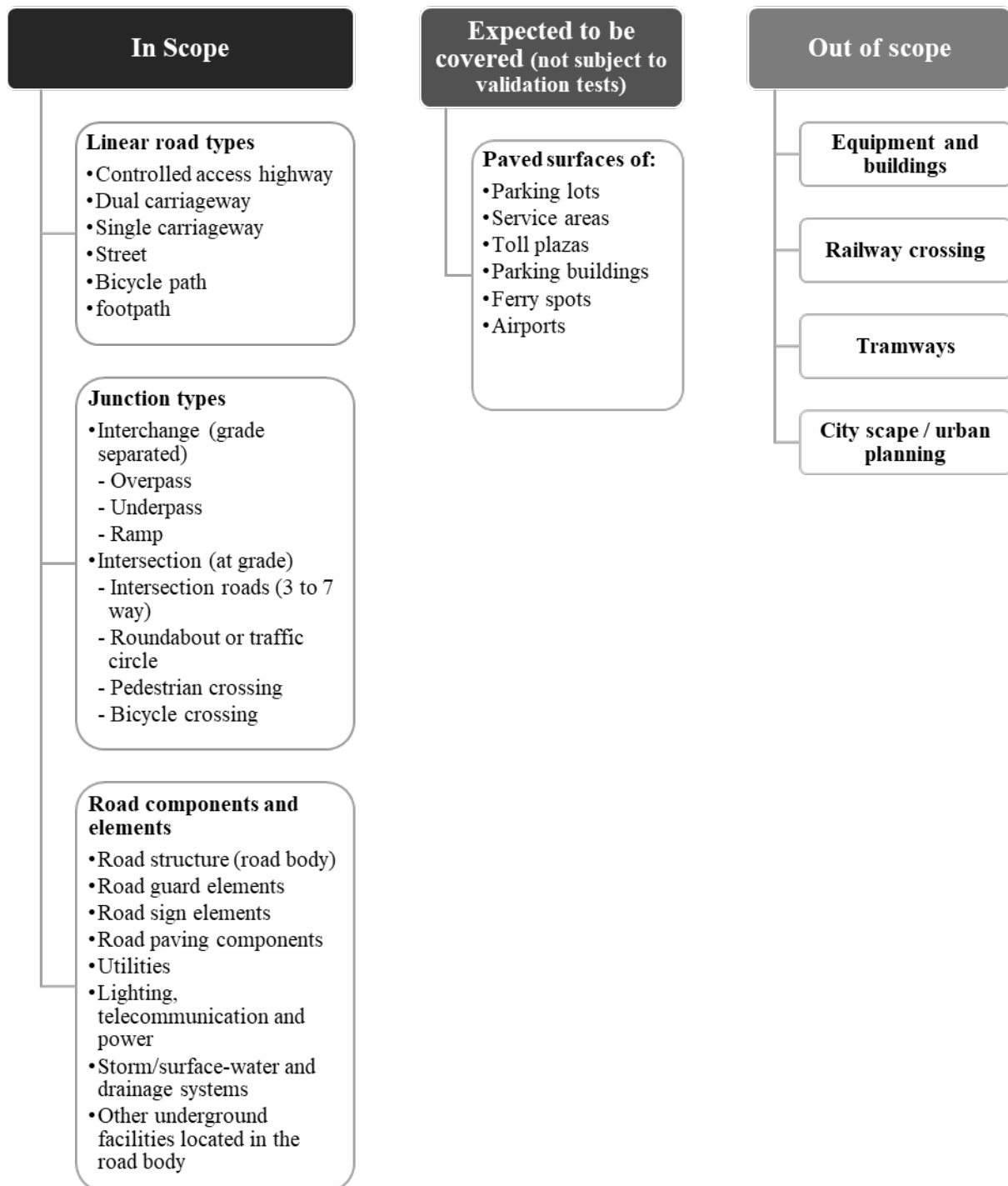


Figure 3. In and out of scope road types and related spaces and components defined by BuildingSMART for IFCRoad project (BuildingSMART 2018)

A road project can be broken down in several ways and in multiple parallel aspects. By following the IFC modelling principles, three main breakdown structures can be considered for any road model:

- spatial (project) breakdown structure;
- (physical) component breakdown structure;
- functional (system) breakdown structure (BuildingSMART 2020).

The central aspect that should be considered for developing the road object model is the road-related elements and their function. Thus, the functional (system) breakdown structure of the roads defined by BuildingSMART for the IFCRoad project is examined in this stage (BuildingSMART 2020).

The following concepts are core IFC concepts used for developing object the road model mentioned in (BuildingSMART 2020).

- **IfcObject:** An IfcObject is the generalisation of any semantically treated thing or process. Objects are things as they appear.

Examples of IfcObject include physically tangible items such as a wall, beam or covering, physically existing items such as spaces, or conceptual items such as grids or virtual boundaries. It also stands for processes such as work tasks, for controls such as cost items, or for actors such as persons involved in the design process.

Objects are independent pieces of information that might contain or reference other pieces of information. There are several relationships in which objects can be involved:

- **Assignment of other objects:** an assignment relationship that refers to other types of objects.
- **Aggregation of other objects:** an aggregation relationship that establishes a whole/part relation. Objects can either be a whole, or a part, or both.
- **Assignment of a type:** a definition relationship that uses a type of asset definition to define the common characteristics of this element, potentially including the common shape representation and common properties of all objects assigned to this type.
- **Systems:** Sets of assets providing a service. These systems developed functionally considering different features and properties of each asset. Each system includes several Categories of assets named “Package”.
 1. Package: Guard systems
 2. Package: Drainage
 3. Package: Lighting, telecom, and power
 4. Package: Signage
 5. Package: Transportation systems

Each category has a general definition. Different Types of assets can be included in those categories.

Types of assets identified by road organisations based on specific design and construction parameters that asset owns. All asset types should not necessarily be used by all organisations, owing to differences between climate, transportation system, construction approaches and infrastructure of each region.

These concepts indicate five functional categories (package) defined for roads; Guard systems, Drainage, Lighting, telecom, and power, Signage, and Transportation systems. Each of these

categories includes several physically tangible items, physically existing items, and conceptual items. These items can be a subcategory for each main category, or an asset type sub defined as a subcategory. Each item may be a subcategory and an asset type for another subcategory at the same time or can be included in several subcategories. In this case, relationships between the common subcategories and asset types will be defined. The following diagram (Figure 4) briefly shows these connections.

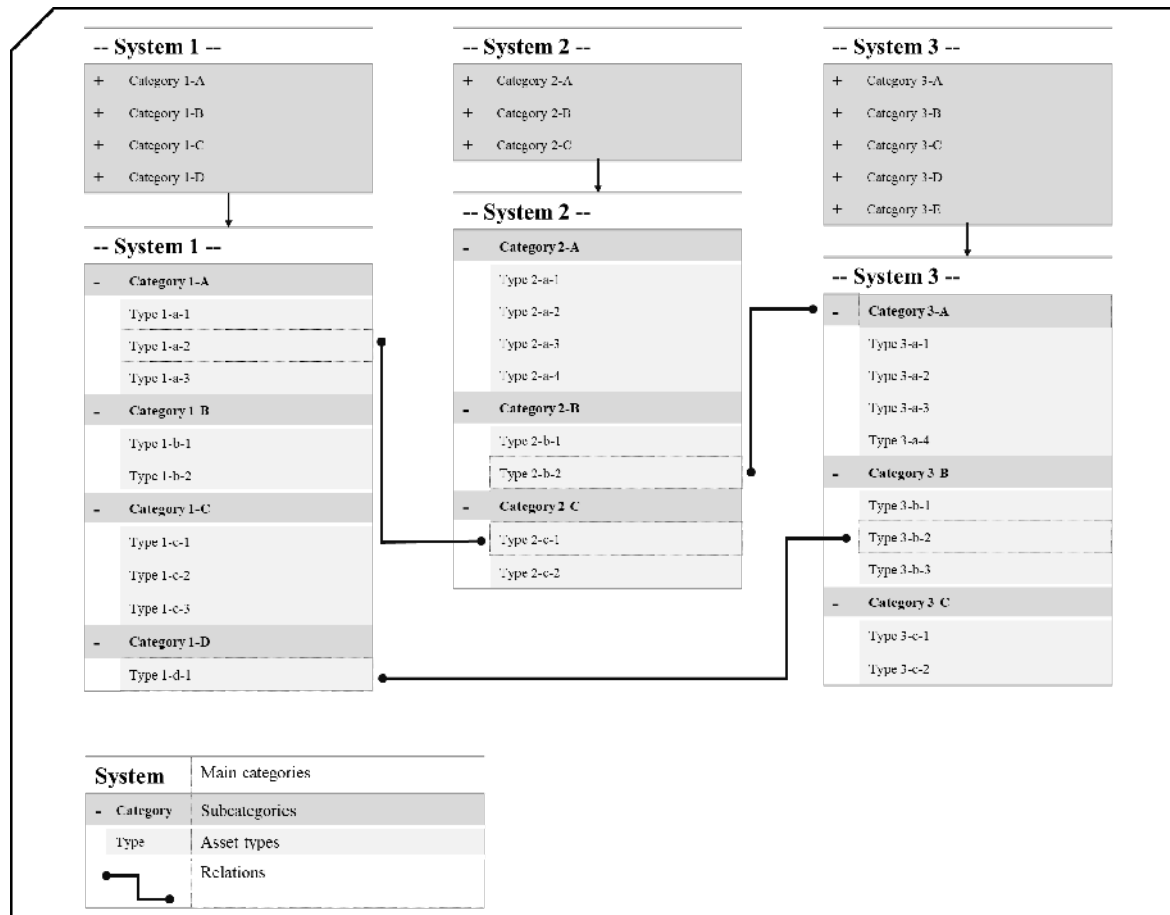


Figure 4. Connection between Systems, Categories, and Asset types developed by authors based on IFCRoad conceptual model (BuildingSMART 2020)

Considering the given information on ANZ road organisations asset management and relevant standards and guidelines, the following parts describe the used method and the findings of this research.

Research Methodology

The scope of the CONie project is aimed explicitly at road authorities in Australia and New Zealand. Several public and private organisations in the road industry are collaborating with this research as raw data providers for developing a harmonised asset database. The public organisations are Australia and New Zealand state road organisations such as MainRoads Western Australia (MRWA), Transport for New South Wales (RMS NSW), Department of Transport and MainRoads Queensland (TMR QLD), Vicroads for Victoria, and New Zealand

Transport Agency (NZTA). The private organisation that assists in the CONie project and provides data is Aurecon (Kenley *et al.* 2015).

Besides the ANZ road organisations, the publications of two standards developers are referenced in the CONie project, BuildingSMART and Austroads. Those organisations provide information related to road asset, categorisation system and relevant attributes. This information has been published as several guidelines and reports.

All data needed for this research is gathered from the published guidelines and reports by the mentioned organisations. The collected data has been analysed and the similarities and differences have been identified between different groups and individual elements at all levels. The relationship among variables has been established as well.

Data collection

The starting point for collecting data was the identification of the types of data aligned with the needs of the project. The needed data types are:

- The roads asset inventory and the list of all organisational asset possessions,
- Asset categorisations and classification system,
- The functional definition of each category and determined subcategories, and
- Asset types included in each category and subcategory.

As shown in Figure 5, the sources of each data type were identified: road authorities in Australia and New Zealand and the standard development organisations; BuildingSMART and Austroads. This type of data gathered from the publicly available information that was published by each individual organisations and data standard developers as part of their road asset inventory and classification system, reports and guidelines related to operation and maintenance of roads, inspection instructors, design guides and standards, asset management databases, and annual funding and expenditure reports.

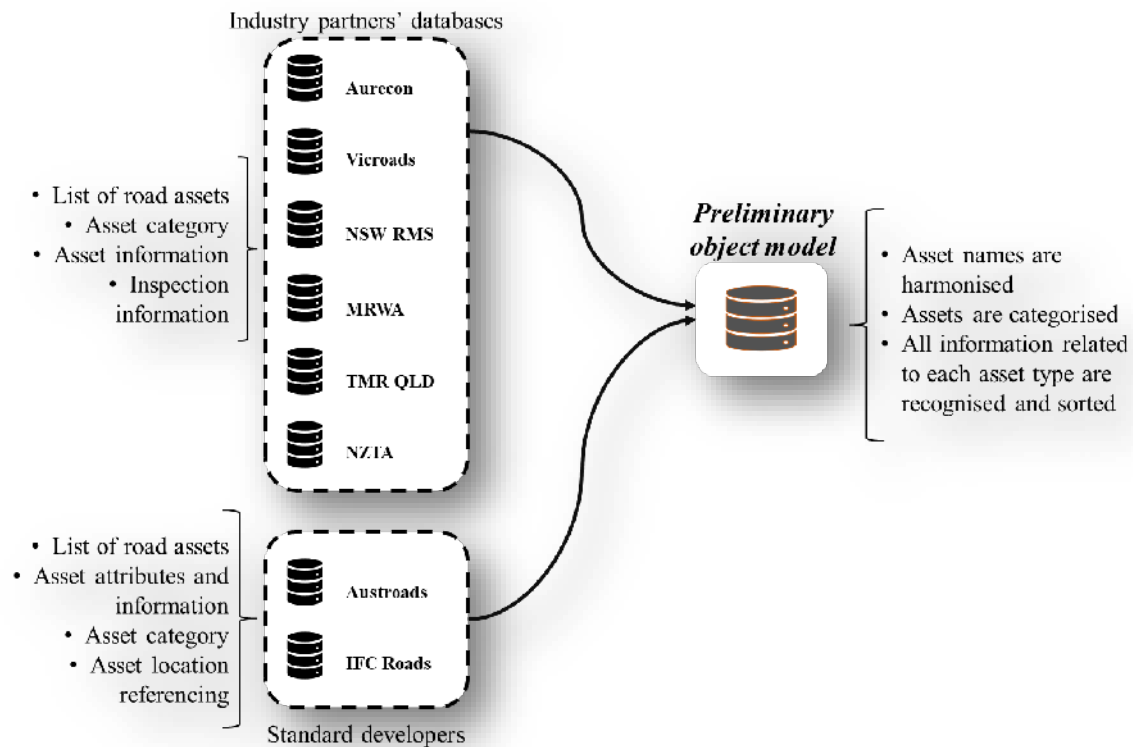


Figure 5. Source of data, the types of data extracted of each group of database, and the harmonised database.

Data analysis

After data collection, the data was analysed, and similarities and differences were detected. The result of this stage of data analysis is structured in Table 1. Each organisation categorised its owned assets and named those categories in a specific way. All those main categories were identified. The similarities in the category naming were identified too and shown in the table below. The percentage of use of specific names by organisations is mentioned in the table as well. It assists in providing a clear view of the similarities and differences.

Each main category has a specific definition and includes several asset types or subcategories. After reviewing all asset categories and relevant types of assets, and the definition of each package, it was found that:

- Some categories have the same definition and also have included the same asset types while there are variations in naming;
- Some of the defined main categories by some organisations have been defined as a subcategory by other organisations, i.e. at a lower level in the definition tree;
- Several differences found related to subcategories and asset types which are mentioned under a main category. For example, some of the asset types are defined as a subset of a category by one organisation while another organisation has defined it under another main category.

According to these findings, the main categories that can be merged are shown together by color in the table below. This merging was identified based on the definition and function of each category, and also the included subcategories and asset types.

The outcome of this process is mentioned in the next section as part of the result of this research.

Table 1. Defined functional categories by ANZ road organisations and the frequency percentage (Developed by authors)

	Main categories labels	Aurecon	MRWA	TMR QLD	Vicroads	NSW RMS	NZTA	Percentage
	Roads			.	.			33%
	Pavement and surfacing		.		.	.	.	66%
	Structure / road structure		.	.	.			50%
	Minor structures / roadside structure (roadside structures and crossing structures)				.		.	33%
	Retaining walls / walls						.	33%
	Bridge				.	.		33%
	Roadside / Roadside area / Roadside landscape		.	.	.			50%
	Road stopping place		.					17%
	Zones					.		17%
	Corridor (roadsides and medians)					.		17%
	Drainage/ Drainage and stormwater	.	.	.	.	.	.	100%
	Surface water channel (SWC)						.	17%
	Shoulder						.	17%
	Signage / signs	.			.		.	50%
	Traffic management devices/ traffic control equipment/ traffic facilities		.		.	.		50%
	Traffic signal and lights	.						17%
	Line Marking / markings						.	17%
	ITS (Intelligent Transportations Systems)	.					.	33%
	Electrical and ITS		.					17%
	Utilities	.						17%
	Features						.	17%
	Operational assets					.		17%
	Electrical and mechanical			.				17%
	Street lighting						.	17%
	Road safety and traffic barrier system		.		.			33%
	Railings						.	17%
	Other				.			17%

After reviewing all asset categories and types, and the definitions of each package, and comparing with IFCRoad several functions related to assets have been identified which are common between all those road authorities and IFCRoad.

Findings and Discussion

According to the data analysis, it has been found that there are some main categories including several subcategories or asset types. Some of these categories were similar on having the same name and functional definition. Some of them had same function but with the different naming. Also, it has been found that some categories defined by one organisation are defined as a subcategory by another organisation. This feature is emphasised by BuildingSMART as an expected probability too.

Based on these findings, a categorisation system is suggested by authors. It introduces the main categories including relevant subcategories and asset types. It also represents the probable relationship between main categories and asset types of other categories. Figure 6 represents this categorisation system.

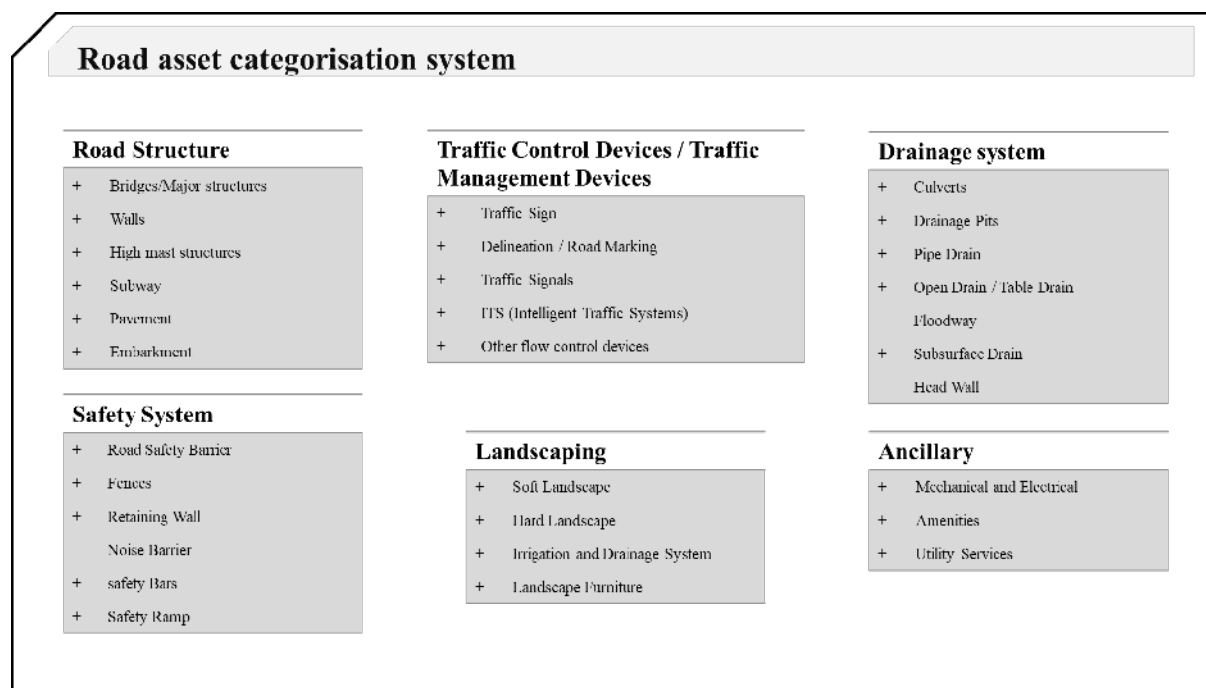


Figure 6. Developed road asset categorisation system

Each category has a general definition. Different Types of assets can be included in those categories. The suggested categories are the result of collecting and analysing data from the road authorities' asset inventory databases.

Types of assets identified by road organisations based on specific design and construction parameters that asset owns. All asset types should not necessarily be used by all organisations, owing to differences between climate, transportation system, construction approaches and infrastructure of each region.

Common aspects of asset inventories and asset categorisation of all mentioned road authorities have been considered for developing the object model. Six main categories have been defined:

- **Road structure:** this category includes major structures, all types of structures that need to be built on-site, high mast structures, and also pavement and surfacing the

road. The subcategories are bridge and major culverts, walls, high mast structures, subway, pavement, and embankment.

- **Traffic control devices/traffic management devices:** this category indicates all types of assets and facilities that help to control and manage traffic flow in a safe and smooth way. This category includes the following subcategories: traffic sign, road marking and delineation, traffic signals, ITS (Intelligent Traffic System), and other flow control devices.
- **Drainage system:** this category was the only one with a high level of agreement among all road organisations. Road surface drainage deals with the drainage of stormwater runoff from the road surface and the surfaces adjacent to the road formation. Several elements can be used to intercept or capture this runoff and facilitate its safe discharge to an appropriate receiving location. This category includes culverts, drainage pits, pipe drain, open drain/table drain, floodway, subsurface drain, headwalls.
- **Safety system:** this category shows all the facilities that assist in the safety of the road users, such as vehicle drivers, pedestrians, cyclists, and roadside users. These facilities reduce the possibility and risk of any accident and reduce the casualty and damages in case of accident happening. This category's subcategories are road safety barriers, fences, retaining walls, noise barriers, safety bars, and safety ramps.
- **Landscaping:** Most of the road organisations mentioned the roadside and median landscape areas as part of the roadside amenities. Owing to its complexity it deserves more attention and emphasis; thus it is noted as a separate category in this developed object model. Landscaping is defined as areas that have been modified for visual effect and typically include planting or vegetation such as gardens. It can also include hard landscaping. This category contains different subcategories of assets such as soft landscape, hard landscape, integration system, drainage system, and landscape furniture.
- **Ancillary:** This category includes all types of assets that exist as part of the road or roadside areas, but they are not considered road assets. Normally road organisations are not the owner of these assets, so they would not be responsible for maintaining those assets. The included subcategories are mechanical and electrical, amenities, and utility services. Knowing these assets' location and authorised organisation is critical for road organisations.

One of the fundamental requirements for developing CONie is a need for a harmonised road asset object model based on existing standards and guidelines that can be used by all road authorities. Based on the literature review, there is a lack of a common data harmonisation framework for road assets. As the scope of this study is limited to Australia and New Zealand road industry, the harmonised object model is developed through studying the operation workflow of all road authorities in this region, the asset categorisation and naming used by each of those organisations and comparing that data with the Austroads and IFCroad (road standard developers) asset database. As a result, an object model system is developed consisting of asset functional category, asset subcategories defined for each main category, and the potential link between main categories and subcategories in common.

- AUS and NZ will benefit from this work owing to providing the harmonised object model which will enable wider sharing of information
- Contractors will benefit through having more consistent BIM models when bidding for and managing projects

Since CONie considers all of the Australasian road authorities, it can provide the basis for the definition of mappings between the object models used by each authority and the software used by the contractors working on their projects.

Conclusion

The data exchanged for road projects should be based on current and expected data standards for performance-based asset management and road network operations. This will ensure that the handover is done reasonably with minimal disruption to network maintenance and asset management information and systems. This information also should be interoperable between different parties involved and phases of a road project. There is an information exchange system for vertical structures available named COBie (Construction Operation Building information exchange). As an extension of the COBie, CONie (Construction Operation Network information exchange) is proposed by Australian and New Zealand road authorities and Austroads organisation for exchanging asset information for horizontal infrastructure designed and built using IFC-Alignment models.

The development of CONie, requires a harmonised and categorised asset data model and data collection process model, checking for interoperability. This development relies on the experience from COBie and COBie specifications, finalising the specification and suggesting a framework for information exchange for road infrastructures. This paper focuses on developing one of the basic requirements for CONie development; a harmonised road asset object model considering existing standards and guidelines. This harmonised road asset naming object model can be applied to the asset management system of all road authorities in Australia and New Zealand. This paper represents the road assets' main categories and relevant subcategories, which is defined based on the functional aspect of road assets.

Future work in this field is needed regarding determining different asset types and sub-types applicable for each subcategory. The next step is identifying and defining the component of each asset type. The combination of these three sets (system, type, and component) is the basis for recognising and addressing the road assets and elements. Other aspects involved in developing CONie are location referencing, space, resources, job, and other essential attributes and documents. Other groups and research projects are working on these mentioned areas and the result of all these studies will be gathered and combined for developing the CONie specification.

The object model presented in this paper should be validated through interviews with experts in road asset management and maintenance and operation fields.

Acknowledgement

This research is funded by ARC LP160100524 CONie: Open Standards design for improved road network information exchange and the Building 4.0 CRC. Their project proposal and goals formed the structure of this research. The authors would like to acknowledge the contribution of the industry partners of these two projects in providing data as the basis for this research. The industry partners of these projects are BuildingSMART, Austroads, Department of Transport and Main Roads (TMR QLD), Main Roads Western Australia (MRWA), Department of Transport for New South Wales (NSW TMR), New Zealand Transport Agency (NZTA), Vicroads, Aurecon, Bentley, and Lendlease.

References

- Anderson, Anne, Andrew Marsters, Carrie Sturts Dossick and Gina Neff. 2012. "Construction to Operations Exchange: Challenges of Implementing COBie and BIM in a Large Owner Organization." In *Construction Research Congress 2012*, 688-697. doi: doi:10.1061/9780784412329.070.
- Aurecon. 2021. "Quartile one asset performance." <https://www.aurecongroup.com/expertise/quartile-one-asset-performance>.
- Austrroads. 2015. *Austrroads Glossary of Terms*. 6 ed: austrroads.
- Austrroads. 2018a. *Asset Data Harmonisation Stage III: BIM IFC Alignment Review*: Austrroads. <https://austrroads.com.au/publications/asset-management/ap-t333-18>.
- Austrroads. 2018b. *Guide to Asset Management - Overview Part 1: Introduction*. 3 ed, *Guide to Asset Management*: Austrroads. https://austrroads.com.au/publications/asset-management/agam01/media/AGAM01-18_Overview_Introduction.pdf.
- Austrroads. 2019. *Data Standard for Road Management and Investment in Australia and New Zealand Version 3.0*: Austrroads. <https://austrroads.com.au/publications/asset-management/ap-r597-19>.
- BITRE. 2020. *Australian Infrastructure Statistics - Yearbook 2020*. https://www.bitre.gov.au/sites/default/files/documents/bitre_aus_infrastructure_yearbook_2020.pdf.
- Bosch, Arnold, Leentje Volker and Alexander Koutamanis. 2015. "BIM in the operations stage: bottlenecks and implications for owners." *Built Environment Project and Asset Management* 5 (3): 331-343. Accessed 2021/11/01. doi: 10.1108/BEPAM-03-2014-0017.
- Boyes, G. A., C. Ellul and D. Irwin. 2017. "EXPLORING BIM FOR OPERATIONAL INTEGRATED ASSET MANAGEMENT - A PRELIMINARY STUDY UTILISING REAL-WORLD INFRASTRUCTURE DATA." *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences IV-4-W5* (4): 49-56. doi: 10.5194/isprs-annals-IV-4-W5-49-2017.
- "BuildingSMART." 2019. <https://www.buildingsmart.org/>.
- BuildingSMART. 2018. *Requirement Analysis Report, IFCRoad*: BuildingSMART.
- BuildingSMART. 2020. *bSI UML Model Report-Part 1 Harmonised UML Report-Introduction and Background, bSI UML Model Report*.
- Drogemuller, Robin. 2009. "Can B.I.M be civil?" *Queensland roads* (7): 47-55. <https://eprints.qut.edu.au/27991/>.
- Drogemuller, Robin, Sara Omrani, Fereshteh Banakar and Russell Kenley. 2020. "Strategy for Defining an Interoperability Layer for Linear Infrastructure." In *International Conference on Computing in Civil and Building Engineering*, edited, 362-371: Springer. doi: https://doi.org/10.1007/978-3-030-51295-8_25.
- East, Bill, Russell Kenley and Toby Harfield. 2015. "CONie: lessons to be learned from COBie specifications and standards." *Project 2.33 New Project Management Structures Briefing Paper. Sustainable Built Environment National Research Centre (SBEnc)*. <https://sbenrc.com.au/app/uploads/2018/06/SBEnc-2.33-New-Management-Structures-Briefing-PaperFINAL.pdf>.
- East, E William. 2007. *Construction operations building information exchange (COBie)*: ENGINEER RESEARCH AND DEVELOPMENT CENTER CHAMPAIGN IL CONSTRUCTION <https://apps.dtic.mil/dtic/tr/fulltext/u2/a491899.pdf>.
- Godø, Vilde Hushovd, Darijus Strasunskas and Asgeir Tomasgard. 2010. "On Valuing Advanced Technologies in Greenfield Projects." In *Business Information Systems Workshops, Berlin, Heidelberg*, edited by Witold Abramowicz, Robert Tolksdorf and Krzysztof Węcel, 25-28: Springer Berlin Heidelberg.
- Hampson, Keith, Jun Wang, Robin Drogemuller, Peng Wu, Sara Omrani and Ammar Shemery. 2018. *Digital Asset Information Management (DAIM): Case studies (Final Case Studies Report, Project 2.51)*. Australia: Sustainable Built Environment National Research Centre (SBEnc). <https://eprints.qut.edu.au/132029/>.
- Infrastructure Australia. 2020. *Infrastructure Priority List*. <https://www.infrastructureaustralia.gov.au/sites/default/files/2020-02/2020%20Infrastructure%20Priority%20List%20HI%20resolution.pdf>.
- ISO. 2014. *BS ISO 55000:2014: Asset management. Overview, principles and terminology*: British Standards Institute.
- Kelly, Anthony. 2020. *Road and Bridge Construction in Australia, AU INDUSTRY (ANZSIC) REPORT*. <https://my.ibisworld.com/download/au/en/industry/313/1/0/pdf>.
- Kenley, Russell, Robin Drogemuller, Geoff West, Christopher Heywood, Bill East and Toby Harfield. 2015. "CONie: Open Standards design for improved road network information exchange ". Australia.
- Kenley, Russell, Toby Harfield and Ali Behnam. 2016. "BIM Interoperability Limitations: Australian and Malaysian Rail Projects". Les Ulis: EDP Sciences.
- Lee, J, W Jeong, V Faghihi and J Kang. 2013. "Automatic Generation of COBIE Data from Revit." In *The 30th International Symposium on Automation and Robotics in Construction*, edited.

- Love, Peter E. D., Ian Simpson, Andrew Hill and Craig Standing. 2013. "From justification to evaluation: Building information modeling for asset owners." *Automation in Construction* 35: 208-216. doi: <https://doi.org/10.1016/j.autcon.2013.05.008>.
- Love, Peter, Jane Matthews and Steve Lockley. 2015. "BIM for Built Asset Management." *Built Environment Project and Asset Management* 5 (3). Accessed 2020/02/11. doi: 10.1108/BEPAM-12-2014-0062.
- Love, Peter, Jane Matthews, Ian Simpson, Andrew Hill and Oluwole Olatunji. 2014. "A benefits realization management building information modeling framework for asset owners." *Automation in Construction* 37: 1-10. doi: <https://doi.org/10.1016/j.autcon.2013.09.007>.
- Martin, Steve. 2011. "The Use of BIM in Asset Management." *Area Development Site and Facility Planning* 46 (6): 10.
- MRWA. 2021. "Main Roads Western Australia." <https://www.mainroads.wa.gov.au/>.
- New Zealand Ministry of Transport. 2019. *The New Zealand Transport Evidence Base Strategy*. <https://www.transport.govt.nz/mot-resources/transport-knowledge-hub/>.
- Nezamian, Abe. 2018. "Smart asset management for critical urban infrastructure " Accessed 26 OCT. <https://www.aurecongroup.com/thinking/thinking-papers/smart-asset-management-urban-infrastructure>.
- NIBS. 2012. "National building information modeling standard". Washington D.C.: NIBS (National Building Information Science)
- Niestroj, M. G., D. A. McMeekin and P. Helmholtz. 2018. "OVERVIEW OF STANDARDS TOWARDS ROAD ASSET INFORMATION EXCHANGE." *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* XLII-4: 443-450. doi: 10.5194/isprs-archives-XLII-4-443-2018.
- Perumpilly, R., R. Kenley and T. Harfield. 2019. "CONie is not COBie: information exchange differences between network and building handover to asset management." *IOP Conference Series: Materials Science and Engineering* 512: 012041. doi: 10.1088/1757-899x/512/1/012041.
- RMS-NSW. 2021. "Transport for New South Wales, Road and Maritime." <https://www.rms.nsw.gov.au/>.
- Smith, Dana K and Michael Tardif. 2009. *Building information modeling: a strategic implementation guide for architects, engineers, constructors, and real estate asset managers*: John Wiley & Sons.
- TMR-QLD. 2021. "Department of Transport and Main Roads Queensland ". <https://www.tmr.qld.gov.au/>.
- Vicroads. 2021a. "Road management plan." <https://www.vicroads.vic.gov.au/about-vicroads/acts-and-regulations/road-management-plan>.
- Vicroads. 2021b. "Victoria Road Authority ". <https://www.vicroads.vic.gov.au/>.
- WAKA KOTAHI - New Zealand transport agency. 2020. "Transport data and tools." Accessed 12 Aug. Last modified 28 Feb 2020. <https://www.nzta.govt.nz/planning-and-investment/learning-and-resources/transport-data/data-and-tools/>.

Development of BIM-Enabled Asset Management Planning Model: Using an Integrated Knowledge Complexity-Maturity Concept

John Jiang*, Theunis. F.P. Henning, Yang Zou

The University of Auckland.

**Corresponding author: johnj@hdc.govt.nz*

Abstract

Local governments in New Zealand manage a great number of community buildings and facilities that are important assets to community's wellbeing. As the asset owner, local governments are responsible for the upkeep of these assets through operation, maintenance, and renewal activities, of which the complex processes require a systemic management approach supported by the standardised decision-making frameworks and structured planning tools. The current studies indicate that such frameworks are lacking and the available tools are limited. Although the Knowledge Management Maturity model (KMM) is one of the scarce tools used in the management practice, However, the lack of complexity considerations has been identified as the key limitation in its applications.

This study intends to integrate both the complexity and maturity aspects of the planning process and develop a fit-for-purpose planning framework based on the building information modelling (BIM) technology. In addition to the state-of-the-art review, this study adopted the method of case study based on a real BIM implementation project carried out by a local council. The case study demonstrates a step-by-step process for the development of a novel planning framework by integrating the well-established IDEF0 and KMM concepts.

BIM has the great potential to support asset management practices through BIM-based asset repository, the baseline model for asset's Lifecycle planning, and BIM being an analysis tool in asset management decision-making. This research provides a BIM-based tool for asset's long-term planning that is currently lacking in the local government asset management sector. The contributes of this study also include the creation of a BIM-enabled baseline model, which sets the foundation for developing more advanced processes to address various long-term decision-making scenarios, such as planning for climate change resilience in a more complex and uncertain built environment.

Keywords

Asset Management Planning, BIM, IDEF0, Local Government, Knowledge Management Maturity.

Introduction

Local governments and other public entities worldwide play an important role in taking stewardship and custodianship responsibilities of public infrastructure assets that are fundamental to the local economy (OAG 2017). Their responsibilities have also been reinforced further to promote the local communities' well-being beyond the economic aspect by satisfying social, environmental and cultural requirements. Collectively, local governments in New Zealand owned \$123.4 billion worth of the built assets and had an annual operating expenditure of \$10.3 billion in 2018 alone (DIA 2021). Among those assets, the public building and community facility sector accounted for 9% of the total capital expenditure (Stats NZ 2018). The public buildings and community facilities, defined as the “social infrastructure”, form part of the ecosystem of the overall construction industry. As the largest industry in the world, the construction sector constituted 13% of the global GDP (Manyika et al. 2017). Meanwhile, building and construction activities are responsible for 39% of all carbon emissions globally (WorldGBC 2019, UNEP 2018). In New Zealand, it has been estimated that buildings are directly and indirectly responsible for up to 20% of the nation's greenhouse gas emissions (NZGBC 2019).

Consequently, the local government sector faces great challenges both at present and in the future. It not only requires continuous investments in the ageing infrastructure that requires consistent maintenance, refurbishments, and rehabilitation, as well as the replacement of the existing infrastructure coming to the end of its useful life (Edirisinghe et al. 2012, NZPC 2018), but it also presents the unprecedented challenges in the next 50 years to face the major issues such as: the growing demand in new infrastructure, technology obsolescence, compound with climate change effects and extreme events (e.g., natural disasters, pandemics, and global recessions) (MLG 2021). Hence, to confront the great challenges ahead, local governments are obligated to adopt a systematic, structured, agile, and resilient approach with the primary focus on the long-term asset lifecycle management and overall assets' sustained performance, rather than focusing on the short-term and day-to-day operational activities.

In recent years, the concept of asset management (AM), including its principles and practices, has been gradually adopted in managing local governments' infrastructure assets. These principles and practices have gained credibility worldwide in recent years and AM is now a professional discipline in its own right (Lloyd et al. 2019).

Benefiting from the local government reform back in the 1980s (Wallis and Dollery 2000), local governments in New Zealand have systemically implemented various asset management systems to support their planning and decision-making. The development and implementation of international standards such as ISO 55000 series provide asset management professionals with the guidance to adopt a long-term management approach via a whole-life-cost and lifecycle management principle (ISO 2014).

Despite the great efforts put into developing standards and best practice guidelines, the majority of local governments' planning and decision-making practices still focus on the short to medium term. Long-term planning that deals with the consistent social, economic, and environmental changes the community faces is lacking (OAG 2017). In addition, the lack of well-developed decision-making and long-term planning tools and methods also greatly attributes to the longevity of the built assets, sophisticated asset systems, and the complexity of managing the various activities (IPWEA 2015).

Even though the current industry standards such as (ISO 2014) and guidelines such as (IPWEA 2015), have defined “what” an organisation should do in order to achieve and align asset management with the organisational objectives; however, in terms of “how” to achieve these objectives is not well-defined in these standards or guidelines (Ruitenburg et al. 2017). Consequently, a critical part of the asset management methodology that supports asset managers in the development of a systematic and fit-for-purpose planning framework is missing from the current practices. Given that the levels of capability for service delivery within the local government sector vary depending on the governance area size, population, resource, and organisational structure, the demand for a flexible and fit-for-purpose planning framework that can meet the different needs has drawn interests from both the industry and academia and a number of practical planning processes have been created using a step-by-step development approach. For example, IPWEA (2016) provides a six-step guideline for the preparation of long-term asset plans especially designed for public buildings and properties. Web-based asset management training programmes such as AMPLE (Howard 2008) and SIMPLE (Sneesby et al. 2012) are designed and used by infrastructure operators, including railway, roads, and water supply management in the local governments of South Africa, Australia, and the United States. Working with large infrastructure service providers such as Scottish Water and Transport for London (TFL), Woodhouse (2014) developed asset management planning guidelines to help asset owners and service providers make the right investment decisions through the SALVO process (Thomson 2012, Woodhouse 2014).

Despite numerous processes, models, and tools have been developed during the years, none of the aforementioned planning frameworks or methods have been widely adopted by industry due to various factors particularly the complexity of the asset management functions. Moreover, there is no indication that the current practice has utilised the opportunities offered by industry digitalisation and the emerging technology such as Building Information Modelling (BIM) or Digital Twins (DT).

The advent of digital technology has dramatically changed routines and practices in most areas of human work. Advocates of BIM technology in the engineering and construction industry often envisage similar dramatic changes in the design, construction, and management processes of buildings and other physical assets (Solas 2016), therefore it is not a question of “if”, but rather “when” and “how” to adopt and implement BIM in asset management practices. yet, despite the huge potential, the slow and low adopting rate in comparison with others such as automotive and aerospace industries (Manyika et al. 2017) has made the construction industry

one of the least digitalised industries globally. In fact, BIM use in asset management practices is even rarer and an integrated planning model with BIM is absent from both the industry practices and research.

The lack of asset management planning methodologies and the absence of BIM use in the long-term asset planning has fostered this study. One of the objectives of this paper is to develop a theoretical design framework using an enhanced knowledge management maturity model KMM, the Incrementally Elevated Complexity and Maturity model (IECM), and integrating with the Integration Definition for Function (IDEF0) method (KBSI 2021), one of the most commonly used modelling methodologies in business process, to support the development and validation of the proposed BIM applications in asset management planning process. The reason why an enhanced KMM model is needed is because: although the KMM model is widely used in improving management performance, however the authors argue that considering the maturity alone does not reflect the complex nature of public assets such as the community buildings, nor does it address the various levels of capability of management delivery, hence the IECM model. The second objective of this study is to explore the feasibility of a computerised/automated approach for asset management planning by examining and realising the potential of BIM in asset management, in order to support the creation and improvement of the bespoke asset planning process to meet the various requirements from local governments.

As the result, the key contributions of the study are threefold. Firstly, it presents a novel development framework for planning long-term lifecycle interventions (e.g., renewals, upgrades, replacement, and asset disposal), by taking a holistic approach to integrate the standard DIEF0 modelling and an enhanced knowledge complexity and maturity concept; Secondly, it further proposes a BIM-based baseline asset planning model as the core piece of the framework that can be evolved through an incremental, step-by-step planning process in order to accommodate asset owner's various planning capabilities. Finally, the study examines BIM as an emerging digital technology, its applications in the overall development process by demonstrating how BIM use can be transformed from a project delivery focused to a service delivery perspective. More importantly the study not only provides a novel model and concept that can be adopted in the construction industry, but also it provides a methodology and learning pathway in the knowledge domain of the built asset management that is currently lacking in the higher education sector.

This is a phased research project where Phase one is the development of an BIM-enabled asset management planning framework and the baseline model, and Phase two study involves the more advanced uses of the framework and advanced models to examine the different planning scenarios in a more complex and uncertain decision-making environment. Phase one is the focus of this study and is organised in the following sections.

Literature Review

As a professional discipline, asset management in infrastructure is not a new concept (Too 2010, Woodhouse 2003). Emerged as a branch of management applications and studies since 1990s, asset management has played an essential part in asset intensive organisations, such as local government. Infrastructure assets have a huge influence of day-to-day lives of their citizens and businesses. By providing services such as water, transport, flood protection, and waste management, local governments utilise infrastructure assets to enable the local communities to function effectively, as well as to support their wellbeing (NZPC 2018); therefore, it is important that these services are delivered effectively, efficiently, and affordably in a systematic manner to ensure value for money (Woodhouse 2019).

The Concept of Asset Management

During its evolvement, the concept of asset management has adopted various definitions to reflect its core principles, as well as its functions. For example, the international standards, such as ISO (2014), describe asset management as the coordinated activity of an organisation to realise value from assets that emphasis on the goal of value realisation through a number of management activities. IPWEA (2015), in its well-adopted International Infrastructure Management Manual (IIMM), defines the purpose of asset management as providing a desired level of service through the management of assets in the most cost-effective manner for present and future. Thus, asset management is about the long-term sustainability of assets and the services they support. It further suggests that local government must have the required knowledge to choose the right projects at the right time for the right reasons in order to perform complex management tasks where a good methodology, data, and analytical systems are required (IPWEA 2020).

The complexity of asset management is also unveiled in the definitions of its multi-disciplinary nature. Asset management is integral to strategic, operational, service, and financial planning (Too 2010). It brings together multiple disciplines, including engineering, financial planning, economic and demographic planning, corporate and strategic planning, performance monitoring and management, risk management and lifelines planning, and political decision-making and leadership, as summarised in (OAG 2017).

Asset management's lifecycle aspect is no doubt one of the most fundamental principles that are widely recognised in asset management practice and literature. Together with the aspect of long-term strategic planning function, the two aspects have been discussed in numerous studies (Lloyd et al. 2019, Woodhouse 2003, Vanier 2001, Ruitenburg et al. 2017, Too 2010), best practices (e.g., IIMM, AMBoK, and Asset Management – an Anatomy (IAM 2015)), and industry standards (e.g., PAS 55 and ISO55000 series).

While developing asset lifecycle plans for the largest Dutch energy network operator, Ruitenburg et al. (2017) highlighted the concept of asset management as a multidisciplinary

practice, where technical and financial, as well as environmental and social perspectives, are all important factors in the planning process. Data collection and analysis, planning and scheduling, operational excellence, rules and regulations, IT, human resources, and innovation activities should also be considered when developing the asset management framework. However, despite the important thinking of a multiple view of asset management, the researcher argues that the current practices are limited to the technical or the financial factors.

Asset Management Functions and Principles

In terms of the asset management function of long-term strategic planning, asset managers are required to take a proactive management approach instead of being reactive (Too 2010). They should be capable of forecasting and making forward asset plans that align them with the organisation's long-term goals and business objectives. However, Too argues that the current practice is short of strategic approach, where asset operational related activities, such as maintenance and operations, emphasis on the application of asset management concept. This observation is support by Pathirana et al. (2018) who, makes the point that traditional asset management is designed for maintaining the status quo of service levels in a resource-restricted, sometimes risk-increasing environment. Accordingly, rather than treating asset management from the holistic and strategic perspective to support long-term asset needs, the principle of asset management in the current practice focuses on making decisions to maintain the level of service with limited resources in a consistently changing environment (Pathirana et al. 2018). Meanwhile, governments and their agencies including local government, are facing great challenges in the upkeep of infrastructure assets in the next 50 years (DIA 2021), from the ageing infrastructure, growing population, to climate change resilience and extreme weather events that have long-term and uncertain impacts on the existing assets. In other words, the normal operation and maintenance activities cannot cope with the asset requirements triggered by the said challenges. Indeed, Woodhouse (2003) points out that although maintenance plays an important role, it is however really only one of the variables in managing assets by performing short-term trading against long-term sustainability and operations that respond to the organisation's strategic management decisions. In fact, the current practice shows that there are few frameworks or tools available to guide asset managers to make those decisions (Ruitenburg and Braaksma 2017). Consequently, a systematic, structured, agile, and resilience approach to managing these assets effectively and efficiently through a strategic and systematic analysing and planning process, is required.

The strategic and long-term view of asset management is also reiterated in the definition (Too 2010) (p37) that: asset management

“... is a strategic and systematic process of optimising decision-making in resources allocation with the goal of achieving planned alignment of an infrastructure asset with corporate goals throughout its lifecycle”

Thus, it is essential that effective asset management planning includes management and planning for the cycle of activities associated with the various stages of an asset's lifecycle, i.e. planning, creating, operating, maintaining, replacing, rehabilitating, and disposing assets, of which the concept is not only being widely adopted in the standards (e.g., ISO 55000s) and industry best practices (e.g., IIMM), but it also is the least arguable principle in the practice with numerous literatures published in this area.

Asset Management Planning and Process

The asset management as a business process aspect is reinforced by Sun et al. (2012), who states that different businesses have common characteristics in asset management focusing on the physical assets, which are dynamic over a long time span, generally hierarchically structured and closely related to decision support processes using a diversity of information and data. Numerous planning processes and models have been created by either the industry or academia and can be categorised in three sectors, they are: asset management institutions, industry practitioners, and the academic researchers. Table 1 presents an overview of the selected planning processes and methods provided by these sectors. For example, IPWEA (2016) provides a six-step guideline to help asset managers to prepare asset long-term plans especially designed for public buildings and properties. Also focused on public buildings and community facilities, NAMS (2014) uses a seven-step process to demonstrate asset management principles and functions that asset managers should understand and follow in order to carry out the structured and systematic asset planning. As a property asset management manual, NAMS also provides the basic data collection and information structure including attributes and survey form at an asset component level.

In the industry sector, while working with the railway industry and local governments in Australia and South Africa, Howard (2008) developed a web-based asset management knowledge tool, the Asset Management Program Learning Environment (AMPLE), that provides process and guidelines for developing asset management plan using a step-by-step approach. The AMPLE that can be implemented over several years from basic up to advanced levels. More recently, AMPLE was released by the Water Environment Research Foundation (WERF) in the United States and rebranded as Sustainable Infrastructure Management Program Learning Environment (SIMPLE) (Sneesby et al., 2012). In the meantime, partnering with large infrastructure service providers, such as Scottish Water and Transport for London (TFL), the SALVO project (Thomson 2012, Woodhouse 2014) addresses the existing infrastructure assets and helps asset owners make the right investment decisions. Using a five-step decision-making process. SALVO provides the guide and method to support asset management interventions by identifying and evaluating asset life extension options and optimal renewal timings about what to do, and when, based on the limited data or uncertain assumptions (Woodhouse 2019).

In the academic arena, scholars have sought to develop the planning tools using multi-staged methodologies. For example, Vanier (2001) presented an asset management plan development

process in the form of a six-question response. The six questions constitute of “What do you own? What is it worth? What is its condition? What is the remaining service life? What is the differed maintenance, and what do you fix first?” Vanier’s study concludes that the planning tools should focus on the need for a central data repository, lifecycle analysis, long-term service life prediction, and the enhancement and standardization of planning tools. Vainer acknowledges that few tools actually exist to support the planning using comprehensive solutions.

In a similar vein, Edirisinghe et al. (2012) presents a planning process using six specific planning elements, which also represent various stages of the planning process that help asset managers assess long-term management performance, as well as develop long-term asset management plan for local councils to manage their public buildings and community facility assets. The six elements to be developed for the process include infrastructure system and elements hierarchy, condition rating method, data collection method, deterioration prediction method, cost forecasting, and decision making. Upon realising the short-term nature of the current asset management practices, Ruitenburg et al. (2017) developed a twelve-step asset management plan (AMP) development process to take into consideration the five main lifetime impacts that influence decision-making. The five lifetime impacts have been identified as technical, economic, compliance, commercial, and the organisational perspective (TECCO).

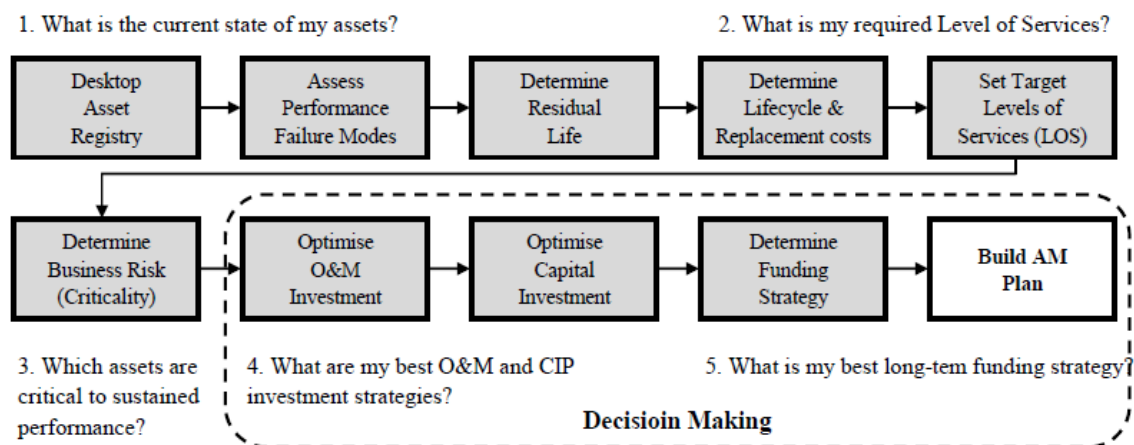


Figure 1. Five core questions and ten steps of planning development (Sneesby et al. 2012)

While the majority of the planning processes reviewed in this study demonstrate a commonly adopted development approach, which is featured with a linear, sequential, and step-by-step “waterfall” path. A typical example is presented in Figure 1. Other researchers such as Too (2010) uses a cyclical planning approach based on asset’s key lifecycle phases i.e. asset planning, creation, and operation supported by a number of core activities, for example, capacity management and options evaluation processes at the asset planning phase, where asset information and knowledge management play a central role to support all other processes during the planning. Although sequential in nature, Too’s planning framework demonstrates

the flexibility, with which the development of planning process can be accomplished in many different configurations through linking different planning elements and activities.

Review Summary

In summary, the state-of-the-art review has unveiled that the core practice of asset management planning is about strategically aligning with an organisation's long-term objectives, effectively dealing with the complex challenges due to the multi-disciplinary, multi-stakeholders focused, and multi-staged process nature. Most importantly, it requires to take a whole-life cycle management approach. As one of the fundamental principles, the lifecycle management approach is commonly adopted in asset management practices and widely studied in literature. Consequently, it is essential to plan for the cycle of activities associated with asset planning, creating, operating, maintaining, replacing, rehabilitating, and disposing. The outcome of the asset planning therefore must result in one or more of these activities in various stages of the asset lifecycle.

By emphasising on the current asset management planning processes, the review helps to identify the key elements and steps required in developing and advancing the planning process, as well as the gaps that need to improve or require future studies in asset management practices. These review findings are summarised in the following.

Firstly, it is not an overstatement to suggest that data and asset information are crucial, and the creation of an asset repository (e.g., asset register) that contains critical asset information describing the assets, their values, cost for replacement, and asset conditions is the first step of developing the planning framework and processes. However, the current studies are short of discussions on how data and database lifecycle relate to data collection, storage, uses, disposal, as well as data structure, format, or the level of detail that form the important part of information input for analysis and decision-making, hence there is a lack of data management framework that represents the requirements of asset data and information in the various stage of asset lifecycle.

Secondly, in order to sustain public assets in a long-term perspective, the driving force for managing changes through asset interventions needs to be thoroughly explored to identify the influence factors that may have impacts on management's design-making and planning for intervention. The decision influence factors can be the internal factors determined by the operation environment, asset physical conditions, natural deteriorations,

Table 1 Overview of the selected asset management planning processes and methods

	Scope and objective	Asset type	AM Principle addressed	Number of steps	Analysis	Framework
(IPWEA 2016)	Guideline of principles to carry out asset management activities for asset and financial planning	Public buildings and Properties	Service lead asset planning (LoS) Lifecycle planning for sustainability Information Management strategy Risk based predictive modelling Long term financial planning Continuous improvement	Seven	Condition assessment based Estimate of remaining useful life Risk analysis	Linear sequential Asset management plan Maturity levels of core and advanced
(NAMS 2014)	Guide to the management of property assets. It consists of a manual, interactive website and the demonstration asset planning system.	Public buildings and Properties	Asset Data and Information, lifecycle consideration development solutions, making decisions Optimised decision making, levels of service risk management financial forecasts Deliver Outcomes	Seven	Condition assessment based Estimate of remaining useful life Risk analysis	Linear sequential Asset management plan Baseline data structure, attributes, and survey form
(Vanier 2001)	A retrospective overview of asset management in the construction industry. Emphasis is placed on assessing decision-support tools for municipal infrastructure planning.	Review study Municipal infrastructure portfolios	Central data repository Lifecycle analysis Long-term service life prediction Shared experience and best practices Enhancement and standardization of planning tools	Six	Maintenance and Renewal based No external factors discussed	Linear sequential strategic asset management decision-support tools
(Sneesby et al. 2012, GHD 2021)	Asset Management improvement programs by tailoring the approach to suit their individual organisation, rather than trying to make one model fit all	Railway infrastructure, Water service, local government	Lifecycle Process and Practices Asset Information support system Data and Knowledge Service Delivery Organisational Issues People Issues Total AMP	Ten	Multiple analysis tools Capital Renewal Decision Making Benefit Cost Analysis Business Case Analysis SAM GAP - Gap analysis tool	Linear sequential Asset management best practices Education programme

(Woodhouse 2014)	Process for Strategic Asset Lifecycle Value Optimization (SALVO) Lifecycle decision-making in asset replacement, maintenance, modifications, refurbishments and disposals.	Municipal infrastructure portfolios Large industrial and equipment assets	Optimal combinations of costs, risks, performance and sustainability Integrated optimisation of an asset's lifecycle Total activity programme coordination and delivery of multiple activities across multiple assets	Five	Risk and whole life cost-based Root Cause Analysis (RCA) FMEA/RCM and RBI techniques	Linear sequential Asset management best practices Learning programme
(Edirisinghe et al. 2012)	Whole of life infrastructure management process for efficient building management of community building asset in Australia, to address the aspects of assessing long term performance and developing long term management strategies	Community buildings in Australia. Six local councils used as case studies	The analysis of the current practices against the whole of life building management process led to identification of gaps to be filled.	Six	Performance gap analysis Condition Rating method Deterioration Prediction method Age, material, exposure condition, and type of use Demand, risk, sustainability, social, stakeholder needs analysis	Linear sequential Asset management best practices Existing assets focused
(Ruitenburg and Braaksma 2017)	Asset multidisciplinary and strategic practice focused lifecycle management planning Considering lifetime impacts that influence decision-making	Case study of network asset management	Multi-disciplinary practice Strategic management objectives Lifecycle management Risk and relevant regimes Allocation of resources Lifetime impacts - five perspectives	Twelve	TECCO impact analysis Performance gap analysis External impact factor focused Expert session to identify the impact factors	Linear sequential Asset management plan
(Too 2010)	A lifecycle process-based strategic planning framework grouped into four planning clusters supported by the core of Information management	Case studies to three different types of infrastructure, i.e. Rail, airport, and sea port.	Asset management is a process Alignment of assets with objectives Trade-off among asset performance (LoS), cost and risk exposure. An evidence-base decision making requires Quality asset data and information. Analytical methods and information alignment and integration Lifecycle costing	Five	Multiple criteria analysis similar to PESTEL Rule based Risk based	Circular, flexible, non-linear framework Standalone management element clusters design process strategic infrastructure asset management

normal wear and tear, and the frequency of use. The impact factors can also come from the surrounding built environment that contains the external impact factors such as political, economic, social, technological, environmental, and legal aspects (PESTEL) as described by Pan et al. (2019), or the technical, economic, compliance, commercial, and organisational perspectives (TECCO) as identified by (Ruitenburg et al. 2017). In either cases, the current practices do not intend to explicitly differentiate these factors without realising the

different complexity or degree of their impacts that may influence the process activities by failing to acknowledge that, organisations have the various capability to control and balance asset performance, costs, and risks (IPWEA 2015). In other words, to deliver the right level of service requires the right level of interventions, using the right tools with the right asset information.

Thirdly, asset management planning is a complex task that requires different level of analysing of raw data, asset utilisation, functionality, future demand, risks, as well as forecasting of scope, timing, and costs of management interventions such as renewals, upgrades, and replacement (NAMS 2014). Effective planning links together the objectives, level of service, finances, and the capability to manage and deliver through the application of right analytical tools and analysis methods. Different organisations may require different levels of output in different stages of the asset lifecycle. This will determine what data may be required and using what tools to analyse the data, either it is a simple spreadsheet or a sophisticated mathematical model.

Fourthly, although there are attempts of adopting more agile and flexible approaches in the planning process, (e.g., Too's circular planning framework); yet, the majority of the planning processes reviewed in this study are described as linear, sequential, and step-by-step "waterfall" methods, which would not allow a new step to start until the completion of the previous step. Thus, the waterfall methods have the limitation of flexibility to accommodate the different needs or various levels of capability in asset planning.

And finally, none of the planning methods or process has indicated how emerging technology can support the planning process, although some degree of using software for data analysis is presented. The incorporation and integration of technology, in particular digital technology, are crucial in modern day asset management practice. The adoption and implementation of new technologies will dramatically enhance asset management practice, including planning efficiency and effectiveness. New technologies such as digital tools can simplify the process, or the activities that form the process, to make it more efficient, effective and affordable. In recent years, BIM has emerged as a revolutionary tool in the AEC industry. It has applications in design, construction, and the subsequential research and studies on its application in facility management. However, there is no indication that the current asset management practice has thoroughly taken into consideration BIM. Further observations from the authors indicate that a planning concept integrated with BIM has not yet been published.

Research Methodology

The strategy of this research is to adopt a real BIM implementation project as a case study to demonstrate how BIM can be used in the asset management planning process. The tools and methods used for data collection include the literature review and workshops participated by the key project stakeholders. One of the authors of this paper is the workshop organiser and project manager for overseeing the BIM implementation at the selected case study organisation.

This case study provides insight into the BIM adoption process, from the stages of project planning, execution, and close off. The planning workshop, where the project participants, including BIM consultants, facility operators, and asset managers, undertake the planning activities, plays a key role in mapping the existing business process and developing information requirements. The review workshop, which is conducted by the asset owner and the independent BIM specialists before project handover, carries out a post-project evaluation to review and validate the project deliverables. The data collected from workshop discussions, project observations, and post-project reviews provide the required information to support process analysis, framework design, and model validation of this research. In addition, the research design employs two existing theories, namely, the Integration Definition for Function (IDEF0) method and the Knowledge Management Maturity model (KMM), as the theoretical framework to support the development of the Incrementally Elevated Complexity-Maturity model (IECM) for the proposed planning framework.

Research Theoretical Framework

Integration Definition for Function (IDEF0)

IDEF0 is a graphical language designed to model the decisions, actions, and activities of an organisation or system (Waissi et al. 2015, KBSI 2021). It represents each process of a planning or decision-making activity as a box with four arrows as shown in Figure 2. The model is flexible as each of the four arrows can be replaced with various elements that can also contain sub-element for different processing purposes. For example, the elements are described as inputs, outputs, analysis, and controls in this study. The graphical figures make the concept easy to understand, modify, and use. Furthermore, the model is scalable, adaptable, and can be extended to any depth of detail in varying situations and conditions, of which the flexibility ensures the model is easily interoperable with other systems such as the KMM model described in the following section. The final design of the proposed BIM-enabled planning process is presented in Figure 3.

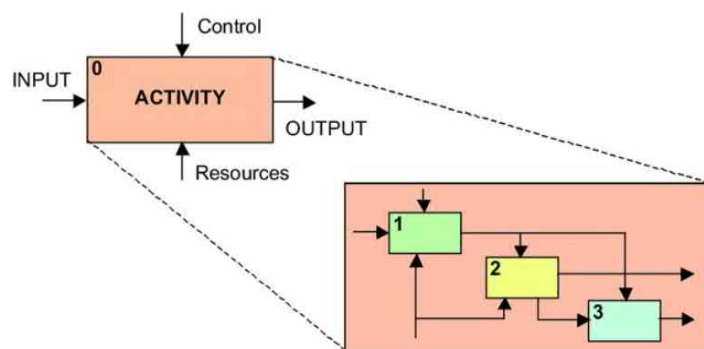


Figure 2. Integration Definition for Function Modelling (IDEF0) (Gonzalez-Prida et al. 2012)

Since it was first introduced in 1993 (Sun et al. 2012), IDEF0 has been used for modelling the decisions, actions, and activities of an organization or system using step-by-step procedures provided for modelling, review, and integration tasks and activities (KBSI 2021). While recognising IDEF0 as one of the commonly used business process modelling methodologies, Sun et al. (2012) reveal the special requirements of modelling by focusing on asset operation decision-making process. Furthermore, Waissi et al. (2015) suggest that the IDEF0 modelling methodology is well suited for the purpose of strategic plan development in addition to

operational and strategic management. For example, Gonzalez-Prida et al. (2012) apply IDEF0 modelling to a strategic management of product warranty taken from the product lifecycle perspective. Waissi et al. (2015) present a proof-of-concept by applying the IDEF0 method in strategy modelling and for the automation of strategic plan development implemented within the small and medium manufacturing enterprises (SME). The standardized, well-defined, well-structured, and easy to understand, modify and use features can be extended to any depth of detail. Also benefiting from its flexibility, scalability, and adaptability to varying situations and conditions, this study uses IDEF0 for the development of the proposed BIM-based asset long-term planning process.

As discussed previously in the review, asset planning is an integrated process that transforms inputs into outputs. The planning process will be a controlled process that is subject to the organisation's objectives, strategies, policies, as well as the impact of internal factors such as physical deteriorations and change of use, and external influences such as the factors described in the PESTEL (e.g., technology obsolescence and climate change) (Nippala 2013). While not all plannings require the sophisticated analysis, given that asset management is a complex system compounded with all the internal and external impact factors, analytic tools may have to be employed particularly in situations where future uncertainty is unknown and forecasting in a long-term range is complicated, thus a fit-for-purpose analytic tool have to be used to support planning and predications.

Asset management is also a lifecycle management process. The output of the planning process therefore leads to a number of "hierarchies of care" in the form of maintenance and repairs (status quo), like-for-like renewals, upgrades that may include refurbishment, renovations, extensions, and retrofits, replacement, and finally disposal, where the decision-making process/tools are applied to further transform outputs into outcomes.

It is noteworthy to mention that IDEF0 modelling should not be a static process or one-stop-fit-all function. Rather it should be dynamic and continuedly evolving and maturing, thus a knowledge maturity model is integrated in this study to form the theoretical framework.

1.1.1 Knowledge Management Maturity Model (KMM)

Organisations are constantly seeking performance improvements through new technologies, processes, and tools (Wettstein and Kueng 2002). Knowledge Management Maturity Model (KMM) is a one of the tools that help asset managers identify performance gaps and provide guidance for improvement. A maturity model is used with various measuring levels to describe advancement paths for developing and improving business or operation process in terms of managing products or service lifecycle, i.e. initiation, acquisition, and management (Yamfashije 2017). For example, the Capability Maturity Model (CMM) and its latest version Capability Maturity Model Integration (CMMI) developed at Carnegie Mellon University are commonly used in the software development industry (Gonzalez-Prida et al. 2012, ISACA 2021, Yamfashije 2017). A typical CMM process that the five maturity levels include: Initial, Repeatable, Defined, Managed, and Optimising. The Business Process Management (BPM) process as described by vom Brocke and Sinnl (2011) also stress the technical approaches to BPM focus on the support of business processes and their design through information systems.

Asset management maturity is defined as "the extent to which the capabilities, performance and ongoing assurance of an organisation are fit-for-purpose to meet the current and future needs of its stakeholders, including the ability of an organisation to foresee and respond to its operating context." (GFMAM 2015) (p.5). In recent years a number of the maturity models

have been developed by various institutions. For example, IPWEA(2015) presents a maturity model that examines the gap between current and target or appropriate levels of asset management maturity. Defined through five maturity levels: Aware, Basic, Core, Intermediate, and Advanced, the model uses a 0~100 scoring method to assess each of the sixteen asset management sections. Best used for assessing the current management performance, the model also provides the guidance for organisations seeking to improve their performance either sectionally or organisation as a whole in association with ISO (2014). In a similar vein, the Asset Management Council has developed an assessment tool, the Asset Management Maturity Model (AMMM), that allows organisations to assess their maturity level and identify their performance gaps and strengths across a range of asset management domains (Asset Management Council 2021). The model includes a five-band maturity scale to measure the level of maturity using an online questionnaire containing 160 questions to test different aspects of the asset management systems implemented in the organisation. The scales show the organisation's asset management maturity level within the 11 asset management system elements.

Similarly, the Institute of Asset Management (IAM) in its Asset Management Maturity Scale and Guidance introduces a 6-band maturity scale, ranging from Innocence to Excellence, along with definitive attributes and symptoms, to measure 39 subject areas through gap analysis and conformance assessment against ISO 55001 (IAM 2016).

Within the industry, Lloyd et al. (2019) present an AMEM model that tests the existence, completeness, effectiveness, and integration of asset management practice using six groups and 39 activities, scored and assessed based on a range of assessment criteria and questions using a six-scale of maturity levels. In the SIMPLE model, Sneesby et al. (2012) use a scoring (e.g., % of overall asset management process and practice criteria) system to determine the competency and maturity level of asset management planning development measured by three levels of system sophistication. Level 1 represents a basic plan with a score up to 60%; level 2 with 75% scoring covers lifecycle function areas, and at 85% rated level 3 requires more advanced processes with specialist areas such as strategic planning, maintenance planning, and risk assessment (GHD 2021).

In summary, a framework should be developed objectively, transparently, and reliably. However, the current maturity models do have limitations in supporting a BIM-based process development. Firstly, these models predominantly focus on organisational management perspective and have a staged, linear, sequential, deterministic, and invariant development character (Escrivão and Luis da Silva 2019). As an example, Lloyd et al. (2019) discuss the benefits of a maturity-based approach to asset management and suggest the use of the maturity model to identify and develop capabilities and practices that are appropriate to achieve organisation's objectives, where the technical capability and performance is not adequately addressed. Secondly, even with the scoring systems being used, the assessment methods of these model can still be intuitive, subjective, and difficult to use. Thirdly, most of these models do not explicitly differentiate the outcomes in association with the complexity of inputs, nor the level of influence of those factors, such as internal changes or external impact factors as defined in PESTEL analysis. In addition, the correlations and alignments between the planning elements such as inputs, outputs, decision influence factors and the analysis are not investigated or discussed; consequently, the misalignment between these elements could result in the situation where a sophisticated management system is employed to be used for basic functions, or large quantity and overly detailed asset data were collected but have no value to the analysis

process. Therefore, an incremental, structured, and aligned development approach needs to be taken when considering a maturity model.

When Escrivão and Luis da Silva (2019) conducted their review of the maturity models, they recognised the connections of both the internal and external networks of organisation that need to be considered in assessing knowledge management to promote continuous improvement; hence, they propose a synthesised approach using four stages of knowledge management maturity levels as shown in Table 2. Accordingly, this study has adopted a similar approach by integrating the complexity measures with the KMM model to create an Incrementally Elevated Complexity-Maturity model (IECM) to be used in supporting IDEF0 model to form a theoretical framework, which will be further explored in the design of the proposed planning framework development.

Table 2. Proposed KMM stages considering the internal and external factors
(Escrivão and Luis da Silva 2019)

Stage 1 Functional Initiation	Stage 2 Functional Specialisation	Stage 3 Internal Integration	Stage 4 External Integration
Consciousness - Isolated use of tools in order to manage organisational knowledge	Formalisation - Development of infrastructure necessary to KM practice (systems, support, technology) - Strategy and planning for KM	Institutionalisation - KM embedded on organisational culture - Control, monitoring, measuring and continuous improvement of KM practices	External network - KM practices integration to the external network - Partnership

Incrementally Elevated Complexity-Maturity Model (IECM)

In order to develop a fit-for-purpose framework, this study proposed an enhanced maturity model by taking into consideration the complexity in the planning process. Taking a step-by-step approach, the enhanced maturity model is used to incrementally increase the level of complexity by adding on a layer of complex criteria each time before moving the next planning stage, to fit the purpose and meet the capability level acceptable to the stakeholders, including asset owners and regulators. Contributing to the improvement of the asset planning process through an evolutionary path, the IECM model will allow asset managers to enhance the planning capability, from scratch with unorganised or non-structured chaos toward a more mature and disciplined management approach. For that purpose, the proposed development is categorised and specifically quantified in four progressive levels, which will be demonstrated in the following case study section.

Case Study

The proposed IECM model is validated through a pilot BIM implementation project for a historical opera house complex (aka Toitoti Arts & Events Centre) built in Hastings, New Zealand. Toitoti is one of the 140 public buildings and community facilities owned by Hastings District Council, a local government representing 78,000 residents. This case study highlights the process and value of using BIM for asset management activities in the operational stage of the asset's lifecycle.

Background

Toitoti building was constructed in 1915 and has had numerous renovations and modifications over its life. With a combination of new and old building blocks, the complex has a total floor area of 5,000m² that comprising of theatre, exhibition, office, and amenity facility spaces. The BIM implementation project was driven by the owner's decision to adopt a BIM-based asset management system to support its asset's lifecycle planning. The project encompasses the process of as-built data collection, modelling and the creation of an easy-to-use interface that brings together all the built asset information, including static data such as drawings, documents, asset data, as well as geospatial information. Figure 3 illustrates a sample floor plan and the interior image of the theatre.

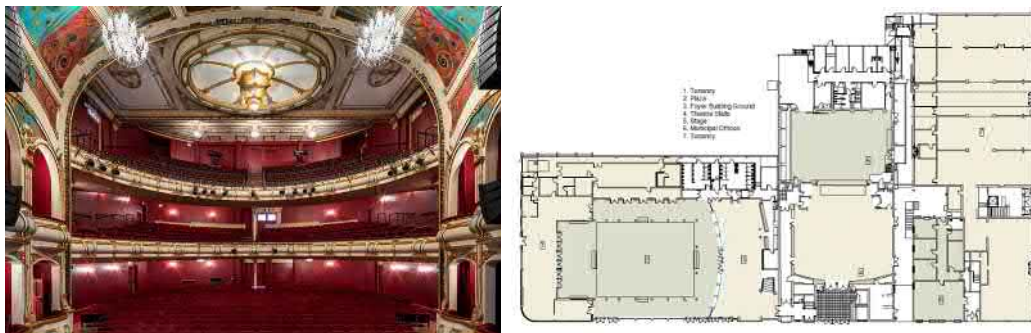


Figure 3: Toitoti Arts & Events Centre (Source: Hastings District Council)

Design

The design methodology is based on the integration of IDEF0 model and the enhanced KMM method, the IECM model, as described in the previous section. The proposed framework consists of four stages; namely, Stage 0 initiation, Stage 1 Baseline model, Stage 2 moderate model, and Stage 3 the advanced model. Figure 4 reveals the elevated development process of the four stages, their features, process activities, and each process element defined in IDEF0 modelling in terms of input, analysis, control, and output. The case study demonstrates the process of the development, in particular the creation of the as-built BIM and the baseline model for the asset lifecycle planning. Each of the development stages is described in the following session.

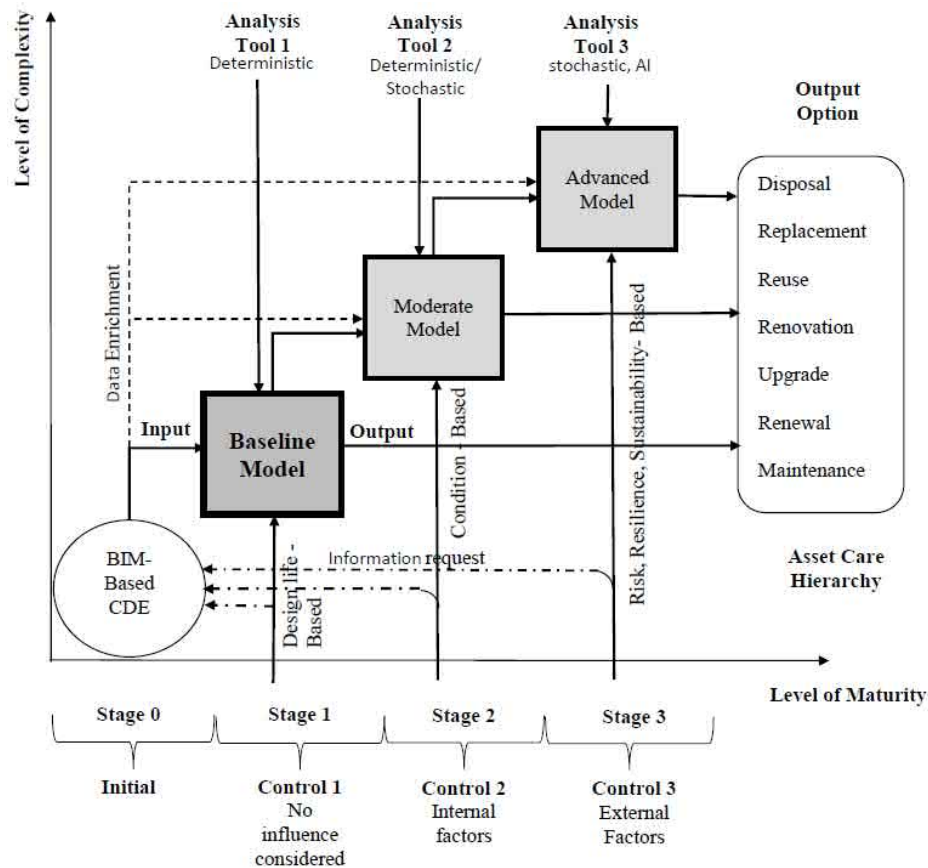


Figure 4. Proposed BIM-enabled Asset Management Planning Development Framework

Stage 0 – Initial Stage

Stage 0 is the initial stage of the planning process for the purpose of establishing a foundational asset information input for the next stages of planning. As shown in Figure 5 of the case study, a BIM-based common data environment (CDE) is made up of an as-built BIM together with data and construction documents, geographic information, building component library provided by external parties, computer added facility/maintenance systems (CAFM/CAMM), and links to external database wherever required. (e.g., the climate-related data that provides the fundamental data and asset information for various planning analysis uses).

It is noteworthy to mention that BIM is multi-dimensional and allows extra dimensions or attributes of data to be linked to a model, for example, the data and information generated from CAFM/CAMM. As more information is made available in addition to that initially obtained through construction as-builts and BIM process of on-site scanning and survey methods, the dynamic data generation process thereby provides a fuller understanding of the asset (Dowd and Marsh 2020) with the endless expansion potentials. On the other hand, the information creation should be constrained to that when it is required for decision-making (ISO 2018). In other words, the process only receives information that will be of value to its uses. It is essential to reflect that the extra dimensions or attributes should only be added if this information is needed for the purpose of processing in accordance with the stages or the modules selected for development. By using the IECM model, asset data and information can be fed into the (analysis) process via a process of data enrichment, so that data and information are aligned with the different level of detail required for analysing at each stage of the development process.

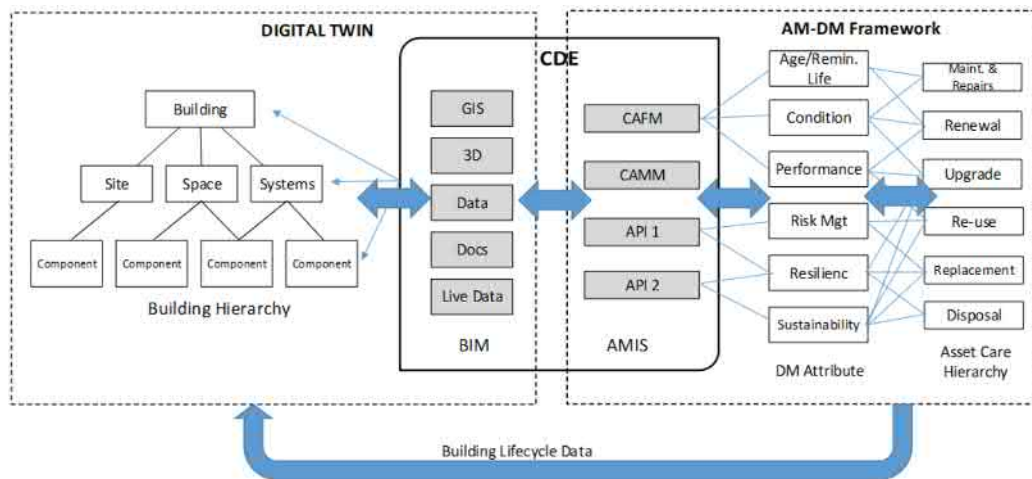


Figure 5. BIM-based Asset Repository and CDE in Case Study

In the case of creating the baseline model (Stage 1), asset data obtained from BIM based CDE created in Stage 0 can be defined with a set of basic data attribute requirements at the building component level to include, (as a minimum), component names, useful lives, construction year, replacement costs, and quantities. These basic data attributes should be defined as sufficient for the creation of a baseline model in Stage 1. While for Stage 2, asset data attributes can be further expanded to include attributes such as criticalities, condition grade, functional performance, and a predefined grading system (e.g., 1-5 or 1-10) can be used to describe the condition deteriorations and performance levels. Similarly at Stage 3, further enriched asset data may include the attributes such as CO2 emission rating, energy consumption, or supply chain IDs to support the more sophisticated impact assessment for a risk, resilience, and sustainability-based planning.

Stage 1 – Baseline Model

At Stage 1 a baseline model is created to plan the basic functional process in order to generate outputs based on the concept, theory, and general assumptions in the scenario of an ideal asset lifecycle in accordance with asset's design life. Without considering either the internal or external impact factors that influence the decision-making, this model is designed to only use the as-constructed information such as the designed or manufacturing specified useful life. Thus, the management intervention at this stage is not required, and the output of the process is deterministic, with output options such as the routine maintenance and like-for-like renewals being the outcomes. The complexity of Stage 1 is low, thus providing a starting point of planning for those with a low-level capability of planning but can still prepare a basic asset management plan with the planned costs, timing, and the scope of work that meet the minimum planning requirements, normally following the strategy of “doing the bare minimum” set by the organisation or regulatory authorities.

As indicated in the case study project, the development of the baseline model is based on the lifecycle concept and the building life indefinite theory that describes the asset as a whole is intended to be maintained indefinitely by the continuing replacement and refurbishment of its components (IPWEA 2015). In addition, various assumptions are made in designing the baseline model. For example, a set of criteria including the current asset service levels, standards, and utilisation, remain unchanged during asset lifecycle planning (VDI 1998). Then

the assumptions are made to include that 1) the system and component levels are to be renewed in accordance their designed life span. 2) The renewal activity is to be conducted in a like-for-like replacement to provide the same level of service as defined as the design specified performance, which is not to be upgraded or downgraded, and 3) The asset, its system, or its component's economic lives will remain as the designed or originally estimated and not change over the planning period, and operation and maintenance practices remain at the handover or current level. The analysis method used in asset lifecycle planning at stage 1 is an easily automated for lifecycle and predictive calculation of the remaining lives of components, where the asset age (consumption) can act as a surrogate to indicate the asset condition deteriorations rate. Figures 6 illustrates the baseline model interface developed to access and utilise BIM data for visualization and analysis, where multiple perspectives of the building and the associated underlying asset data sets (e.g., age, costs, and condition), are displayed.

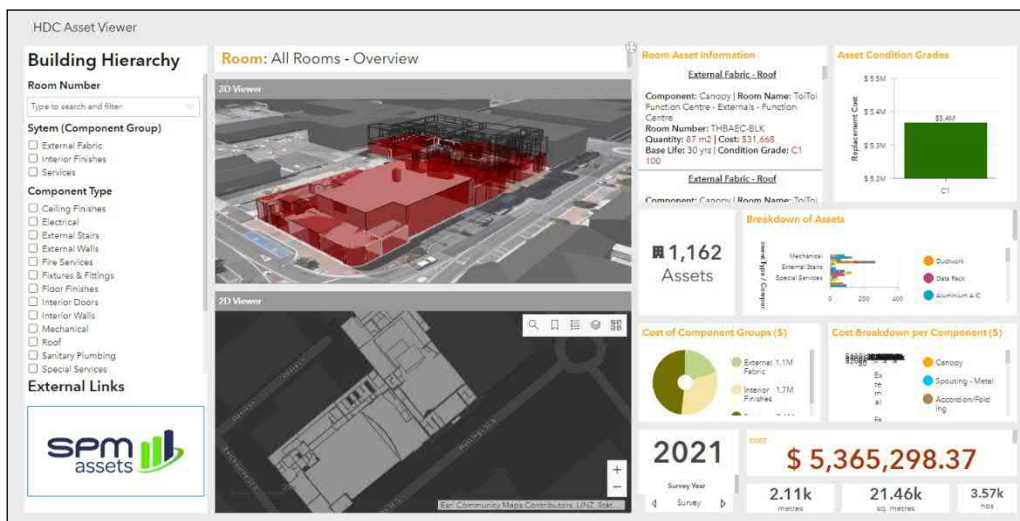


Figure 6. Baseline Model Interface and Asset Data Visualisation

Stage 2 – Moderate Model

Based on the concept of IECM, Stage 2 is created from the baseline model by adding an extra layer of complexity in planning; namely, taking the consideration of the internal influence factors that may have an impact on the assumptions as set in Stage 1. These internal impact factors can be identified as the physical condition that varies due to the actual deterioration in relation to asset location, micro climate environment, quality of built, and “wears and tears” from the different frequencies of use that vary room by room, or building by building. Unlike the Stage 1, which is more of a desktop exercise largely based on the static as-constructed information and the predefined assumptions, Stage 2 requires physical inspections, surveys, or invasive testing in order to determine the actual degree of asset components deteriorations, using a performance rating system. The rating is then translated into the information of remaining life by calculating the scale of the design life consumption. A typical deterioration curve shown in Figure 7 demonstrates the correlations of condition rating between the remaining life.

Furthermore, given the uncertainty and stochastic nature of deterioration, more sophisticated analytical methods such as Markov model (Mohseni et al. 2017), fuzzy logic (Gallab et al. 2019), neural network (Rivas et al. 2020), and genetic algorithm (Abdulwhab et al. 2004) can be used for deterioration prediction using condition data collected on site.

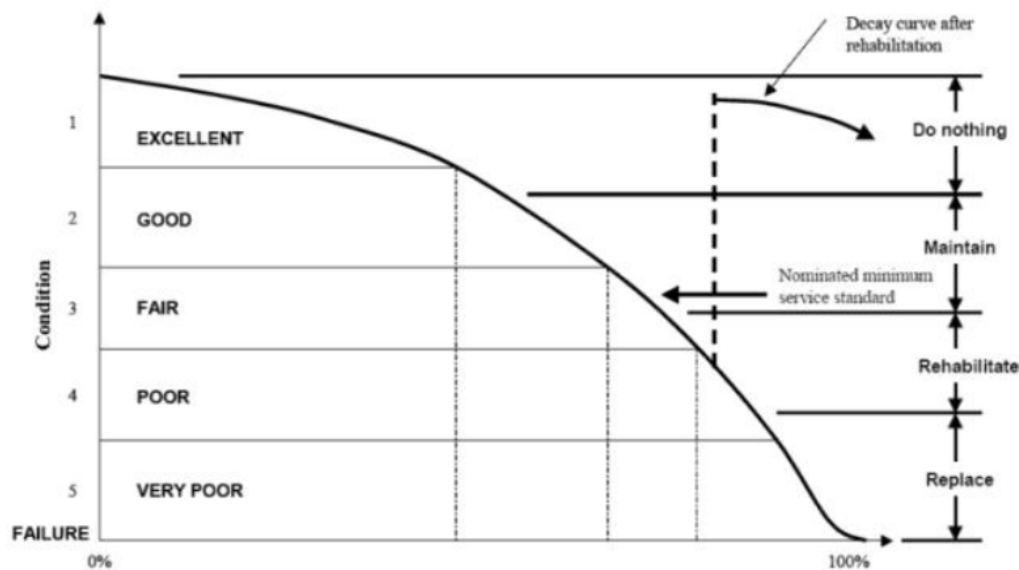


Figure 7. Asset Condition Rating and Remaining Life Correlation (Transport Infrastructure Ireland 2021)

In this stage, the management interventions will be determined by the outcome of the analysis. However, given this model is still a physical condition-based prediction method, the output of the process is reasonably deterministic (although it can become stochastic depending on the complexity of prediction methods and the level of analytical capability). As the result, the routine maintenance, like-for-like renewals, or alternative renewals may be required at this stage.

Stage 3 – Advanced Model

The proposed Stage 3 is the most advanced model that is created to deal with the future uncertainties as the result of the consistent changing built environment, by taking into consideration both the internal and external factors that influence the asset management decision-making. Given that public buildings and community facilities have long-life spans, these assets must sustain in a long-term perspective, which not only requires considering the natural physical condition run down and deterioration, but also the consistent changes from the built environment that will have great impacts on the assets in the future. Therefore, considerations must be given to the various impact factors, such as growing/declining populations, changing business directions, tightening legislation, increasing environment awareness compound with climate change effects, and extreme risk factors, such as natural disasters, pandemics, and global recessions that may change the course of asset uses, capacity, and the performance that are beyond the routine maintenance and renewals. Instead, more complex management interventions such as upgrades, retrofits, extensions, or replacement and asset disposals have to be planned in order to improve the assets' agility, flexibility, resilience, and sustainability. Therefore, a more advanced approach involves more sophisticated analytical methods, as well as the multi-analysis approach such as the PESTEL assessment. As indicated in Figure 4 of the proposed framework, this is a more complex process than the previous two

models, thus it requires more robust asset data, more sophisticated analytical tools, higher capability of resource and, most importantly, the alignment between each of the process elements, where BIM has the potential that needs to be explored in future studies.

Findings and Discussion

The adoption of asset management practice is growing, and research in this field is drawing more and more interest; yet, the empirical evidence supports that the new findings and the ground theories including concepts and methodologies development in asset planning, are still rare. Hence, this paper intends to develop and present a conceptual framework that supports the development of BIM-enabled process by utilising the existing theories and concepts such as IDEF0 and KMM as described in this study.

The state-of-the-art review in this study has unveiled that asset management is a complex business process that deals with a great number of challenges by making the evidence-based decisions and using a whole-life cycle management approach. The focus of this study is on the long-term asset planning aspects. The reason for this focus is that, to ensure assets to sustain in long-term asset managers not only have to consider the natural physical condition run downs, deteriorations (e.g., the normal wear and tear, and the frequency of use), but they also must take the consideration of the various impacts that may change the course of asset uses, capacity, and the performance, which are beyond the routine operation and maintenance activities. Instead, asset management interventions including upgrades, reuse, replacement, and sometimes asset disposals, need to be considered as options in order to enhance the assets' agility, flexibility, resilience, and sustainability by taking account of the external impact factors, such as climate change, technology obsolesce, population growth, and the extreme events (e.g., pandemic and natural disaster), where multi-criteria performance assessment methodologies, such as the PESTEL assessment, are used.

Moreover, asset managers are constantly struggling with the lack of asset knowledge due to the poor quality of asset data and information, which are inaccurate, incomplete, outdated, and difficult to access (OAG 2017, buildingSMART International 2021). Research findings further suggest that the asset information system's capacity should extend beyond using asset knowledge database predominantly as decision-making input by increasing the capability to analyse the output; however, the current government report reveals that even the former use is hardly achieved (OAG 2017). BIM, as the emerging digital technology in construction industry, has the potential to deliver a radical change in the asset management sector. Yet, the current BIM research and industry practice is piecemeal and lacks a holistic approach in its application at each step of the planning process. A view of BIM beyond the "single source of truth" philosophy, where more analytical functions of BIM use, should be explored.

This study proposed a planning framework that models the various stage of asset management maturity in a IDEF0 modelling method. The method is implemented incrementally, starting with a baseline model, which is purposely designed as low in development (LOD) based on BIM's maturity definitions. The model represents the typical community buildings that consist of a clearly defined hierarchical asset structure attached with basic asset information attributes, where more details and information can be incrementally built up and added on over time as needed. In this case, the stage 0 represents the process of creating a BIM-based CDE for information input. Overall asset data collection and CDE building is a dynamic process. In addition to the data created from the as-builts model, which is static in nature, visual inspection and more sophisticated data capture methods, such as invasive testing, remote monitoring and

smart sensor technology, will offer on-time evidence with live data for a more accurate analysis and better solutions in a dynamic fashion (e.g., live Digital Twins), since the database and details can grow endlessly through the process of enrichment. On the other hand, there is a trade-off between the level of detail and the cost, time, and sometimes practical limitations of data collection. A complex and detailed data and information structure can increase the data collection cost significantly. In the meantime, the higher level of analysis method may require highly detailed planning data, (and vice versa), and may require more advanced methods such as analytical hierarchy model, fuzzy logic, neural network and genetic algorithms that are used to solve much complex predictions. Therefore, the alignment and coordination between the data details, the level of analysis, and the capability of control of impact factors are crucial to the effectiveness of adopting the IDEF0 and the enhanced maturity model. However, the discussion of the alignments is rarely observed in asset planning research literature.

The outputs defined in the proposed planning process provide the various options for management's consideration (Ruitenburg et al. 2017, New Zealand Treasury 2017) based on the asset lifecycle interventions with a selection of various construction activities, such as maintenance and repairs, like-for-like renewals, upgrades, replacement, and even the disposals as described in the list of asset care hierarchies shown in Figure 3. It is noteworthy to mention that the planning process proposed in this study is about planning "what to do", where the actual actions for solutions (interventions) needed (e.g., either to simply renew or to upgrade), will require a decision-making process using the specific analysis tools or methods such as the multiple-criteria decision-making (MCDM) or multiple-criteria decision analysis (MCDA) methods, which are out of the scope of this research. Instead, the authors of this research adopted the concept of lifecycle intervention options to define the outputs of planning process, while the final decision(s) become the outcome of the planning process.

And finally, asset management is a complex process; it requires a balance of people, processes, and technology. The three elements must be in alignment in order to achieve the desired outcome, where the people factor plays a more important role than the other two elements. Arrow (2020) agrees and concludes that digital transformation initiatives in an organisation often fail due to overlooking the people factor. Given the rapid pace of technological development, both the employees and management can be disadvantaged due to a "data literacy gap", which creates a great barrier when implementing an efficient process using advanced digital technology such as BIM. One of the limitations of this study is that the human factor is not examined or discussed. Nevertheless, the authors recognise the crucial role people play in asset management, thus believing that the people element of the asset planning certainly warrants a fresh new chapter and requires further research.

This study is the first stage of a two-phase research project, where a baseline model is developed and reviewed in this phase. It is expected that the next phase of the project will be further experimented with applications of BIM use in asset management planning process, particularly the advanced use of BIM in a complex analysis process in more sophisticated planning scenarios, such as dealing with asset's climate change adaptation and mitigation issues.

Conclusion

Local governments worldwide are facing great challenges in efficiently and effectively managing their vast infrastructure assets for now and in the future. In addition to meeting the growing demand and enhancing the current management practice, numerous key factors

influencing local government's long-term asset management planning have been identified. These key factors include the need to replace existing built assets coming to the end of their useful life, and the adaptation of local communities and infrastructure to mitigate risks and hazards associated with climate change and the extreme natural events. Consequently, there is a need for local governments to adopt a systematic asset management approach that is comprehensive, robust, as well as flexible, standardised, and technologically advanced. However, such an approach is lacking in the current practice within the local governments due to the resource constraints and various levels of management capability. The lack of asset management planning methodologies and the fast growth of BIM use and research have fostered the need to develop a fit-for-purpose planning framework and easy-to-use planning process. Accordingly, the goal of this study is to create a BIM-based planning process that is agile, flexible, but still comprehensive to meet the various planning requirements.

Through a state-of-the-art review and the authors' observations through a case study, this research proposed a novel knowledge maturity concept by integrating the complexity measures with the existing KMM modelling to objectively reflect the complex nature of asset management as a profession. In addition, the IDEF0 model that is widely adopted in developing and improving business processes, is used in the design of the planning framework supported by BIM. The study provides solid evidence that BIM can play an important role in areas such as: establishing asset database and information source CDE platform, creating a baseline model that is scalable for multi-level planning, and ultimately becoming a tool in managing more sophisticated scenarios such as asset's climate change adaptation and mitigation. As the result, a BIM-enabled four-staged asset planning model is presented with a step-by-step development process based on the enhanced KMM model, the IECM concept. Overall, the IECM model is not only helpful for articulating a clear approach to adopting BIM in asset management planning that is novel in its applications, but it also provides the insight of complex asset management systems to develop asset managers' knowledge base through the lens of BIM knowledge domain, thereby adopting an incremental step-by-step development approach achieves the objects set out as follows:

- BIM as digital representation through data collection and the creation of an asset repository
- BIM as the baseline model that is capable for expansion for asset planning, and
- BIM as an analysis tool in managing more advanced planning scenarios

The key contributions of this study are three twofold. Firstly, it develops a process maturity concept (IECM) to support the development and improvement of the business process framework. The IECM concept helps to fill the knowledge gap in the asset management planning field that has been identified as lacking ground theories and practical industry guidelines. Secondly, it proposes a BIM-enabled planning framework with the baseline asset planning model as the core piece and sets the foundation for further development through a staged and scale up advancement process. The model is generic in nature; thus, it can be applied to various types of public infrastructure assets in any asset intensive organisation outside of the local government sector. And finally, as the first phase of the two-phase BIM application and planning research project, this study reveals the potential of BIM in asset management, in particular the long-term planning aspect. This study and the succeed phase will not only provide insight to the complexity of asset management as a profession, which helps asset managers develop their knowledge base step-by-step in both asset management planning and BIM technology; but it also sheds light on the standardising, digitalising, and automating approach

as the future of asset management planning. The methodologies created from this research will also support asset management educations, providing course materials and learning programmes, which the sector lacks.

Although the case study used in this research provides a way of concept validation, future real case applications, reviews, and other validation methods (e.g., conducting comparative research between BIM and the existing asset information systems) need to be examined, and more BIM applications in the asset management arena are suggested to be explored further.

References

- Abdulwhab, A., Billinton, R., Eldamaty, A. A. & Faried, S. O. 2004. Maintenance Scheduling Optimization Using a Genetic Algorithm (GA) with a Probabilistic Fitness Function. *Electric Power Components and Systems*, 32, 1239-1254.
- Arrow, J. 2020. *Construction Technology: Building the future in a Mirror World* [Online]. RICS. Available: <https://www.rics.org/en-za/news-insight/future-of-surveying/talent-and-skills/construction-technology-building-the-future-in-a-mirror-world/> [Accessed 10 October 2021].
- Asset Management Council. 2021. *Asset Management Maturity* [Online]. Available: <https://www.amcouncil.com.au/knowledge/asset-management-maturity.html> [Accessed 05 August 2021].
- buildingSMART International. 2021. *Liberating Built Asset Information to Achieve your Organizational Objectives* [Online]. Available: <https://www.buildingsmart.org/buildingsmart-international-publishes-asset-management-white-paper/> [Accessed 10 Oct 2021].
- Department of Internal Affairs (DIA). 2021. *Local authorities' economic contribution to New Zealand* [Online]. Available: https://www.localcouncils.govt.nz/lcip.nsf/wpg_URL/About-Local-Government-Index?OpenDocument [Accessed 29 August 2021].
- Dowd, T. & Marsh, D. 2020. The future of BIM: Digital transformation in the UK construction and infrastructure sector. Royal Institution of Chartered Surveyors (RICS).
- Edirisinghe, R., Setunge, S., Zhang, G. & Wakefield, R. Council Building Management Practices, Case Studies and Road Ahead. 2012 London. Springer London, 165-179.
- Escrivão, G. & Luis da Silva, S. 2019. Knowledge management maturity models: identification of gaps and improvement proposal. *Gestão & Produção*, 26.
- Gallab, M., Bouloiz, H., Alaoui, Y. L. & Tkouat, M. 2019. Risk Assessment of Maintenance activities using Fuzzy Logic. *Procedia Computer Science*, 148, 226-235.
- GHD. 2021. *Sustainable Infrastructure Management Program Learning Environment (SIMPLE) - Step by step approach* [Online]. Available: [https://simple.waterrf.org/Books/Contents/Getting-Started-\(2\)/Options-for-Getting-Started/Step-By-Step-Approach](https://simple.waterrf.org/Books/Contents/Getting-Started-(2)/Options-for-Getting-Started/Step-By-Step-Approach) [Accessed 09 October].
- Global Forum on Maintenance and Asset Management (GFMAM). 2015. *Asset Management Maturity: A Position Statement First Edition* [Online]. Available: https://gfmam.org/sites/default/files/2019-08/GFMAM_ASSET%20MANAGEMENT%20MATURITY_FIRST%20EDITION_ENGLISH%20VERSION.pdf [Accessed 06 June 2021].
- Gonzalez-Prida, V., Barberá, L., Gomez Fernandez, J. F. & Crespo Marquez, A. 2012. Contractual and quality aspects on warranty: Best practices for the warranty management and its maturity assessment. *International Journal of Quality & Reliability Management*, 29, 320-348.
- Howard, A. 2008. Applying the lessons learnt in Asset Management around the world to the development of the AMPLE tool. *WIT Transactions on The Built Environment*. Southampton, UK: WIT Press.
- Institute of Public Works Engineering Australasia 2015. *International infrastructure management manual*, IPWEA Sydney, NSW & Wellington, N.Z. NAMS Group.
- Institute of Public Works Engineering Australasia 2016. *Practice Note 3: Building Condition and Performance Assessment Guidelines*, IPWEA & NAMS.AU Group Sydney, NSW
- Institute of Public Works Engineering Australasia. 2020. *Asset management decisions come into focus for local government during Covid-19* [Online]. Available: <https://www.ipwea.org/blogs/intouch/2020/07/22/asset-management-decisions-come-into-focus-for-local-government-during-Covid-19> [Accessed 10 August 2021].
- ISACA. 2021. *Build Capability, Drive Performance* [Online]. Available: <https://cmmiinstitute.com/> [Accessed 06 October 2021].
- ISO 2014. ISO 55000:2014 Asset management — Overview, principles and terminology. Geneva, Switzerland.: International Organization for Standardization.

- ISO 2018. ISO 19650-1:2018 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. Geneva, Switzerland.: International Organization for Standardization.
- Knowledge Based Systems Inc (KBSI). 2021. *IDEF0 - Function Modelling Method* [Online]. Available: https://www.idef.com/idefo-function_modeling_method/ [Accessed 09 Sept 2021].
- Lloyd, C., Corcoran, M. & Pilling, M. 2019. Asset management maturity and the pursuit of value. *Asset Management*. ICE Publishing.
- Manyika, J., Chui, M., Miremadi, M., Bughin, J., George, K., Willmott, P. & Dewhurst, M. 2017. A future that works: automation, employment, and productivity. McKinsey Global Institute: McKinsey Global Institute.
- Minister of Local Government (MLG) 2021. The Future for Local Government Review Interim report.
- Mohseni, H., Setunge, S., Zhang, G. & Wakefield, R. 2017. Markov Process for Deterioration Modeling and Asset Management of Community Buildings. *Journal of Construction Engineering and Management*, 143, 04017003.
- National Asset Management Steering Group (NAMS) 2014. NAMS Property Manual for the Strategic to Tactical Long-term Planning for Property Assets. V2.0.
- New Zealand Green Building Council (NZGBC). 2019. *A Zero Carbon Road Map for Aotearoa's Buildings* [Online]. Available: https://www.nzgbc.org.nz/Attachment?Action=Download&Attachment_id=2528 [Accessed 16 June 2021].
- New Zealand Productivity Commission (NZPC) 2018. Local government funding and financing: Issues Paper.
- New Zealand Treasury 2017. New Zealand Asset Metadata Standard – Residential Housing and Light Commercial Buildings Volume 2 Asset Management and Performance. In: UNIT, N. Z. T. N. I. (ed.).
- Nippala, E., & Vainio, T. Infrastructure construction in change: What is the sensible path forward? In: TECHNOLOGY, Q. U. O., ed. 19th CIB World Building Congress: Construction and Society 2013 Brisbane Australia CIB Publication 26-36.
- Office of the Auditor-General (OAG) 2017. Reflections from our audits: Investment and asset management.
- Pan, W., Chen, L. & Zhan, W. 2019. PESTEL Analysis of Construction Productivity Enhancement Strategies: A Case Study of Three Economies. *Journal of Management in Engineering*, 35, 05018013.
- Pathirana, A., Radhakrishnan, M., Bevaart, M., Voost, E., Mahasneh, S. & Rob, H. 2018. Fit-for-Purpose Infrastructure Asset Management Framework for Water Utilities Facing High Uncertainties. *Infrastructures*, 3, 55.
- Rivas, A., Fraile, J. M., Chamoso, P., González-Briones, A., Sittón, I. & Corchado, J. M. A Predictive Maintenance Model Using Recurrent Neural Networks. In: MARTÍNEZ ÁLVAREZ, F., TRONCOSO LORA, A., SÁEZ MUÑOZ, J. A., QUINTIÁN, H. & CORCHADO, E., eds. 14th International Conference on Soft Computing Models in Industrial and Environmental Applications (SOCO 2019), 2020// 2020 Cham. Springer International Publishing, 261-270.
- Ruitenburt, R. J. & Braaksma, A. J. J. 2017. Evaluation of the Lifetime Impact Identification Analysis: Two tests in a changeable context. *CIRP Journal of Manufacturing Science and Technology*, 17, 42-49.
- Ruitenburt, R. J., Braaksma, J. & Dongen, L. 2017. Asset Life Cycle Plans: Twelve Steps to Assist Strategic Decision-Making in Asset Life Cycle Management. In: M. C. CARNERO, V. G.-P. (ed.) *Optimum decision making in asset management*.
- Sneesby, A., Rose, D., Byrne, R., Graf, W. & Hodgins, M. 2012. SIMPLE—Sustainable Infrastructure Management Program Learning Environment.
- Solas, A. R. a. M. Z. 2016. Shaping the Future of Construction A Breakthrough in Mindset and Technology. Cologny/Geneva Switzerland.
- Stats NZ 2018. Local Authority Financial Statistics - LAF.
- Sun, Y., Ma, L. & Mathew, J. 2012. Improving Asset Management Process Modelling and Integration. In Brown, K, Mathew, J, Willett, R, & Amadi-Echendu, J (Eds.) *Asset condition, information systems and decision models*. Springer, United Kingdom,.
- The Institute of Asset Management (IAM). 2015. *Asset Management – an anatomy* [Online]. Available: <https://theiam.org/knowledge-library/asset-management-an-anatomy/> [Accessed 12 July 2021].
- The Institute of Asset Management (IAM). 2016. *Asset Management Maturity Scale and Guidance* [Online]. Available: <https://theiam.org/knowledge-library/asset-management-maturity-scale-and-guidance/> [Accessed 12 July 2021].
- Thomson, A. 2012. The SALVO project : Innovative approaches to decision-making in the management of aging assets. *Asset Management and Maintenance Journal*, 25, 36-43.
- Too, E. G. 2010. A Framework for Strategic Infrastructure Asset Management. In: AMADI-ECHENDU, J. E., BROWN, K., WILLETT, R. & MATHEW, J. (eds.) *Definitions, Concepts and Scope of Engineering Asset Management*. London: Springer London.

- Transport Infrastructure Ireland. 2021. *Network Management – Asset Management (Pavements)* [Online]. Available: <https://www.tii.ie/roads-tolling/operations-and-maintenance/Pavements/> [Accessed 08 August 2021].
- United Nations Environment Programme (UNEP) 2018. 2017 Global Status Report for Buildings and Construction.
- Vanier, D. 2001. Why Industry Needs Asset Management Tools. *Journal of Computing in Civil Engineering*, 15.
- Victoria Department of Infrastructure (VDI) 1998. Facing the renewal challenge: Victorian local government infrastructure study. Melbourne: Department of Infrastructure.
- vom Brocke, J. & Sinnl, T. 2011. Culture in business process management: a literature review. *Business Process Management Journal*, 17, 357-378.
- Waissi, G. R., Demir, M., Humble, J. E. & Lev, B. 2015. Automation of strategy using IDEF0 — A proof of concept. *Operations Research Perspectives*, 2, 106-113.
- Wallis, J. & Dollery, B. 2000. Local government reform in New Zealand.
- Wettstein, T. & Kueng, P. 2002. A maturity model for performance measurement systems. *Management Information Systems*, 113-122.
- Woodhouse, J. 2003. *Asset Management: concepts & practices* [Online]. Available: https://www.researchgate.net/publication/228905772_Asset_Management_concepts_practices [Accessed 05 July 2021].
- Woodhouse, J. 2014. *Asset management decision-making: The SALVO process*, Hampshire, UK The Woodhouse Partnership Ltd. .
- Woodhouse, J. 2019. What is the value of asset management? *Infrastructure Asset Management*, 6, 102-108.
- World Green Building Council (WorldGBC). 2019. *Bringing Embodied Carbon Upfront* [Online]. Available: <https://www.worldgbc.org/bringing-embodied-carbon-upfront-report-webform> [Accessed 20 July 2021].
- Yamfashije, J. 2017. *Capability Maturity Model Integration* [Online]. Available: 10.13140/RG.2.2.35219.94247 [Accessed 12 June 2021].

Employee Turnover in the Construction Industry: A Comprehensive Review

Goldis Abdolmaleki^{*1}, Nariman Ghodrati¹, Mostafa Babaeian Jelodar², Nicola Naismith¹

¹*School of Future Environment, Auckland University of Technology, New Zealand.*

²*School of Built Environment, Massey University, New Zealand.*

**Corresponding author: Goldis.abdolmaleki@aut.ac.nz*

Abstract

The construction industry has long been faced with skills shortage issues worldwide. Skills shortages along with high employee turnover represent additional challenges to construction firms. Voluntary employee turnover is costly and results in low competitiveness, particularly for the construction industry due to its knowledge-intensive characteristic. The possible solution to address the perennial turnover issue surrounding construction organizations and minimize its adverse impact is understanding factors contributing to employees' turnover decisions. Voluntary employee turnover has been studied in different occupational groups and sectors. There are, however, few studies on employee turnover in the construction industry. Turnover intention and behaviour are motivated by multiple internal and external factors. To identify those factors in the context of construction, a comprehensive literature review was undertaken. This research investigates the factors that lead to employees quitting decisions and outlines the most common factors affecting their decisions. The results can be used to develop strategies to reduce construction employee turnover. The findings from this review contribute to a deepened understanding of the voluntary turnover phenomenon in the construction context. Findings from this research provide valuable implications for Construction organizations wishing to retain their skilled employees.

Keywords

Employee retention, Construction industry, Employee turnover, Skilled employees

Introduction

The construction industry is labor-intensive and faces significant challenges such as low skill levels and unprecedented workload (Chih et al., 2018, Engineering New Zealand, 2020). The shortage of a skilled workforce is the key issue surrounding the industry (Rice and Forgan, 2016, Wilkinson et al., 2017). The long-term difficulty of taking skilled employees is heightened by the high staff turnover rate (Hee and Ling, 2011, Rice and Forgan, 2016). The term turnover refers to the movement of employees across organizations or sectors (Uğural et al., 2020a, Zhang et al., 2012). The construction industry has long faced employee turnover worldwide (Çelik and Oral, 2019, Chih et al., 2016, Malone and Issa, 2014). For instance, the U.S. construction industry reported a 27.8% quit rate in 2019 (Bureau of Labor Statistics, 2019). Australian Bureau of Statistics (2019) reported 9.7% of the workforce within the construction industry changed their employers or businesses during the last 12 months. In New

Zealand, the turnover rate in the construction industry was 12.9% in the fourth quarter of 2019 (Stats NZ, 2022). Figure 1. shows the latest worker turnover rate from the Linked Employer-Employee Data (LEED). As can be seen in Figure 1, and highlighted by Lawson Williams Consulting Group (2018), in light of the variation across industries, it is crucial for organizations to assess the turnover and retention of staff within their own industry sector instead of relying on the national average turnover rate. High labor turnover has caused significant challenges for construction companies, such as negatively affecting productivity (Chang-Richards et al., 2019). While several studies have been carried out on employee turnover and retention, there has been limited investigation into employee turnover within the construction industry compared to other sectors (Rezvani et al., 2020, Chih et al., 2018). Besides, there has been scant attention to comprehensively reviewing the existing studies on construction employee turnover. This research, therefore, aims to provide a broad view of studies on construction employee turnover. This research organizes the relevant causes for their turnover by reviewing existing literature on employee turnover in the construction context. The remaining part of the paper proceeds as follows. It begins by reviewing employee turnover definition and its potential consequences. Then, the methodology is explained and results are described followed by a discussion on findings, and the conclusion.

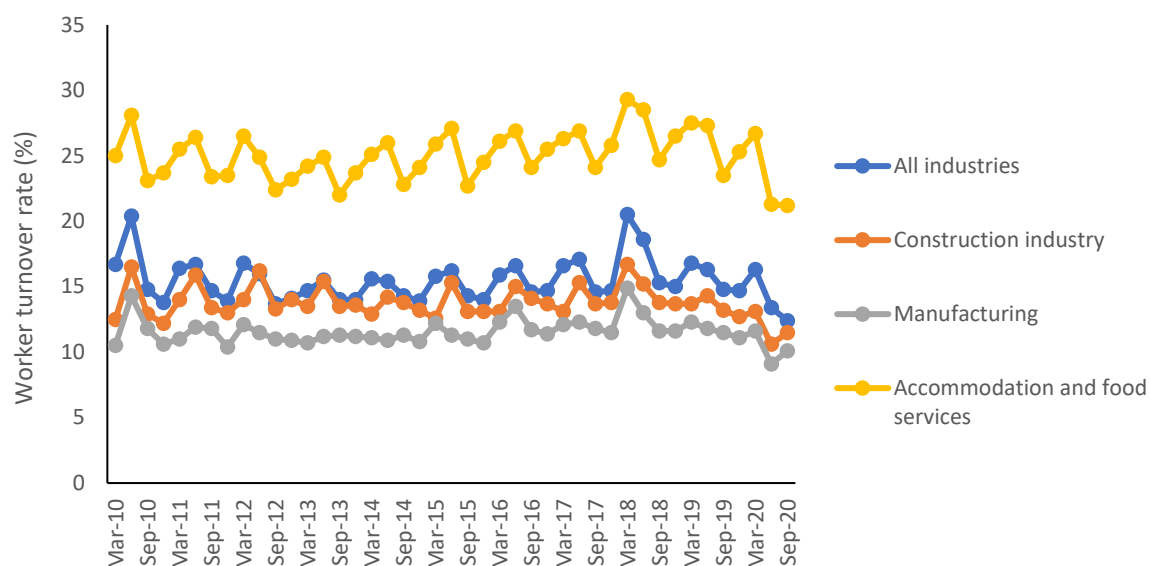


Figure 1. Worker turnover rate by industry in New Zealand (Stats NZ, 2022)

Literature Review

Employee turnover rate refers to the percentage of employees who leave their organizations over the year against the average number of employees in that year (Hee and Ling, 2011). Employee turnover can be categorized into voluntary and involuntary turnover, voluntary turnover depends on the employee's decision to leave the organization, while in involuntary turnover, the termination of employment is initiated by the organization and the organization controls this process (Long et al., 2012). Employee turnover leads to slower business growth, reduced service and product quality, delays, and project failures (Jiang et al., 2001, Wang et al., 2020). Turnover results in lower organizational effectiveness due to knowledge loss, work disruptions, and damaged relationships with clients due to discontinuity (Allen et al., 2010, Reina et al., 2018). The cost of losing each staff depends on different factors, including the

industry, job content, and availability of the replacements (Childs et al., 2017, Holtom et al., 2008). For instance, the turnover cost of research and development (R&D) workers was estimated to be three to six times higher than the loss of administrative staff (Chang et al., 2008). Employee turnover is costly, particularly related to professionals, managerial, and technical roles, as their knowledge and skills, can hardly be replaced (Childs et al., 2017, Chang et al., 2008). All industries face employee turnover (Ababneh, 2020, Wang et al., 2020, DiPietro et al., 2020), and it has been an issue for the construction industry worldwide (Chih et al., 2016, Uğural et al., 2020b). The loss of even one key project member substantially affects the project's success and performance and adversely impacts other members' confidence (Rehman et al., 2020). The construction industry highly depends on employees' knowledge (Uğural et al., 2020b). Companies with lower-skilled employee turnover can offer high-quality services to their clients (Hee and Ling, 2011). Construction organizations must determine how to cope with losing their knowledgeable personnel (Uğural et al., 2020b). Therefore it is essential to understand why employees tend to leave their employers. In the present research, we focused on identifying the main influencers on construction employee turnover. Identifying factors contributing to voluntary turnover enables the development of efficient strategies for not only turnover intention reduction but also raising employees' retention rate (Posthuma et al., 2013).

Research Methodology

Factors affecting construction employee turnover have been identified through a comprehensive literature review. Literature searches based on "article title, abstract, keywords" were conducted in the Scopus search engine. Scopus is a complete database that has been widely used for literature review purposes (Zhang et al., 2019). It was selected as it provides higher journal coverage and accuracy than other databases such as google scholar (Akinade et al., 2018, Falagas et al., 2008). The time span for the literature search was set from 2000 to 2020. The Keywords such as "Turnover" OR "employee turnover" AND "Construction" OR "Construction industry" OR "construction organization" were used. The search was restricted to journal articles only in the English language. After the exclusion of studies irrelevant to the research purpose, a comprehensive literature review was carried out based on 23 articles. The qualitative content analysis using full-text reading of selected papers was conducted to fulfill the review objective. As it is a robust observational method to classify data into categories (Tijani et al., 2020).

Findings and Discussion

Different individual and organizational factors influence the turnover decisions of employees. Table 1. shows the summary of reviewed studies. The main factors studied in construction employee turnover literature with sample studies are depicted in Table 1. Those factors include age, gender, satisfaction, commitment, work-life conflict, and burnout. The comprehensive investigation of those factors and their antecedents will provide valuable insight to address employee turnover issues within construction organizations.



Table 1. Main investigated factors affecting construction employee turnover

Investigated factors	Sample studies
Age	Sun (2011), Fu and Deshpande (2012), Chih et al. (2016),
Gender	Du et al. (2006), Sang et al. (2007)
Satisfaction	Sang et al. (2007), Sang et al. (2009), Hee and Ling (2011), Malone and Issa (2014), Kerdngern and Thanitbenjasith (2017), Çelik and Oral (2019), Rezvani et al. (2020)
Commitment	Leung et al. (2004), Chow et al. (2015), Rehman et al. (2020), Wang et al. (2020), Rezvani et al. (2020)
Work-life conflict	Sang et al. (2007), Malone and Issa (2014), Liu et al. (2020)
Burnout	Chih et al. (2016), Yang et al. (2017)

Factors related to individuals such as age and gender have been found significantly associated with turnover. But contradictory results have been found. For example, the study of Chih et al. (2016) on construction workers indicated that younger workers who experience psychological contract breaches are more likely to leave their organizations than older workers. However, Du et al. (2006) reported insignificant influences of age and gender on construction project managers and technical staff. Another study by Sang et al. (2007) reported higher turnover intention for female architects than their male counterparts.

Construction employees' satisfaction has been recognized as a critical behavioural indicator that necessitates management attentions (Chih et al., 2018, Cox et al., 2003). Work satisfaction as a measure indicates the degree to which employees feel happy about their jobs (Hackman and Oldham, 1980, Ling et al., 2016). Extensive evidence supports the negative effect of job satisfaction on turnover (Hee and Ling, 2011, Chow et al., 2015, Sang et al., 2007, Wang et al., 2020). A wide range of factors, including work environment-related and individual-related factors, affect employees' satisfaction and commitment to their organizations (McMurtrey et al., 2002). According to the job characteristic theory, all jobholders do not respond to job motivating potentials positively, and the characteristics of jobholders determine a fit between them (Hee and Ling, 2011, Hackman and Oldham, 1980). Job characteristic theory was investigated in a sample of quantity surveyors, and it was partially supported for the retention of this occupational group (Hee and Ling, 2011). This study revealed lower satisfaction with monetary benefits, chances for promotion and skill development, sense of accomplishment, fit between job and trait, physical work environment than the perceived importance level for quantity surveyors results in higher turnover intention among them (Hee and Ling, 2011). Individual characteristics such as gender may affect Job satisfaction, Sang et al. (2007) found higher overall job satisfaction for male architects than their female counterparts. The study of Rezvani et al. (2020) on construction project members indicated that employees with higher emotional intelligence exhibit higher satisfaction, more commitment, and lower intention to quit.

Organizational commitment has been recognized as a consistent and significant predictor of turnover intention (Leung et al., 2008, Malone and Issa, 2014, Wang et al., 2020). Organizational commitment is defined as "the extent to which one is involved in and identifies with one's organization" (Ahuja et al., 2007, King et al., 2005, Mowday et al., 2013).

Attitudinal commitment includes three primary constructs, namely, affective commitment (AC), normative (NC), and continuance commitment (CC) (Leung et al., 2008). The degree of organizational commitment relies on multiple personal and organizational characteristics (Leung et al., 2004). Therefore, commitment is a multidimensional construct that its different forms would impact on project's performance and the team members differently (Leung et al., 2004). The effect of major constructs of commitment, namely, AC, NC, and CC on construction projects among main project stakeholders, was studied, findings from construction professionals indicated that higher AC and NC were related to lower turnover intention. In contrast, CC indicated a positive relationship with the intention to quit the company (Leung et al., 2004). The study by Wang et al. (2020) on construction employees in China also indicated that construction organizations could reduce employees' turnover intention by improving their affective commitment.

Work-family conflict can be perceived as incompatibility between work and family in different aspects (Kahn et al., 1964, Wu et al., 2018). It negatively affects performance and covers both family interference with work (family-to-work conflict; FWC) and work interference with family (work-to-family conflict; WFC) (Wu et al., 2018, Frone et al., 1992, Liu et al., 2020). The primary sources for WFC and FWC are work demands and family demands, respectively (Byron, 2005, Liu et al., 2020). One of the main implications for construction organizations is the positive effect of work-family conflict on the intention to quit (Amstad et al., 2011, Liu et al., 2020). Both WFC and FWC are related to higher turnover intention (Amstad et al., 2011). Work-life balance (WLB) is affected by multiple factors. Its related issues might be more gender-specific in male-dominated occupations such as engineering/construction (Guillaume and Pochic, 2009, Malone and Issa, 2014). For instance, Sang et al. (2007) supported that female architects experience a higher level of work-life conflict, turnover intention, and poorer occupational well-being than their male counterparts. Work overload and long work hours have been recognized as significant factors that negatively affect work-life balance, which is a concern for construction employees (Sang et al., 2009, Ling et al., 2016). Liu et al. (2020) examined the effects of family-supportive supervisor (FSS) and work-family conflict on turnover intention using samples of construction workers. Findings demonstrated the supportive family supervisor reduces work-family conflict which results in lower intention to quit.

Job burnout has a significant and negative effect on organizational behaviour, job performance, as well as health and well-being (Maslach et al., 1986, Yang et al., 2017). Burnout is also associated with the willingness to leave the profession as a defensive mechanism of escape (Yang et al., 2017). Job burnout can be defined as "a psychological syndrome of exhaustion, cynicism, and inefficacy experienced in response to chronic job stressors" (Yang et al., 2017, Leiter and Maslach, 2003). Long work hours and high workload have been recognized as significant stressors for construction employees, which have a detrimental impact on their burnout and project productivity (Ling et al., 2016). The immense workload is linked to lower leisure time, health problems, and stress, which causes depression, lower self-esteem and satisfaction, and consequently intention to quit (Hee and Ling, 2011). job demand stress is a significant contributor to job burnout among construction professionals (Lingard, 2003, Leung et al., 2011, Pinto et al., 2016). Chih et al. (2016) explored psychological contract breach on emotional exhaustion (one of the main symptoms of burnout) among construction workers in China and the Philippines. Findings indicated that psychological contract breach positively impacts employee turnover through the mediation effect of emotional exhaustion (Chih et al., 2016).

In summary, the literature indicated that the combination of different factors influences employees' turnover decisions. Given the importance of addressing the construction firms'

turnover issue, it is crucial to fully understand how different constructs impact employees' desire to leave or remain with their employers. Although the employee turnover topic has received extensive attention from organizational behaviour scholars, few studies focused on construction employee turnover (Chih et al., 2018). While findings from those studies provide a valuable perception of turnover and retention issues, there still is a need for more empirical studies in the construction context. The significance of such consideration is heightened during this crisis time given the significant impact of the Covid-19 pandemic on economic, social, and cultural systems. There have been huge consequences for the construction industry as well including labour shortage, difficulty in getting suitable staff, logistic, and supply chain issues (Ministry of Business, 2021, Jeon et al., 2022). It has significantly changed employees' work and family roles, worldwide (Vaziri et al., 2020). Organizations are forced to step into a territory that they have never managed before involving in human resource changes in physical, technical, and scio-psychological aspects (Carnevale and Hatak, 2020). Covid-19 is expected to deteriorate job attitudes and organizational behaviours as it can lead to higher job insecurity and poorer psychological responses (Mahmoud et al., 2021).

Conclusion

High employee turnover rates have been considered as a significant drawback affecting construction firms. The critical skills shortage issue facing the industry and detrimental consequences of employee turnover necessitates the development of strategies to minimize losing skilled employees. This research reviewed employee turnover literature focused on the construction workforce to identify the main factors affecting their turnover. A review of 23 studies from 2000 to 2020 identified age, gender, satisfaction, commitment, work-life conflict, and burnout as main influencers on employees' quitting decisions in construction organizations. The findings from this review suggest construction companies take into account those key factors for the development of strategies aiming at skilled employees retention. It provides managers in construction firms with insight to prioritize key influencers on employee turnover, thus effective human resource management strategies can be developed. The limitation of this study is that only peer-reviewed journal papers were included, which may limit access to findings from books or conference papers.

Regarding future research, the authors suggest that the current challenge of covid-19 presents an opportunity for researchers to investigate the impact of Covid-19 and changes that it has caused on construction employee turnover. Researchers may also conduct a comparative study in different working environments such as consulting and contracting organizations to see how identified factors affect employee turnover in different contexts. As there may be differences in job stressors at consulting and contracting companies (Yip and Rowlinson, 2009).

References

- ABABNEH, K. I. 2020. Effects of met expectations, trust, job satisfaction, and commitment on faculty turnover intentions in the United Arab Emirates (UAE). *The International Journal of Human Resource Management*, 31, 303-334.
- AHUJA, M. K., CHUDоба, K. M., KACMAR, C. J., HARRISON MCKNIGHT, D. & GEORGE, J. F. 2007. It road warriors: Balancing work-family conflict, job autonomy, and work overload to mitigate turnover intentions. *MIS Quarterly: Management Information Systems*, 31, 1-17.
- AKINADE, O. O., OYEDELE, L. O., AJAYI, S. O., BILAL, M., ALAKA, H. A., OWOLABI, H. A. & ARAWOMO, O. O. 2018. Designing out construction waste using BIM technology: Stakeholders' expectations for industry deployment. *Journal of Cleaner Production*, 180, 375-385.

- ALLEN, D. G., BRYANT, P. C. & VARDAMAN, J. M. 2010. Retaining talent: Replacing misconceptions with evidence-based strategies. *Academy of management Perspectives*, 24, 48-64.
- AMSTAD, F. T., MEIER, L. L., FASEL, U., ELFERING, A. & SEMMER, N. K. 2011. A meta-analysis of work–family conflict and various outcomes with a special emphasis on cross-domain versus matching-domain relations. *Journal of occupational health psychology*, 16, 151.
- AUSTRALIAN BUREAU OF STATISTICS. 2019. *Participation, Job Search and Mobility, Australia, Feb 2019* [Online]. Available: <https://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/6226.0Feb%202019> [Accessed 26/04/2020].
- BUREAU OF LABOR STATISTICS. 2019. Available: <https://www.bls.gov/news.release/jolts.t18.htm> [Accessed 27/04/2020].
- BYRON, K. 2005. A meta-analytic review of work–family conflict and its antecedents. *Journal of vocational behavior*, 67, 169-198.
- CARNEVALE, J. B. & HATAK, I. 2020. Employee adjustment and well-being in the era of COVID-19: Implications for human resource management. *Journal of Business Research*.
- ÇELİK, G. T. & ORAL, E. L. 2019. Mediating effect of job satisfaction on the organizational commitment of civil engineers and architects. *International Journal of Construction Management*.
- CHANG-RICHARDS, A., BROWN, C. & SMITH, N. 2019. Building risk management strategies into the vertical construction sector.
- CHANG, J. Y., CHOI, J. N. & KIM, M. U. 2008. Turnover of highly educated R&D professionals: The role of pre-entry cognitive style, work values and career orientation. *Journal of Occupational and Organizational Psychology*, 81, 299-317.
- CHIH, Y.-Y., KIAZAD, K., CHENG, D., EMAMIRAD, E. & RESTUBOG, S. L. 2018. Interactive effects of supportive leadership and top management team's charismatic vision in predicting worker retention in the Philippines. *Journal of Construction Engineering and Management*, 144, 04018095.
- CHIH, Y.-Y., KIAZAD, K., ZHOU, L., CAPEZIO, A., LI, M. & D. RESTUBOG, S. L. 2016. Investigating employee turnover in the construction industry: A psychological contract perspective. *Journal of Construction Engineering and Management*, 142, 04016006.
- CHILDS, B. R., WEIDMAN, J. E., FARNSWORTH, C. B. & CHRISTOFFERSON, J. P. 2017. Use of personality profile assessments in the US commercial construction industry. *International Journal of Construction Education and Research*, 13, 267-283.
- CHOW, P. T., CHEUNG, S. O. & WA, Y. K. 2015. Impact of Trust and Satisfaction on the Commitment-Withdrawal Relationship. *Journal of Management in Engineering*, 31.
- COX, R. F., ISSA, R. R. & AHRENS, D. 2003. Management's perception of key performance indicators for construction. *Journal of construction engineering and management*, 129, 142-151.
- DIPIETRO, R. B., MOREO, A. & CAIN, L. 2020. Well-being, affective commitment and job satisfaction: influences on turnover intentions in casual dining employees. *Journal of Hospitality Marketing & Management*, 29, 139-163.
- DU, J. J., ZHOU, J., LIU, C. & PICKEN, D. 2006. Exploring turnover intention of construction managers in China. *Journal of Construction Research*, 7, 191-205.
- ENGINEERING NEW ZEALAND 2020. Construction sector transformation plan.
- FALAGAS, M. E., PITSOUNI, E. I., MALIETZIS, G. A. & PAPPAS, G. 2008. Comparison of PubMed, Scopus, web of science, and Google scholar: strengths and weaknesses. *The FASEB journal*, 22, 338-342.
- FRONE, M. R., RUSSELL, M. & COOPER, M. L. 1992. Antecedents and outcomes of work-family conflict: testing a model of the work-family interface. *Journal of applied psychology*, 77, 65.
- FU, W. H. & DESHPANDE, S. P. 2012. Antecedents of Organizational Commitment in a Chinese Construction Company. *Journal of Business Ethics*, 109, 301-307.
- GUILLAUME, C. & POCHIC, S. 2009. What would you sacrifice? Access to top management and the work–life balance. *Gender, Work & Organization*, 16, 14-36.
- HACKMAN, J. R. & OLDFHAM, G. R. 1980. Work redesign.
- HEE, C. H. & LING, F. Y. Y. 2011. Strategies for reducing employee turnover and increasing retention rates of quantity surveyors. *Construction Management and Economics*, 29, 1059-1072.
- HOLTOM, B. C., MITCHELL, T. R., LEE, T. W. & EBERLY, M. B. 2008. 5 turnover and retention research: a glance at the past, a closer review of the present, and a venture into the future. *The Academy of Management Annals*, 2, 231-274.
- JEON, J., PADHYE, S., BHATTACHARYYA, A., CAI, H. & HASTAK, M. 2022. Impact of COVID-19 on the US Construction Industry as Revealed in the Purdue Index for Construction. *Journal of Management in Engineering*, 38, 04021082.
- JIANG, J. J., KLEIN, G. & BALLOUN, J. L. 2001. The joint impact of internal and external career anchors on entry-level IS career satisfaction. *Information and Management*, 39, 31-39.

- KAHN, R. L., WOLFE, D. M., QUINN, R. P., SNOEK, J. D. & ROSENTHAL, R. A. 1964. Organizational stress: Studies in role conflict and ambiguity.
- KERDNGERN, N. & THANITBENJASITH, P. 2017. Influence of contemporary leadership on job satisfaction, organizational commitment, and turnover intention: A case study of the construction industry in Thailand. *International Journal of Engineering Business Management*, 9, 1847979017723173.
- KING, R. C., XIA, W., QUICK, J. C. & SETHI, V. 2005. Socialization and organizational outcomes of information technology professionals. *Career Development International*, 10, 26-51.
- LEITER, M. P. & MASLACH, C. 2003. Areas of worklife: A structured approach to organizational predictors of job burnout. *Research in occupational stress and well being*, 3, 91-134.
- LEUNG, M. Y., CHAN, Y. S. I. & DONGYU, C. 2011. Structural linear relationships between job stress, burnout, physiological stress, and performance of construction project managers. *Engineering, Construction and Architectural Management*.
- LEUNG, M. Y., CHEN, D. Y. & YU, J. Y. 2008. Demystifying Moderate Variables of the Interrelationships among Affective Commitment, Job Performance, and Job Satisfaction of Construction Professionals. *Journal of Construction Engineering and Management*, 134, 963-971.
- LEUNG, M. Y., CHONG, A., NG, S. T. & CHEUNG, M. C. K. 2004. Demystifying stakeholders' commitment and its impacts on construction projects. *Construction Management and Economics*, 22, 701-715.
- LING, F. Y. Y., LEOW, X. X. & LEE, K. C. 2016. Strategies for Attracting More Construction-Trained Graduates to Take Professional Jobs in the Construction Industry. *Journal of Professional Issues in Engineering Education and Practice*, 142.
- LINGARD, H. 2003. The impact of individual and job characteristics on 'burnout' among civil engineers in Australia and the implications for employee turnover. *Construction Management & Economics*, 21, 69-80.
- LIU, B., WANG, Q., WU, G., ZHENG, J. & LI, L. 2020. How family-supportive supervisor affect Chinese construction workers' work-family conflict and turnover intention: investigating the moderating role of work and family identity salience. *Construction Management and Economics*.
- LONG, C. S., THEAN, L. Y., ISMAIL, W. K. W. & JUSOH, A. 2012. Leadership styles and employees' turnover intention: Exploratory study of academic staff in a Malaysian College. *World Applied Sciences Journal*, 19, 575-581.
- MAHMOUD, A. B., REISEL, W. D., FUXMAN, L. & HACK-POLAY, D. 2021. Locus of control as a moderator of the effects of COVID-19 perceptions on job insecurity, psychosocial, organisational, and job outcomes for MENA region hospitality employees. *European Management Review*.
- MALONE, E. K. & ISSA, R. R. A. 2014. Predictive Models for Work-Life Balance and Organizational Commitment of Women in the U.S. Construction Industry. *Journal of Construction Engineering and Management*, 140.
- MASLACH, C., JACKSON, S. E., LEITER, M. P., SCHAUFELI, W. B. & SCHWAB, R. L. 1986. *Maslach burnout inventory*, Consulting psychologists press Palo Alto, CA.
- MCMURTREY, M. E., GROVER, V., TENG, J. T. C. & LIGHTNER, N. J. 2002. Job satisfaction of information technology workers: The impact of career orientation and task automation in a CASE environment. *Journal of Management Information Systems*, 19, 273-302.
- MINISTRY OF BUSINESS, I. A. E. M. 2021. The COVID-19 pandemic and its impact on building system actors.
- MOWDAY, R. T., PORTER, L. W. & STEERS, R. M. 2013. *Employee—organization linkages: The psychology of commitment, absenteeism, and turnover*, Academic press.
- PINTO, J. K., PATANAKUL, P. & PINTO, M. B. 2016. Project personnel, job demands, and workplace burnout: The differential effects of job title and project type. *IEEE Transactions on Engineering Management*, 63, 91-100.
- POSTHUMA, R. A., CAMPION, M. C., MASIMOVA, M. & CAMPION, M. A. 2013. A high performance work practices taxonomy: Integrating the literature and directing future research. *Journal of management*, 39, 1184-1220.
- REHMAN, S. U., SHAHZAD, M., FAROOQ, M. S. & JAVAID, M. U. 2020. Impact of leadership behavior of a project manager on his/her subordinate's job-attitudes and job-outcomes. *Asia Pacific Management Review*, 25, 38-47.
- REINA, C. S., ROGERS, K. M., PETERSON, S. J., BYRON, K. & HOM, P. W. 2018. Quitting the boss? The role of manager influence tactics and employee emotional engagement in voluntary turnover. *Journal of leadership & organizational studies*, 25, 5-18.
- REZVANI, A., ASHKANASY, N. & KHOSRAVI, P. 2020. Key Attitudes: Unlocking the Relationships between Emotional Intelligence and Performance in Construction Projects. *Journal of Construction Engineering and Management*, 146.
- RICE, C. & FORGAN, R. 2016. Valuing the role of construction in the New Zealand economy.

- SANG, K. J. C., DAINITY, A. R. J. & ISON, S. G. 2007. Gender: A risk factor for occupational stress in the architectural profession? *Construction Management and Economics*, 25, 1305-1317.
- SANG, K. J. C., ISON, S. G. & DAINITY, A. R. J. 2009. The job satisfaction of UK architects and relationships with work-life balance and turnover intentions. *Engineering, Construction and Architectural Management*, 16, 288-300.
- STATS NZ. 2022. *Dataset: Table 13: LEED measures, by sex and industry (based on ANZSIC06)* [Online]. Available: <http://nzdotstat.stats.govt.nz/wbos/Index.aspx?DataSetCode=TABLECODE7018> [Accessed].
- SUN, K.-S. 2011. The turnover intentions for construction engineers. *Journal of Marine Science and Technology*, 19, 550-556.
- TIJANI, B., XIAOHUA, J. & OSEI-KYEI, R. 2020. Critical analysis of mental health research among construction project professionals. *Journal of Engineering, Design and Technology*.
- UĞURAL, M. N., GIRITLI, H. & URBANŠKI, M. 2020a. Determinants of the Turnover Intention of Construction Professionals: A Mediation Analysis. *Sustainability*, 12, 954.
- UĞURAL, M. N., GIRITLI, H. & URBANŠKI, M. 2020b. Determinants of the turnover intention of construction professionals: A mediation analysis. *Sustainability (Switzerland)*, 12.
- VAZIRI, H., CASPER, W. J., WAYNE, J. H. & MATTHEWS, R. A. 2020. Changes to the work–family interface during the COVID-19 pandemic: Examining predictors and implications using latent transition analysis. *Journal of Applied Psychology*, 105, 1073.
- WANG, Y. P., HU, N., ZUO, J. & RAMEEZDEEN, R. 2020. Project Management Personnel Turnover in Public Sector Construction Organizations in China. *Journal of Management in Engineering*, 36.
- WILKINSON, S., TOOKEY, J., POTANGAROA, R., MACGREGOR, C., MILICICH, M., GHODRATI, N., ADAFIN, J., STOCCHERO, A. & BAYNE, K. 2017. Transforming The Building Industry: State of Nation Knowledge report.
- WU, G. D., WU, Y., LI, H. Y. & DAN, C. L. 2018. Job Burnout, Work-Family Conflict and Project Performance for Construction Professionals: The Moderating Role of Organizational Support. *International Journal of Environmental Research and Public Health*, 15.
- YANG, F., LI, X. D., ZHU, Y. M., LI, Y. L. & WU, C. L. 2017. Job burnout of construction project managers in China: A cross-sectional analysis. *International Journal of Project Management*, 35, 1272-1287.
- YIP, B. & ROWLINSON, S. 2009. Job burnout among construction engineers working within consulting and contracting organizations. *Journal of Management in Engineering*, 25, 122-130.
- ZHANG, F., CAO, C., LI, C., LIU, Y. & HUISINGH, D. 2019. A systematic review of recent developments in disaster waste management. *Journal of Cleaner Production*, 235, 822-840.
- ZHANG, M., FRIED, D. D. & GRIFFETH, R. W. 2012. A review of job embeddedness: Conceptual, measurement issues, and directions for future research. *Human Resource management review*, 22, 220-231.

Lead extrusion damper force modelling for seismic protection application in buildings using finite element modelling

V.Vishnupriya^{1*}, G.W. Rodgers², J.G. Chase³

¹*School of Built Environment, Massey University, Auckland, New Zealand.*

²*Department of Mechanical Engineering, University of Canterbury, Christchurch, New Zealand.*

³*Department of Mechanical Engineering, University of Canterbury, Christchurch, New Zealand.*

*Corresponding author: p.vishnu@massey.ac.nz

Abstract

Supplemental energy dissipation devices are increasingly used to protect structures, limiting loads transferred to structures and absorbing significant response energy without sacrificial structural damage. Lead extrusion dampers are supplemental energy dissipation devices, where recent development of smaller volumetric size with high force capacities, called high force to volume (HF2V) devices, has seen deployment in a large series of scaled and full-scaled experiments, as well as in three new structures in Christchurch, NZ and San Francisco, USA.

HF2V devices are currently designed using limited precision models, so there is variability in force prediction. Further, while outcome force is predicted, the knowledge of the exact internal mechanisms resulting in these device forces is lacking, limiting insight and predictive accuracy in device design. There is thus a major need for detailed design models to better understand force generation, and to aid precision device design. These outcomes would speed the overall design and implementation process for uptake and use.

Design parameters from experimental HF2V device tests are used to create finite element models using ABAQUS. The analysis is run using ABAQUS Explicit, in multiple small step times of 1 second with automatic increments. The output is obtained as plots from the history output of the contact pressure forces including the normal and friction forces on the lead along the shaft. These values are compared with the plots from the experimental tests. Results of these highly nonlinear, high strain analyses are analysed for qualitative validation.

Keywords

Building sustainability, Earthquakes, Lead extrusion damper, Simulation, Structural protection

Introduction

It is important to protect structures using protective systems to reduce their seismic vulnerability. High Force-to-Volume Lead Extrusion Dampers (LED) are supplemental energy dissipation devices that enhance structural energy dissipation and reduce seismic structural response. The advantages of LEDs/HF2Vs have long been recognised and have been applied for improved damping systems (Rodgers 2009, Latham, Reay, and Pampanin 2013a, Skinner et al. 1980, Rodgers 2012). Prediction of lead extrusion damper forces, stress, and force distribution are essential for device design. Few analytical models have been proposed to estimate the lead extrusion damper force capacities (Vishnupriya et al. 2018a, Parulekar et al. 2004, Tsai et al. 2002, Rodgers et al. 2007, Rodgers et al. 2006, V. Vishnupriya, G.W. Rodgers, and Chase 2021).

Design based models that can precisely predict the HF2V force capacity are very limited (Vishnupriya et al. 2018a). Currently, devices are manufactured and tested for determining the precise exact force capacities before application. Thus, there is a need for a more detailed methodology to better estimate the device force capacity in the design phase. Finite element (FE) analysis is an effective method for studying the nonlinear mechanics of device operations and computing the resulting force capacities and has not been used before as a damper force prediction tool (Li et al. 2004, Jin and Altintas 2012).

Finite Element Analysis

Finite element (FE) analysis is an effective method for simulating complex nonlinear mechanics of device operations and computing resulting force capacities (Lesar 1982, Jin and Altintas 2012). There are numerous FE software packages available for simulating metal forming, such as MARC (Heislitz et al. 1996), LS-DYNA (Maker and Zhu 2000), PAM-STAMP (Heislitz et al. 1996), ADINA (Gierzyńska-Dolna and Lacki 2003), ANSYS (Facchinetti and Miszuris 2016), along with specialist tools like DEFORM (Karamyshev et al. 2012), HyperXtrude (Liu et al. 2011), MSC/SuperForge (Mehta et al. 2001) and FORGE (Marie et al. 2014). However, ABAQUS is popular for simulating complex contact problems with large deformation, as well as similar highly nonlinear problems (Chaudhari and Chakrabarti 2012) like cutting, machining and extrusion (Li 2004, Nasr and Ammar 2017, Lei, Shin, and Incropera 1999, Kathirgamanathan and Neitzert 2006, Sevier et al. 2007, Sevier et al. 2008). ABAQUS is also widely used to estimate forces produced during cutting, machining, milling, forming and extrusion (Weber et al. 2008, Jin and Altintas 2012, Ali et al. 2013, Saffar and Razfar 2010, Adetoro and Wen 2010, Henrard et al. 2011, Kang, Kim, and Choi 2010). It is highly efficient in simulating quasi-static, complex contact, non-linear and dynamic problems (Kang, Kim, and Choi 2010). Using device-specific material properties and the design dimensions of a device, it can be expected to realistically simulate HF2V internal lead deformation mechanics within a device, and thus estimate device capacity in the device and building design phases.

Thus, computer simulations could be used to predict device forces to optimize HF2V device design and performance, which has not been done before. Furthermore, such parametric design studies can be undertaken on broader range of devices without the time and cost involved with experimentally testing every configuration. This goal thus adds precision to the device design process itself, where a detailed device design can be produced to match desired overall response behaviour.

HF2V device operation involves large strain inelastic deformations due to displacement of the shaft during an earthquake. Large deformation analysis is challenging and requires advanced FE coding or use of other FE packages to describe material behaviour models and parameters. This study aims to create a generalizable and repeatable FE modelling technique for the HF2V devices which does not require advanced FEA or input to apply the model. This approach thus enables easy uptake by engineers or researchers.

Research Methodology

A 2D axisymmetric model comprising of an analytical rigid shaft, deformable lead and analytical rigid wall was created using ABAQUS/CAE (ABAQUS-Users-Manual 2013). A 2D model is less computationally intensive than 3D models and is enabled through the

axisymmetric nature of the devices. The modelling parameters of the HF2V FE model are tabulated in Table 1.

The model consists of a fixed wall, moving shaft, and a deformable volume lead. Reference points (RP) are applied on the analytical rigid parts. An Arbitrary Lagrangian–Eulerian (ALE) moving mesh is applied on the deformable lead meshed with fine mesh along the shaft and coarse mesh along the walls. ALE method is used to simulate large deformation problems, allowing a moving mesh along with the moving part (Gadala 2000, Zhao 2012, Zhuang 2008). The motion of the mesh is only constrained at the boundaries and allowed to move under high strain within these fixed boundaries. The mesh is smoothed constantly to reduce element distortion without changing the number of elements and their connectivity (Donea, Giuliani, and Halleux 1982). This re-meshing allows the simulation of lead flow within the cylinder and around the shaft, providing a visual guide to the evolution of stress distributions with changing strain/strain rates in the devices as the shaft moves and the dissipation forces are generated. No meshing is required on the analytical rigid parts (ABAQUS-Users-Manual 2013).

Table 1- Device data used for modelling (Vishnupriya, Rodgers, and Chase 2022)

ABAQUS Module		Model Parameter		
Parts		Analytical rigid shaft	Deformable lead	Analytical rigid wall
Material properties of lead	Elastic Data	Young's Modulus (E) = 16 GPa	Poisson's Ratio (ν) = 0.44	Density (ρ) = 11340 kg/m ³
	Plastic Data	Lead stress-strain data available from (Loizou 1953, Lindholm 1964)		
Step		Step type : Dynamic Explicit		
		Step time = 1s		
Interaction		Friction type: Kinematic friction		
		Coefficient of friction = 0.25		
Contact		Contact surfaces: Shaft – lead interface and lead – wall interface		
		Contact type: Master-slave formulations		
Boundary Conditions		Fixed end conditions at lead to endcap interface and lead to cylinder wall interface		
		Displacement on shaft along Y direction		
		Velocity of 0.5mm/s at reference point on shaft (RP-1)		
Meshing		Element type: CAX4R/CAX3		
ALE mesh		Frequency = 10		
		Remeshing sweep per increment = 1		
Output		Type : History Output		
		Forces : Contact pressure force and Friction force		

The boundary conditions where the lead working material meets the device endcaps is considered as a fixed boundary. Displacement in Y direction and velocity of 0.5 mm/s is applied on the reference point (RP-1) on shaft and a zero displacement condition is applied on RP-2 as shown Figure 1. A frictional condition is applied between the shaft and the lead using a coefficient of friction of 0.25. The force output from the model is analysed for its accuracy in prediction of experimental device behaviour. The total resistive force from the HF2V devices

is calculated by summing the normal and friction force produced during extrusion at the interaction between the shaft and the lead.

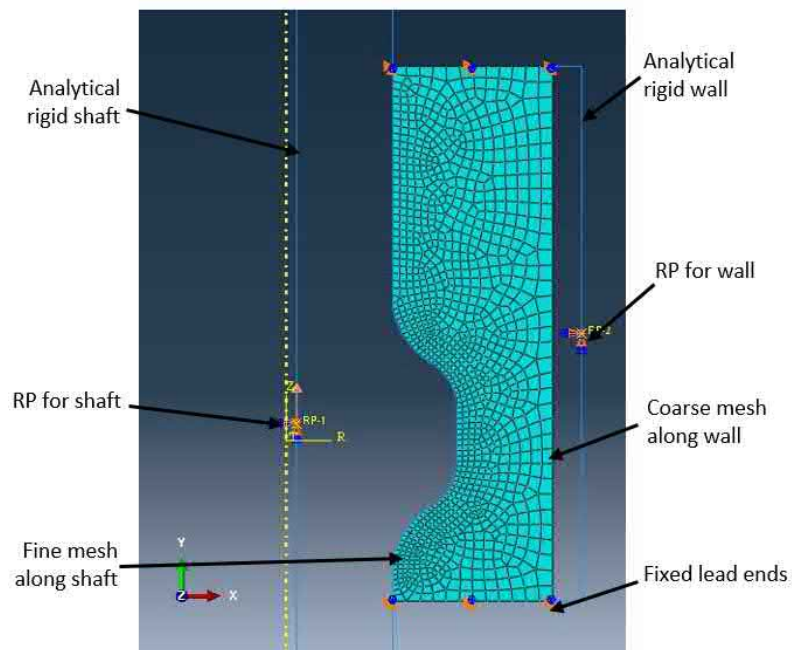


Figure 1- 2D HF2V model parts, boundary conditions and meshing

The model approach is applied the same way to all 17 devices of different sizes and forces considered in this study, without any changes (other than the device geometry) (Vishnupriya *et al.* 2018b), which are from a range of studies (Rodgers 2009, Latham, Reay, and Pampanin 2013b, Wrzesniak). D_{cyl} is cylinder diameter; D_{shaft} is shaft diameter; D_{blg} is bulge diameter and L_{cyl} is cylinder length (Vishnupriya, Rodgers, and Chase 2022). F_{exp} indicates the experimental peak force attained from experiments.

Findings and Discussion

Model performance is assessed for its ability to realistically replicate the lead flow in the HF2V devices with shaft displacement. An ideal model simulates the lead flow around the bulge with the displacement of shaft in the HF2V damper. In HF2V dampers, the lead is deformed by the bulge during shaft motion and displaced through the annular orifice between the bulge and the cylinder wall, which then flows behind the shaft and sticks to the shaft behind the bulge. The flow of lead through the annular restriction generates device force, along with friction (Vishnupriya *et al.* 2018b). The simulations replicate the expected actual behaviour of lead in the lead extrusion damper under loading. The ALE meshing technique applied to the lead in the FE model enables the realistic simulation of lead flow around the bulge in the HF2V devices as shown in Figure 2.

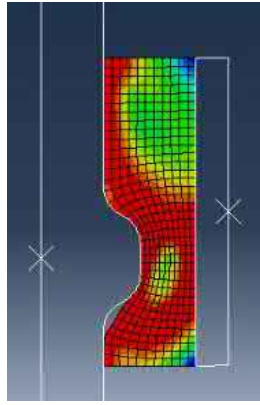


Figure 2. Stress distribution and lead deformation and displacement in the HF2V device

The force output from the model is analysed for its accuracy in prediction of peak experimental device force. The elastoplastic behaviour of lead yields a hysteresis loop with numerous force values. The precision of the model in estimating the device forces is determined by comparing the nominal yield force obtained from the model against experimentally measured peak device forces. The peak force of the HF2V devices is the maximum force obtained during shaft displacement. The load vs displacement plots generated from FE modelling are compared with the plots from the experiments as shown in Figure 3., where the orange plot indicates the FE plot and the blue plot indicates the experimental test results. The FEM plots for these devices are similar to experimental forces results. The plots give an estimation of peak expected device force from the hysteresis plot.

However, while the model within 0% error for some devices the error from other devices could be within 20%. The plots may match perfectly in overall shape in some cases. While in other cases the peak forces may match well with imperfect plot shapes. This can be attributed to severe mesh deformations in these simulations. This model does not predict very well for small lead extrusion dampers with small force capacities.

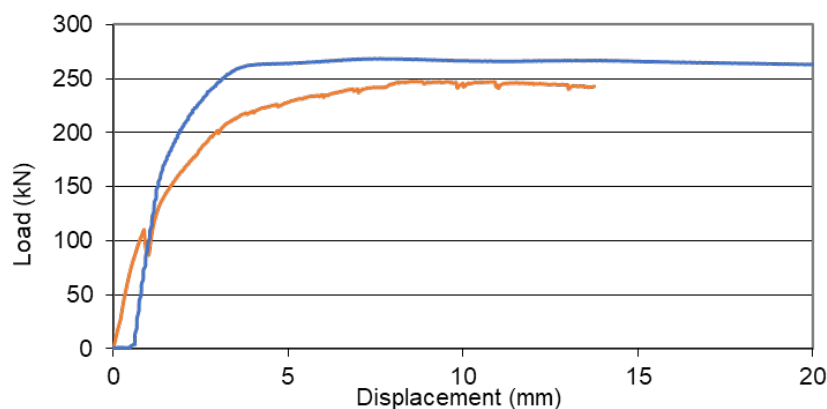


Figure 3. Comparison of experimental results to finite element model plots

Overall, this modelling predicts the HF2V lead extrusion damper device forces by finite element modelling. The experimental force plots match the modelling plots in overall shape and predict the device forces precisely. This model is a generic tool which can be applied to lead extrusion dampers of medium to large force capacities in varying sizes.

Conclusion

This research uses ABAQUS to model and validate a general modelling nonlinear FE approach to predict HF2V device forces by generating plots for Force vs displacement, where a validated general approach allows any user to apply it with confidence and without specialized operator inputs to the modelling, eliminating error due to subjectivity or bias. The force-displacement plots from the FE method provide an insight to the mechanisms involved during the nonlinear behaviour of dampers during operations. Additionally, it is an excellent tool for visualizing the changing flow patterns, stress concentration and distributions of load within the lead with varying geometric device parameters.

References

- ABAQUS-Users-Manual. 2013. "Version 6.13-2." *Dassault Systèmes Simulia Corp., Providence, Rhode Island, USA.*
- Adetoro, OB, and PH Wen. 2010. "Prediction of mechanistic cutting force coefficients using ALE formulation." *The International Journal of Advanced Manufacturing Technology* 46 (1-4):79-90.
- Ali, Moaz H., Basim A. Khidhir, M. N. M. Ansari, and Bashir Mohamed. 2013. "FEM to predict the effect of feed rate on surface roughness with cutting force during face milling of titanium alloy." *HBRC Journal* 9 (3):263-269. doi: 10.1016/j.hbrj.2013.05.003.
- Chaudhari, SV, and MA Chakrabarti. 2012. "Modeling of concrete for nonlinear analysis using finite element code ABAQUS." *International Journal of Computer Applications* 44 (7):14-18.
- Donea, Jean, S Giuliani, and Jean-Pierre Halleux. 1982. "An arbitrary Lagrangian-Eulerian finite element method for transient dynamic fluid-structure interactions." *Computer methods in applied mechanics and engineering* 33 (1-3):689-723.
- Facchinetti, Maurizio, and Wiktoria Miszuris. 2016. "Analysis of the maximum friction condition for green body forming in an ANSYS environment." *Journal of the European Ceramic Society* 36 (9):2295-2302.
- Gadala, M.S., Wang, J. 2000. "Elasto-plastic finite element simulation of rolling and compression between wedge-shaped dies." *Journal of Materials Processing Technology* 97 (1-3):132-147.
- Gierzyńska-Dolna, M, and P Lacki. 2003. "Some aspects of modelling of metal forming processes." *Computers & structures* 81 (8-11):605-613.
- Heislitz, Frank, Haydar Livatyali, Mustafa A Ahmetoglu, Gary L Kinzel, and Taylan Altan. 1996. "Simulation of roll forming process with the 3-D FEM code PAM-STAMP." *Journal of Materials Processing Technology* 59 (1-2):59-67.
- Henrard, Christophe, Chantal Bouffieux, Philip Eyckens, H Sol, JR Duflou, Paul Van Houtte, Albert Van Bael, Laurent Duchene, and AM Habraken. 2011. "Forming forces in single point incremental forming: prediction by finite element simulations, validation and sensitivity." *Computational mechanics* 47 (5):573-590.
- Jin, Xiaoliang, and Yusuf Altintas. 2012. "Prediction of micro-milling forces with finite element method." *Journal of Materials Processing Technology* 212 (3):542-552.
- Jun, Yang. 2001. "An investigation on extruded lead dampers used to reduce the seismic response of building structures " *Building Technique Development* 4.
- Kang, Ji Ho, Gyeong Ho Kim, and Woo Seok Choi. 2010. Impact-Contact Analysis of Prismatic Graphite Blocks Using Abaqus. Korea Atomic Energy Research Institute.
- Karamyshev, AP, II Nekrasov, VS Parshin, AA Fedulov, and AI Pugin. 2012. "Modeling metal-shaping operations in DEFORM-3D in order to efficiently design production processes." *Metallurgist* 56 (1-2):115-118.
- Kathirgamanathan, Padmanathan, and Thomas Neitzert. 2006. "Modelling of metal extrusion using ABAQUS." *The Proceedings of 3rd NZ Metals Industry Conference.*
- Latham, D.A., A.M. Reay, and S. Pampanin. 2013a. "Kilmore Street Medical Centre: Application of an Advanced Flag-Shape Steel Rocking System." *New Zealand Society for Earthquake Engineering–NZSEE–Conference, Wellington.*
- Latham, D.A., A.M. Reay, and S. Pampanin. 2013b. "Kilmore Street Medical Centre: Application of an Advanced Flag-Shape Steel Rocking System." *New Zealand Society for Earthquake Engineering–NZSEE–Conference, Wellington, New Zealand.*

- Lei, S., Y. C. Shin, and F. P. Incropera. 1999. "Thermo-mechanical modeling of orthogonal machining process by finite element analysis." *International Journal of Machine Tools and Manufacture* 39 (5):731-750. doi: [https://doi.org/10.1016/S0890-6955\(98\)00059-5](https://doi.org/10.1016/S0890-6955(98)00059-5).
- Lesar, Douglas E. 1982. Calculation of contact pressures and frictional effects on mechanical contact surfaces by finite element methods with application to fretting damage prediction. DAVID W TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER BETHESDA MD.
- Li, S, MAM Bourke, IJ Beyerlein, DJ Alexander, and B Clausen. 2004. "Finite element analysis of the plastic deformation zone and working load in equal channel angular extrusion." *Materials Science and Engineering: A* 382 (1-2):217-236.
- Li, S., Bourke, M.A.M., Beyerlein, I.J., Alexander, D.J., Clausen, B. 2004. "Finite element analysis of the plastic deformation zone and working load in equal channel angular extrusion." *Materials Science and Engineering: A* 382 (1-2):217-236.
- Lindholm, US. 1964. "Some experiments with the split hopkinson pressure bar*." *Journal of the Mechanics and Physics of Solids* 12 (5):317-335.
- Liu, Gang, Ke Huang, Jie Zhou, and Jurek Duszczyk. 2011. "Simulation of steady-state extrusion through a hollow die using HyperXtrude FE software." *Computer methods in materials science* 11 (2):259-264.
- Loizou, N., Sims, R.B. 1953. "The yield stress of pure lead in compression." *Journal of the Mechanics and Physics of Solids* 1 (4):234-243.
- Maker, Bradley N, and Xinhai Zhu. 2000. "Input parameters for metal forming simulation using LS-DYNA." *Livermore Software Technology Corporation* 4:43-46.
- Marie, Stephane, Richard Ducloux, Patrice Lasne, Julien Barlier, and Lionel Fourment. 2014. "Inverse Analysis of Forming Processes based on FORGE environment." *Key Engineering Materials*.
- Mehta, Bhavin V, Ibrahim Al-Zkeri, Jay S Gunasekera, and Arjaan Buijk. 2001. "3D flow analysis inside shear and streamlined extrusion dies for feeder plate design." *Journal of Materials Processing Technology* 113 (1-3):93-97.
- Monir, Habib Saeed, and Ali Naser. 2008. "Seismic design of steel structures with lead-extrusion dampers as knee braces." *AIP Conference Proceedings*.
- Nasr, Mohamed NA, and Mohamed MA Ammar. 2017. "An evaluation of different damage models when simulating the cutting process using FEM." *Procedia CIRP* 58:134-139.
- Parulekar, Yogita M, G.R Reddy, K.K Vaze, and H.S Kushwaha. 2004. "Lead Extrusion Dampers for Reducing Seismic Response of Coolant Channel Assembly." *Nuclear Engineering and Design* 227 (2):175-183.
- Patel, C. C. "Seismic Analysis of Parallel Structures Coupled by Lead Extrusion Dampers." *International Journal of Advanced Structural Engineering* 9 (2).
- Rodgers, G.W. 2009. "Next Generation Structural Technologies: Implementing High Force-to-Volume Energy Absorbers." Ph.D. thesis, Mechanical Engineering, University of Canterbury, Christchurch, New Zealand, Ph.D. thesis.
- Rodgers, G.W., J.G. Chase, J.B. Mander, N.C. Leach, and C.S. Denmead. 2007. "Experimental Development, Tradeoff Analysis and Design Implementation of High Force-to-Volume Damping Technology." *Bulletin of the New Zealand Society for Earthquake Engineering* 2007 40 (2):35-48.
- Rodgers, G.W., J.G. Chase, J.B. Mander, N.C. Leach, C.S. Denmead, L. Cleeve, and D. Heaton. 2006. "High Force-to-Volume Extrusion Dampers and Shock Absorbers for Civil Infrastructure." *Proceedings of 19th Australasian Conference on the Mechanics of Structures and Materials*.
- Rodgers, G.W., Solberg, K.M, Mander J.B, Chase, J.G, Bradley, B.A, Dhakal, R.P. 2012. "High-Force-to-Volume Seismic Dissipators Embedded in a Jointed Precast Concrete Frame." *Journal of Structural Engineering* 138 (3):375-386. doi: 10.1061/(ASCE)ST.1943-541X.0000329.
- Saffar, R. Jalili, and M. R. Razfar. 2010. "Simulation of end milling operation for predicting cutting forces to minimize tool deflection by genetic algorithm." *Machining Science and Technology* 14 (1):81-101. doi: 10.1080/10910340903586483.
- Sevier, M, HTY Yang, S Lee, and S Chandrasekar. 2007. "Severe plastic deformation by machining characterized by finite element simulation." *Metallurgical and Materials Transactions B* 38 (6):927.
- Sevier, M, HTY Yang, W Moscoso, and S Chandrasekar. 2008. "Analysis of severe plastic deformation by large strain extrusion machining." *Metallurgical and materials transactions A* 39 (11):2645-2655.
- Skinner, RI, RG Tyler, AJ Heine, and WH Robinson. 1980. "Hysteretic dampers for the protection of structures from earthquakes." *Bulletin of the New Zealand National Society for Earthquake Engineering* 13 (1):22-36.
- Soydan, Cihan, Ercan Yüksel, and Erdal İrtem. 2018. "Retrofitting of pinned beam-column connections in RC precast frames using lead extrusion dampers." *Bulletin of Earthquake Engineering* 16 (3):1273-1292.
- Tsai, C.S, W.S Lai, C.W Chang, and M.C Li. 2002. "Testing and Analysis of a New Lead-Extrusion Damper." *ASME 2002 Pressure Vessels and Piping Conference*.

- V. Vishnupriya, G.W. Rodgers, and J.G. Chase. 2021. "Modeling limit force capacities of high force to volume lead extrusion dampers." *Front. Struct. Civ. Eng.* 15 (3):609-622. doi: 10.1007/s11709-021-0724-x.
- Vishnupriya, G. W. Rodgers, J. B. Mander, and J. G. Chase. 2018a. "Precision Design Modelling of HF2V Devices." *Structures* 14:243-250. doi: <https://doi.org/10.1016/j.istruc.2018.03.007>.
- Vishnupriya, V., G. W. Rodgers, J. B. Mander, and J. G. Chase. 2018b. "Precision Design Modelling of HF2V Devices." *Structures* 14:243-250. doi: 10.1016/j.istruc.2018.03.007.
- Vishnupriya, Vishnupriya, G. W. Rodgers, and J. G. Chase. 2022. "Nonlinear Finite-Element Modeling of HF2V Lead Extrusion Damping Devices: Generic Design Tool." *Journal of Structural Engineering* 148 (1):04021227. doi: doi:10.1061/(ASCE)ST.1943-541X.0003170.
- Weber, M., H. Autenrieth, J. Kotschenreuther, P. Gumbsch, V. Schulze, D. Löhe, and J. Fleischer. 2008. "Influence of friction and process parameters on the specific cutting force and surface characteristics in micro cutting." *Machining Science and Technology* 12 (4):474-497. doi: 10.1080/10910340802518728.
- Wrzesniak, D., Rodgers, G.W., Fragiaco, M., Chase, J.G. "Experimental Testing of Damage-Resistant Rocking Glulam Walls with Lead Extrusion Dampers." *Construction and Building Materials* 102:1145-1153.
- YAN, Weiming, Yong LI, Yanjiang CHEN, and Liang SU. 2011. "Study on Application of Lead Extrusion Dampers in Seismic Control of Viaducts [J]." *Journal of Highway and Transportation Research and Development* 4.
- Yang, MF, ZD Xu, and XC Zhang. 2015. "Experimental study on lead extrusion damper and its earthquake mitigation effects for large-span reticulated shell." *Steel and Composite Structures* 18 (2):481-496.
- Zhao, He, Wang, He-nan, Wang, Meng-jun, Li, Guang-yao. 2012. "Simulation of extrusion process of complicated aluminium profile and die trial." *Transactions of Nonferrous Metals Society of China* 22 (7):1732-1737.
- Zhuang, Xin-Cun, Zhao, Zhen, Xiang, Hua, Li, Cong-Xin. 2008. "Simulation of sheet metal extrusion processes with Arbitrary Lagrangian-Eulerian method." *Transactions of Nonferrous Metals Society of China* 18 (5):1172-1176.

Regenerative public-spend projects in New Zealand built environment: perceptions from across the system on creating the conditions for success

Jas Qadir^{1*}, Dave Moore², Ali Ghaffarian Hoseini³, Clare Tedestedt George⁴, James O. Rotimi⁵

¹ School of Future Environments, Auckland University of Technology (AUT), Auckland, New Zealand.

² Health and Safety by Design, Health and Technical Services Group, WorkSafe New Zealand.

³ School of Future Environments, AUT, New Zealand.

⁴ Mackie Research and Consulting Ltd.

⁵ School of Built Environment, Massey University, New Zealand.

*Corresponding author: jas.abdul@aut.ac.nz

Abstract

This paper presents perceived definitions, benefits, barriers and proposed solutions for the contextualisation and application of regenerative development concept in New Zealand built environment public-spend projects from a strategic decision-making perspective.

The research design was based on a qualitative, critical interpretivist approach using systems theory with Rasmussen's Socio-Technical Model to develop the boundaries for participant selection and Ecological System Model to present the findings for reported barriers and proposed solutions for application of regenerative development in NZ built environment projects.

The research design employs phased data collection in the form of archival data mining and pilot interviews (Phase One), semi-structured interviews (Phase Two) and focus group discussions (Phase Three) to arrive at the findings. The sampling criteria for these phases included a selection of system-wide participants from politicians, central and local government, industry professionals, industry body representatives, researchers, and community, iwi, and mana whenua groups.

Various themes resulted from the findings of Phases One and Two which were then prioritised to three main themes in Phase Three. These themes, with regards to contextualisation of regenerative development in NZ built environment are funding and finance, skills and capability, and NZ built environment system with regards to project owner buy-in, trust, and diverse representation in project teams.

Key conclusion is that the regenerative development concept requires a paradigm shift in how decisions are made, and funded. It requires current system-wide decision-making and funding structures, processes, skills, training, reporting tools, and system-wide collaboration to mature to successfully deliver regenerative projects and measure success.

Keywords

Regenerative development; Regenerative; Built Environment: New Zealand: Public-sector.

Introduction

This study investigated the perceptions relating to the definitions, benefits, barriers and potential solutions regarding the contextualisation and application of a Regenerative development concept, in New Zealand built environment public-spend projects. Regenerative development is the approach and process of achieving positive, broader social, natural, financial and human outcomes (multiple capitals) collectively through built environment investment decisions, especially in the early pre-feasibility stage.

Sustainability – staying where we are, is not sufficient. New Zealand Government investments need to consciously rebuild capitals, and in specific strategic ways. Due to the novelty of this emerging field, the mechanisms and potential impacts of regenerative development and design in New Zealand were overwhelmingly unresearched and undocumented. A more exploratory approach was adopted for this work, in response.

The over-arching research question was: How would (the New Zealand domestic) public-spend development (process) need to change, in order to deliver (multi-capital) regenerative development projects?

The research design was based on a qualitative, critical interpretivist approach. Employing Rasmussen's socio-technical framework (Risk Management Framework), to develop the boundaries for the study, and an Ecological System Model to develop the conceptual frameworks to manage the findings. Data collection was carried out in three phases, with each research stage informing the next. Starting with archival data review and exploratory interviews, followed by semi-structured interviews with a wider system sample, and finally focus group discussions. The 50 participants included: politicians, central and local government officials, industry professionals, researchers, and community, and mana whenua representatives.

1. Regenerative development presents with clear conceptual merits, but complex system-wide barriers.
2. Regenerative development requires innovators in New Zealand to progress, but the public-sector generally sits further back in the Diffusion of Innovation 'pack.' Public-spend projects may be an attractive target for Regenerative development, given their huge scale and extensive potential for societal benefits, but is it realistic to expect Government alone to achieve such a profound step?
3. The cycle times for Regenerative project learnings are far longer than Government election intervals. Some Regenerative developments will be inter-generational in scope, beyond even the normal 80 year lifecycle of a major facility. This research indicates the need for Regenerative development concepts to be shaped in parallel with Anticipatory Governance advances that allow beneficial iterative development across multiple changes of Government.

This doctoral study was the first of its kind in New Zealand, providing valuable insights on the contextual prerequisites for the successful adoption of a Regenerative development concept in New Zealand.

Literature Review

Projects with Regenerative approaches adopt a living systems-based approach, within which buildings are not considered individual objects, but instead are designed as parts of larger nested systems, allowing complex and mutually beneficial interactions between the built environment, the living world, and human inhabitants (Regenesi, 2016). For the purposes of this study the Robinson and Cole definition was adopted as a starting point for its match with contemporary anecdotal usage in the New Zealand Regenerative development (RD) community, “Regenerative development aims to restore or create the capacity of ecosystems where potential is created by the social, cultural, human, natural and financial values of the place collectively informing the development process” (Robinson & Cole, 2015).

The motivation for the study arose from a combination of current international socio-economic-political issues, that jointly resulted in the New Zealand Government seeking to systematically gain wider measured benefits from public building and infrastructure projects. Hall (2019) points out that in trying to resolve these inter-related issues, we should be wary of creating new ones, specifically in the socio-political domain.

The interactions between costs and benefits are as important strategically as the elements themselves. These can be seen as Governance barriers, that provided further motivation for this specific study to be undertaken. Barriers of this type include reportedly fragmented interaction; between Central and Local governments and, between the public and private sector - especially regarding planning for climate change adaption and mitigation.

Benefits

Reed (2007) and Zari (2009) highlight the following eight potential outcome / impact benefits from the use of regenerative development:

1. Improved and integrated decision-making, including coordination of physical design and policy across different sectors, to create holistic benefits.
2. Improved feedback mechanisms and lines of communication, due to a systems-based approach.
3. Creation of more equitable communities and relationships through participation and local place-based approach resulting in enhanced political efficacy, well-being, democratic processes, and an increased sense of ownership and belonging.
4. An increased emphasis on local traditions and place-based indigeneity - this could be particularly significant in New Zealand given existing traditions and knowledge, related to specific places.
5. An improved economic benefit, due to the development of place-based indigeneity resulting in the creation of a ‘unique selling point’ for the development.
6. An improved understanding, appreciation, and celebration of the place through design and project planning elements that further celebrate the personal and cultural expression of the place.
7. Improved used of resources and waste prevention.
8. Development of positive outcomes for human society and culture which are less present in conventional, green, and restorative approaches (Reed, 2007).

The built environment is not responsible for all factors that contribute to healthy communities, but a Regenerative approach does potentially positively affect more aspects of this, such as cultural identity, personal satisfaction, and psychological health. This is attributed

to a Regenerative approach including more than just a small design team in the design processes and decision-making. Which in turn has been seen to contribute to the recognition of the indivisibility of environmental, economic, social, and cultural health (Mang et al., 2009).

Barriers

One of the most significant challenges discussed anecdotally in New Zealand is simply the life cycle of existing natural and built environment. Both are long-term resources. With regards to the built environment, the typical design life for infrastructure in New Zealand is 100 years. For buildings, it is 80 years (MBIE, 2019). If progress towards a fully sustainable built environment follows a conventional, business-as-usual approach, significant opportunities to influence the built environment may be missed for many decades to come. A key consideration is how to build on progress to date to make the required shift to regenerative development, in a way which addresses the barriers and subsequent challenges.

Research undertaken by the multi-nation EU-based COST Action Programme (Brown, Haselsteiner, Apro, Kopeva, Luca, Pulkkinen, and Rizvanolli. 2018), identified six commonly encountered barriers to developing a more sustainable approach to the built environment. As summarised below:

1. Sustainability requires an holistic approach across sectors and environmental, economic, political, and social factors. This is different from the 'silo' approach of working within well-defined disciplines, which is the traditional way of constructing and maintaining the built environment. It can be further improved to include cultural and human factors.
2. There are poor links between systemwide decision-makers. And although designers are often aware of sustainability issues, these are not often included at high-level decision-making; which this prohibits their implementation and inclusion in practice. In other words, design for sustainability is often appreciated by designers and there is an increasing number of buildings that demonstrate sustainable design, but it is rarely a priority for both private and public high-level decision-makers.
3. There are tools available to assist with incorporating sustainability into design, but they are often theoretical and do not take account of the needs of the practice. Furthermore, there is a lack of knowledge and skills relating to what tools to use and how to use them, and what indicators and benchmarks relate to specific projects.
4. Most projects are driven by capital costs. There is a lack of reliable data or intelligence relating to whole-life cost-benefits. Consequently, sustainability appears as an additional capital cost, whereas on a whole-life cost basis it can result in large cost savings.
5. There is a lack of knowledge transfer from one project to another, both in terms of the positive benefits and the lessons learnt from any unsuccessful measures. There can be a tendency to 'greenwash' projects and not make public any failures that occur. This has sometimes resulted in a cynical attitude to sustainability, with rumours of failure discouraging others. There is limited evidence of success because designers and developers are afraid of exposing failure.
6. Many projects are fast-tracked, and sustainability does not feature strongly, if at all, in many of the day-to-day decision-making procedures. Even if a sustainable approach is adopted in the early concept stages of a project design, it is often ill-defined and lost when it comes to the real-time and cost pressures of the project programme. It is most often the 'last line item' that is traded-off for increased floor space.

Limitations

Cole (2012), Zari (2012), and Clegg (2012) in their papers identify a lack of theoretical and applied literature as limitations to Regenerative development. Some of the academic literature contains so called case studies, but these are typically short vignettes performed by practitioners, often with vested interests. There is also low independent commentary on these projects, especially from the research and academic community.

Cole (2012) points out that the project examples in existing literature are almost exclusively non-urban, set within relatively coherent community contexts, and with greater access to natural amenities. Cole adds that it remains unclear at this stage how the notion of ‘place’ and the Regenerative approach might accommodate densely urban settings with more complex and diversified communities and obliterated natural amenities. Furthermore, the cherry-picking option provided by the currently available green and Regenerative design certification tools may cause the living systems approach to not be fully realised to its potential (Ade, 2017).

Further, there is a need to understand ecosystem services at a larger scale (city, region, or ecosystem boundary) when devising goals and targets for individual buildings or small developments. Careful thought needs to be put into whether it is more appropriate to use human-defined urban boundaries or those related to ecosystems themselves, such as, for example, habitat-type demarcations, or water catchment zones when using ecosystem services analysis (Zari, 2012).

Concept vs Application

With regards to presenting a critical view, Clegg (2012) argues that:

1. The daunting complexity of systems thinking is a key consideration. Increasing complexity, in an already complex decision-making process that accompanies most architectural and urban design projects, could reduce the capacity for change. The unexpected negative outcome is to impede the flow of design ideas that eventually produce a building. Added complexity in the design process does not ensure a better building.
2. Some of the systems that are beginning to develop around the idea of Regenerative design hold the potential to stultify innovation and cause stagnation in decision-making. There is a danger in complete reliance on the idea that building design needs to emerge from a very broad-based all-encompassing consensus of stakeholders.
3. Consultation and empowerment have to be part of the design process, but that process needs to be skilfully facilitated, and often leaps in an individual’s imagination is needed to derive from a shared holistic understanding of Regenerative design principles. Defining a system (particularly a complicated one) and engaging stakeholders in a process is not a guarantee of high-quality sustainable design.
4. There is a need to evaluate the existing building stock carefully and devise ways of working with it. The old attitude of ‘demolish and re-build’ is inappropriate as the building stock is a neglected resource. In future thinking, this needs to be brought more into the design equation, and ‘regeneration’ as we used to know it will become synonymous with a newly defined regenerative design process.

5. Current funding, policy and legal decision-making structures may not allow inclusion of social, cultural, natural, and economic benefits together. However, the trade-offs between capitals and benefits must be identified, and the transfer of risk or externality to funding and other capitals must also be recognised. It is beneficial to ask the questions. “Who will bear the consequences of these decisions?” and if not included in this project, where is this risk transferred?”.

3. Research Methodology

This exploratory, sequential research was undertaken in three phases, guided by a qualitative, critical interpretive approach. Figure 1 summarises how the three phases of activities fed into the next and how the system proponents aligned with the Diffusion of Innovations Theory (Rogers, 1962).

The research questions for this research are as follows:

1. What are the perceived definitions of regenerative development, as held by parties active in the shaping of the New Zealand built environment?
2. What are the potential benefits of regenerative development in New Zealand?
3. What are the potential barriers for regenerative development in the New Zealand context?
4. How may a regenerative approach for built environment development fit within the strategic pre-feasibility decision-making process of public-spend projects in New Zealand?

Phase One: Review of archival data and exploratory interviews

Phase One comprised of two activities, the review of archival data and a series of exploratory interviews. Purposive sampling alongside the Risk Management Framework (Rasmussen, 1997) was used to select participants for the exploratory interviews. The interviews provided context to the archival data. These interviewees were mainly innovators and early adopters, as per the Diffusion of Innovations Model enabling the researcher to gain insight into practical challenges and barriers being encountered already at this early stage.

The interview questions for Phase One were developed using the literature review and initial conversations with industry informants. The analysis of Phase One findings informed Phase Two Interview questions.

Phase Two: Interviews with system participants

Phase two consisted of semi-structured interviews with system participants. The purpose being to expand and further refine the findings of Phase One by exploring the concept of regenerative development levels across the full public investment decision-making system for the New Zealand built environment. Fifty potential participants were initially selected using purposive sampling of which 39 agreed to be interviewed. The data for the Phase Two Detailed Interviews was collected between June and September 2020. At this point that majority of the interviews were conducted online to adhere to the COVID-19 Ministry of Health Restrictions and AUT Ethics Committee Instructions for Research during COVID-19. The interview protocols and data collection techniques remained the same across Phases One and Two.

The participant selection criteria for Phases One and Two is explained in Table 1.

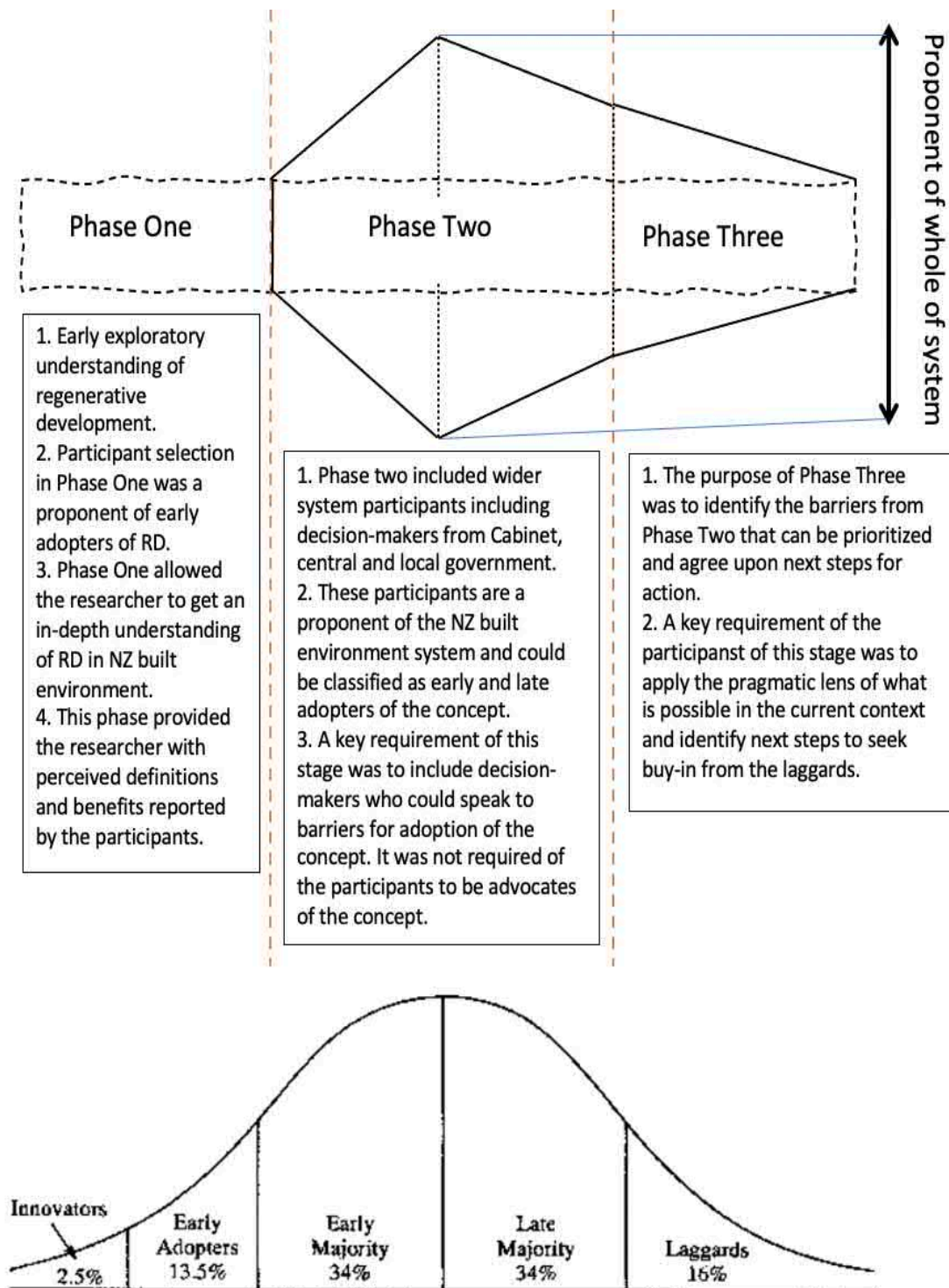


Figure 1: Research Data Collection and Analysis Design

Phase Three: Focus groups with a selection of system participants

Phase three consisted of two focus group discussions, with a total of 16 invited participants all previously interviewed alone in the previous two phases. The purpose of these focus group

discussions was to share and discuss the findings from phases One and Two with the participants to explore and refine the findings collectively. Further, the researcher sought to identify the principal barriers to RD to be, and capture preliminary concepts on what the associated solutions potentially were. Lastly, these group discussions were designed to collectively identify some key next steps required for future research.

Table 1: Phases One and Two participant selection criteria

Participant Systemic areas	Invitation Criteria
Government departments responsible for public-spend decisions	1. Involved in the decision and policy making of New Zealand's built environment AND 2. Striving to find innovative and better ways to fund the development of New Zealand's built environment AND 3. Encouraging development of best practice for decision making on public-spend.
Policy makers and local councils informing the public-spend decisions	1. Involved in the decision and policy making of New Zealand's built environment AND 2. Striving to implement best practice through international consultation and education AND 3. Invited to be part of project decision making in the pre-feasibility stage. (Or) Invited to be part of change-making decisions (or) employed in a change-making role AND 4. Invited internationally to provide policy making expertise AND 5. Professionally collaborated with international built environment innovators.
Sector Bodies informing policymakers and local councils	1. Involved in the decision and policy making of New Zealand's built environment AND 2. Striving to implement best practice through international consultation and education AND 3. Invited to be part of project decision making in the pre-feasibility stage. (Or) Invited to be part of change-making decisions (or) employed in a change-making role AND 4. Invited internationally to provide professional expertise AND 5. Professionally collaborated with international built environment innovators.
Individual Organizations undertaking built environment projects	1. Involved in the decision-making process of New Zealand's built environment AND 2. Striving to implement best practice through international consultation and education AND 3. Invited to be part of project decision making in the pre-feasibility stage. (Or) Invited to be part of change-making decisions (or) employed in a change-making role AND 4. Invited internationally to provide professional expertise AND 5. Professionally collaborated with international built environment innovators.
Community Organizations informing sector bodies, policymakers and individual organisations	1. Involved in inter-generational decision making for the public-funded built environment AND 2. Representing the minor population through an organized governance system AND 3. Invited to be part of project decision making in the pre-feasibility stage. (Or) Invited to be part of change-making decisions (or) employed in a change-making role AND 4. Participants involved in the maintenance and upkeep of the built environment.
End Users including Facility Management	1. Involved in inter-generational decision making for the public-funded built environment AND 2. Representing the minor population through an organized governance system AND 3. Participants spend 6-8 hours/day interacting with the same built environment AND 4. Participants involved in the maintenance and upkeep of the built environment.

4. Findings and Discussion

This section presents an overview of the primary themes that emerged from the findings and analysis. This is followed by examples of the use of two models, firstly Rasmussen's Risk Management Framework used for initial, socio-technical system mapping. Then the application of the Ecological model for plotting reported barriers to successful Regenerative development project initiation and execution. An finding regarding comparative international foci on forms of capital in Regenerative exercises is also noted.

Primary themes

Regenerative development presents with clear conceptual merits, but complex system-wide barriers.

1. Regenerative development is perceived to be in the Innovation phase in New Zealand, (as per Diffusion of Innovation theory). However, the findings also suggest that the key public-spend agencies are seen to operate mainly within the late majority and laggard space, with regards to adoption of innovation - having an affinity for stability. This raises the question of whether a Government-only model, is currently capable of framing and driving Regenerative development projects, with the level of innovation required.
2. The use of systems approach tools (in this case Rasmussen's Risk Management Framework and the Ecological System Model) appear valuable in assessing, and potentially harnessing: system-wide collaboration, improved project owner buy-in due to wider consultation, and identification of the required skills and capability to successfully deliver Regenerative projects. These assets better enable: long-term integrated planning, delivery, measurement, and reporting - which collectively would be expected to support the development of enhanced trust across the system.
3. Regenerative development projects will require a fundamental shift in how decisions are made in the public sector, and how the work is funded.
4. To mature and successfully deliver Regenerative projects, changes will be needed to made to: funding structures, processes, skills, training, reporting tools, success measures, and patterns of system-wide collaboration.
5. Greater upstream resource allocation will generally be required to cover extensive extra engagement costs; by comparison to the current more linear model that does not engage with the whole system from the outset.
6. Without high quality facilitation, the whole-of-system engagement process required for Regenerative development projects (Everyone-Early-(talking about)Everything) could potentially stagnate through engagement fatigue and a failure of confidence on the part of the participants. Many of whom will be new to the concept.
7. Regenerative development is currently perceived by non-specialists as more environmentally focussed concept. Examples are needed of contextualisation with particular regards to the other capitals – notably human and social, and in more complex urban settings, rather than rural ones.

8. The experience of the participants points to people in traditional and/or conventional systems struggling to grasp working by default with the inter-connectedness of the system(s), and the associated processes, tools, technology, contextual factors, and all-of-capitals benefits.
9. Boundary-setting in Regenerative development exercises was reported as remaining problematic, even though this sample was skewed towards the more knowledgeable and experienced participants. How whole is whole enough? How integrated is integrated enough? Scope remains a maturity issue to be resolved.
10. Achieving a system-wide transformation (evolution being more realistic than revolution in the New Zealand public sector) is expected to be slow. Iterative cycle lengths are anticipated to be based on the duration taken to evidence success through application of concept, which in built environment can be a decade or more, and several decades in the case of intergenerational projects.
11. The cycle times for regenerative project learnings are longer than New Zealand election intervals. It is expected that, in particular, the long-term intergenerational aspirations captured by Regenerative development work, will continue to be, to some degree, compromised in the political realm by economic, social (and other) priorities.
12. This study indicates concern, that the existing sets of (non-regenerative) priorities may remain effectively the same (as they have over previous decades) without explicit exploration of new multi-capital thinking, and the application of system-wide solutions.
13. Regenerative development thinking is frequently applied in conjunction with other complex-system concepts including: integrated design, systems thinking, whole-of-life approach, and levels of work. These concepts are inter-related and considered challenging to apply together, especially in the more traditional environments of Central and Local Government.
14. Regenerative development, by definition, is a system-wide exercise, requiring collective responsibility, commitment, and input. The concept of public-spend Regenerative development however, may be seen to imply that this is a Government-led and executed endeavour. This raises further questions about the necessary models of governance, management, execution, ownership and stewardship of such projects.
15. It was observed that the participatory burdens may well be disproportionately distributed on those communities and demographic groupings under most pressure, least resourced, and already seeking innovative solutions to address their social, cultural, natural, human, and financial challenges. Achieving genuine outcome equity will almost certainly require sustained attention across several Regenerative project cycles.

System map of the New Zealand public-spend built environment

Figure 2 maps the connections between various system participants, mainly the proponents of the system interviewed in this study. It shows the system and represents the information flow connections between the system levels. In application, this model when used in early strategic decision-making situations, can usefully represent the different stakeholders who need to be engaged early and can further enable a partnership structure for the achievement of positive, broader outcomes.

The dotted lines around the system map in Figure 2 identify the adjoining industries and sectors that directly engage with the New Zealand built environment for capital projects or indirectly to influence decision-making and change. This model of representation is based on the “three lines of work” (Regenesis, 2016) and Whole Systems Economic Development Approach (Ungard & Haggard, 2020; Mang & Reed, 2012).

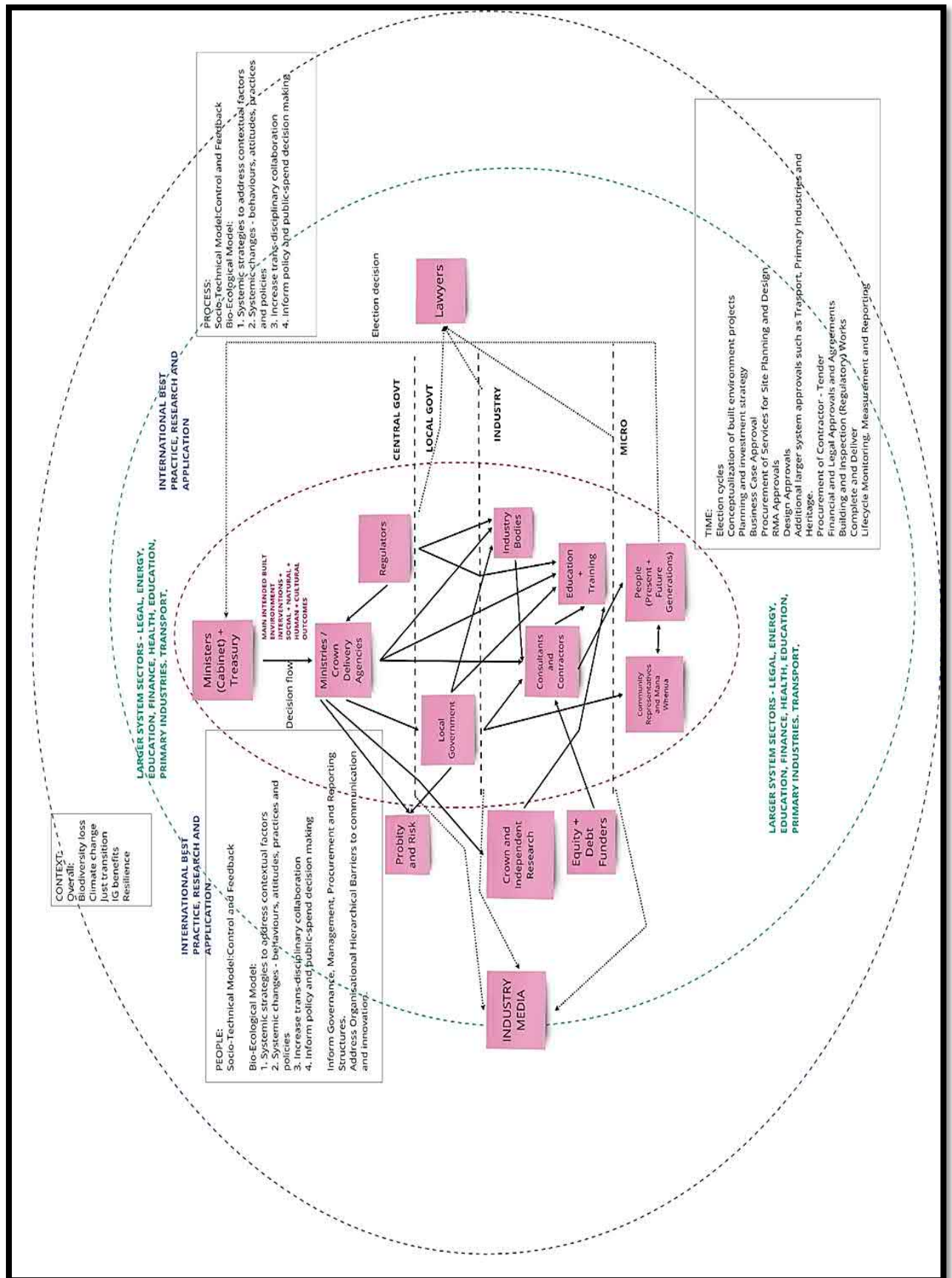


Figure 2: System map and interactions - interpretation of the system based on the findings

The data collected from the participants elucidated understanding of Regenerative development, barriers to application, proposed solutions from throughout the system and how the system elements interacted. Some key points on interactions are summarised below.

From the perspective of Rasmussen's Risk Management Framework, it was observed that there are outer-system elements, such as legal and business professionals, informing the key decision-making for project funding and financing. The findings further showed the reliance of key decision makers on the advice and recommendations from these parties. It was reported that subject matter experts are generally at a considerable distance from the decision-making process, and that there is a need for more collaborative, diverse decision-making and a two-way flow of information involving the full array of subject matter expertise. It was suggested that this would facilitate greater collective ownership of decisions in the system (and presumably higher quality decisions).

Common users of the projects such as the local community and mana whenua, are reported as being positioned even further away from the decision-making process, with little to no visibility of the context, process, or people. They need to be brought into the decision-making process by more innovative approaches, it was suggested.

From a modified Ecological System Model perspective, the barriers and proposed solutions mentioned by the participants were found to be cross-cutting across the micro-meso-exo-macro levels, thereby demonstrating that each system has a role to play in the decision-making and should be represented in the process.

The findings also support the position that the Chrono level of context-process-people-time is perceived as the primary point of access, as a majority of participants spoke to these elements, contextualising their experiences and what's important to this layer. Further, it was found that speaking to context-process-people-time was the most impactful way for the researcher to connect and establish connection with the participants. This happened through case examples and the participants found it simpler to speak to these case examples and were comparatively more motivated.

Ecological System Model - presenting reported barriers

A modified Ecological System Model adapted from Bronfenbrenner's Ecological System Models (1994) as shown in Figure 3 below plots the contextual factors acting as barriers determined as findings from Phases One and Two Interviews.

The purpose of using a modified Ecological System Model (EST) was to represent the various reported barriers and proposed solutions, across system levels, and visually represent the layout of system levels, as per the proponents of the system interviewed in this study and as per research sub-questions 3 and 4. The following adapted EST presents cross-cutting and co-dependent themes, along with the contextual factors and considerations for time, process, and people.

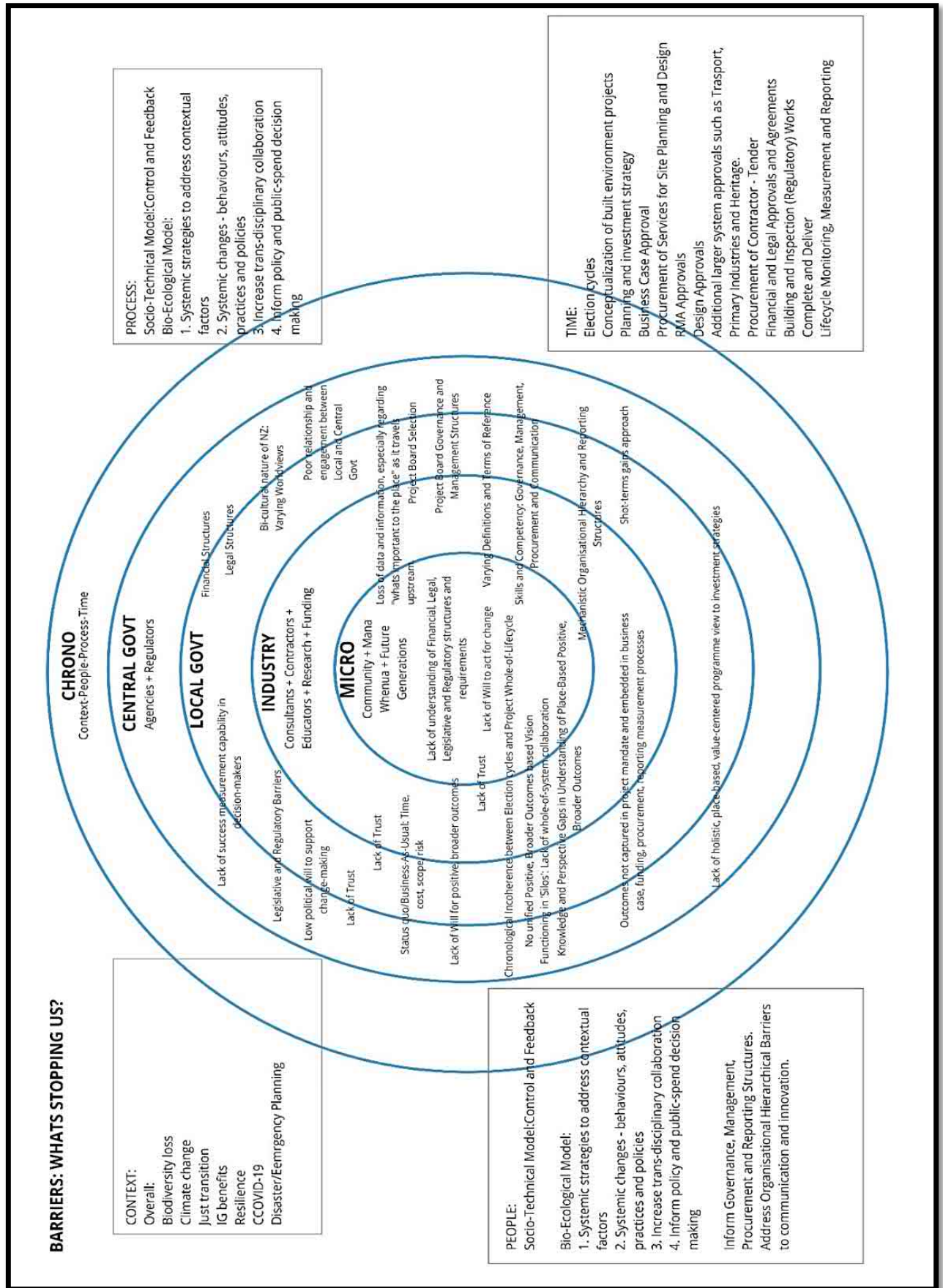


Figure 3: Ecological System Model based on the findings of reported barriers

Ecological system levels of reported barriers

Figure 3 below shows the raw count of participants that included specific ecological system levels in their responses regarding barriers to successful public-spend RD.

Scoring Criteria:

Score 0 for No:

- Participant did not mention the ecological sub-system and/or
- Did not contextualise through a scenario or example and/or
- Did not talk about system's processes and/or time and/or people.

Score 1 for Yes:

- Participant mentioned the ecological sub-system and/or
- Contextualised through a scenario or example and/or
- Mentioned system's processes and/or time and/or people.

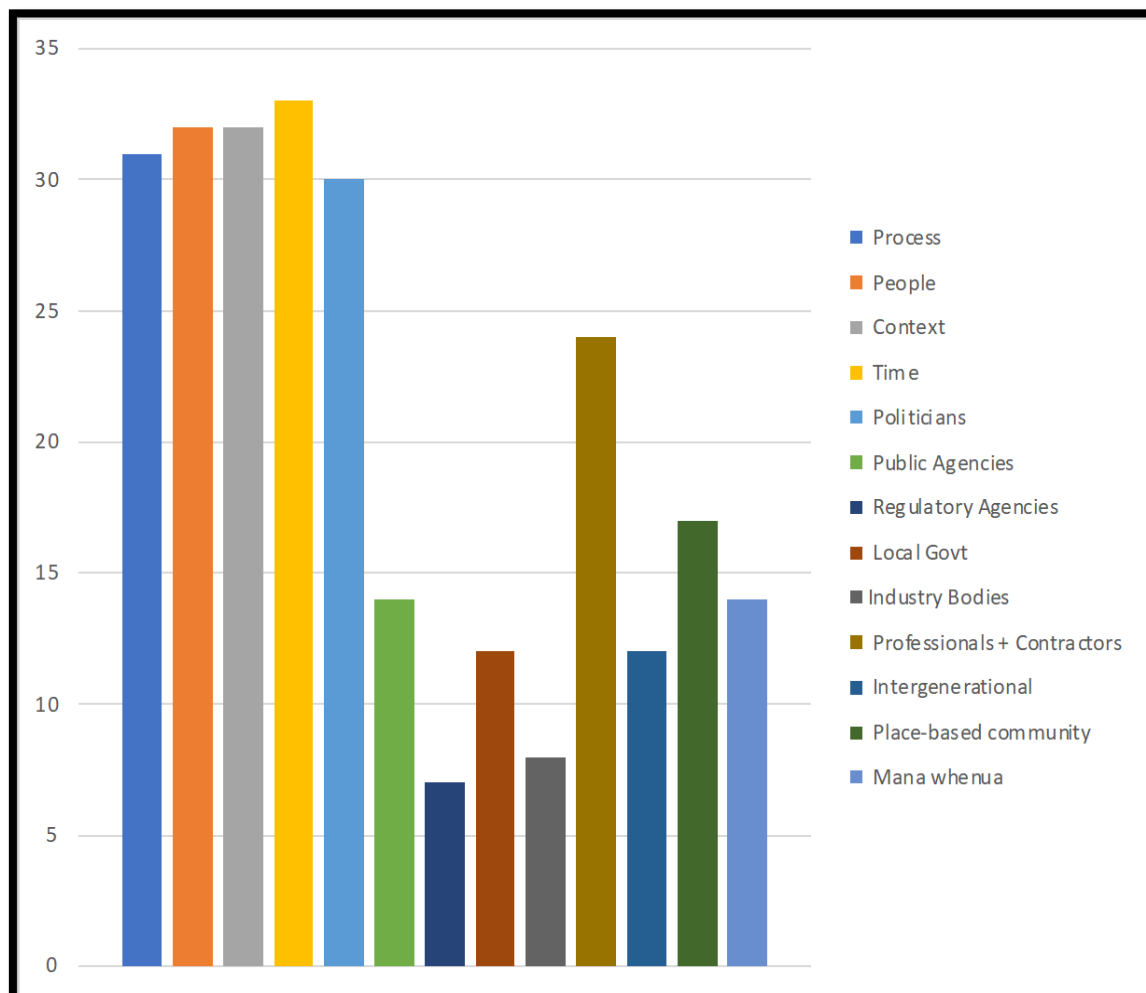


Figure 4: Count of system levels as per Ecological System Model mentioned by the participants in Phase Two

From the graph shown in Figure 4, it can be observed that the participants frequently mentioned: context, process, people, time and Central Government in their answers, indicating a 'front of mind' focus towards these system elements. It can be further noticed that regulatory bodies, local government and industry bodies were the least mentioned or least 'front of mind' system elements. This could point to mental model inconsistencies and practical intervention ideas with questions such as:

- Do government agencies really overestimate their importance in achieving public spend outcomes?
- Or, do the private sector not realise how much happens in government agencies that shapes their practices?
- Or, is there something else again going on – such as the Regenerative development community wanting to see the momentum come from them, and not being owned by big industry or government agencies?
-

Forms of capital raised during interviews

A similar approach was further adopted for scoring the multiple capitals mentioned and not mentioned by the participants.

Scoring Criteria:

Score 0 for No

Score 1 for Yes

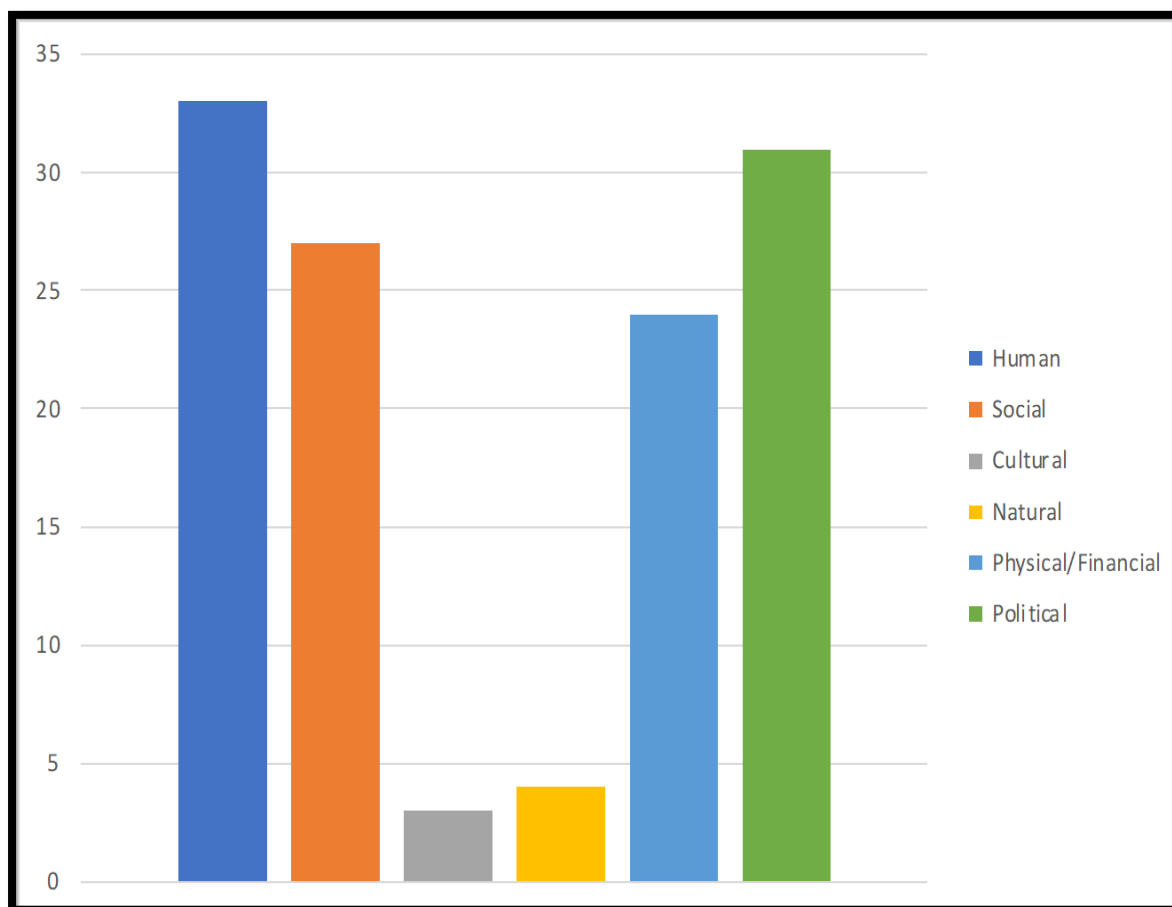


Figure 5: Count of capitals mentioned by all participants in Phase Two

Figure 5 represents how a modified Ecological System Model levels mentioned or spoke to various multiple capitals. Cultural and natural capitals were the least mentioned. This is an important observation as most of the international Regenerative development is rooted in regenerating the natural capital of a place. The findings of this study indicate that by contrast, in New Zealand the social, human, and financial capitals are foremost in the Regenerative landscape. Detailed discussion on these findings with regards to Ecological System Model Levels and Multiple Capitals is presented in the full thesis (Qadir, 2022).

Conclusions

This doctoral study was the first of its kind in New Zealand, providing valuable insights on the contextual prerequisites for the successful adoption of a Regenerative development concept in New Zealand. For the complete conclusions, limitations, and implications of the study on the system, refer to the full thesis from which this paper is drawn (Qadir, 2022).

Acknowledgements

The reported research was internally funded and supported by the Design and Creative Technologies Faculty of Auckland University of Technology, Auckland, New Zealand.

It would also not have been possible without the generous donations in-kind of expert time, by dozens of committed individuals and their supportive private and public organisations. Across New Zealand, and beyond. These include Bill Reed, Ben Haggard, and Pamela Mang from Regenesys Group (USA), Dr Dominique Hes (Australia), Jerome Partington of Jasmax Ltd (New Zealand) and the Regenerative Development community of New Zealand.

References

- Reed, B. (2009). The integrative design guide to green building: redefining the practice of sustainability. Advisian Worley Group. (2019). An examination of issues associated with the use of NZS Conditions of Contract. NZ Treasury: Infrastructure Transactions Unit.
- Beatrice Ungard and B. Haggard (2020). Whole Systems Economic Development: A Regenerative Approach, Medium.
- Clegg, P. (2012). A practitioner's view of the 'Regenerative Paradigm'. *Building Research and Information*, 40(3), 365-368.
- Cole, R. J. (2012). Regenerative design and development: current theory and practice. *Building Research and Information*, 40(1), 1-6.
- Cole, R. J., Busby, P., Guenther, R., Briney, L., Blaviesciunaite, A., & Alencar, T. (2012). A Regenerative design framework: setting new aspirations and initiating new discussions. *Building Research and Information*, 40(1), 95-111.
- Creswell, J. W., & Creswell, J. D. (2017). Research design: Qualitative, quantitative, and mixed methods approaches. Thousand Oaks, CA, US: Sage Publications.
- George, C. T. (2018). An Inquiry into Contextual Factors Impacting the Occupational Health, Safety, and Well-Being of New Zealand Truck Drivers: A Ecological Systems Approach. School of Business, Economics, and Law. Auckland, New Zealand, Auckland University of Technology, Doctor of Philosophy (PhD).
- Gibbs, G. R. (2018). Analyzing qualitative data (Vol. 6). Thousand Oaks, CA, US: Sage Publications.
- Hall, D. (2019). On care and carelessness. In D. Hall (Ed.), *A Careful Revolution: Towards a Low-Emissions Future* (pp. 163-183). New Zealand: BWB Texts.
- Kabir, Syed Muhammad. (2016). Methods of Data Collection.
- MacGregor, C., et al. (2018). The built environment and climate change: A review of research, challenges and the future. BRANZ Study Report SR403. Judgeford, New Zealand, BRANZ Ltd.
- Mang, P., & Reed, B. (2012). Designing from Place: A Regenerative Framework and Methodology. *Building Research and Information*.
- Mang, P., & Reed, B. (2014). The nature of positive. *Building Research and Information*.
- New Zealand Government Procurement. (2019). *Construction Sector Procurement Guidelines*. Retrieved from <https://www.procurement.govt.nz/procurement/principles-charter-and-rules/government-procurement-rules/>
- New Zealand Treasury. (2018). The Treasury Approach to the Living Standards Framework.
- Qadir, J., Moore, D., George, C. T., Hoseini, A. G., & Rotimi, J. O. (2020, 26 & 27 November 2020). To understand the systemic and contextual factors to improve the strategic decision making of Regenerative projects. Presented at the meeting of the 54th International Conference of the Architectural Science Association (ANZAScA) Auckland, New Zealand. Retrieved from <https://anzasca.net/wp-content/uploads/2021/03/ASA-2020-Book-of-Proceedings-WEB-1.pdf>
- Qadir, J., Moore, D., George, C. T., Hoseini, A. G., & Rotimi, J. O. (2020). To improve the strategic decision making for effective governance of public spend Regenerative projects. Presented at the meeting of the 54th International Conference of the Architectural Science Association, Auckland, New Zealand. Retrieved from <https://anzasca.net/wp-content/uploads/2021/03/ASA-2020-Book-of-Proceedings-WEB-1.pdf>
- Regenesis, G. (2016). Regenerative development and design: A framework for evolving sustainability. Retrieved from <https://ebookcentral.proquest.com>
- Robinson, J., & Cole, R. J. (2015). Theoretical underpinnings of Regenerative sustainability. *Building Research and Information*, 43(2), 133-143.
- Sertyesilisik, B. (2017). A preliminary study on the Regenerative construction project management concept for enhancing sustainability performance of the construction industry. *International Journal of Construction Management*, 17(4), 293-309. doi:10.1080/15623599.2016.1222665
- The Construction Sector Accord. (2019). *Construction Sector Accord: Transformation Plan*. Retrieved from <https://www.constructionaccord.nz/>
- Zari, M. P. (2019). Ecosystem services impacts as part of building materials selection criteria. *Materials Today Sustainability*, 3-4(2019).
- Zari, M. P., Kiddle, G. L., Blaschke, P., Gawler, S., & Loubser, D. (2019). Utilising nature-based solutions to increase resilience in Pacific Ocean Cities. *Ecosystem Services*.

Computer modelling and control system design for full scale concrete 3D printing using an industrial robotic arm

Roohollah Kalatehjari ^{1*}, Misha Versteeg ², Beatriz Mena Barreto Dos Santos ², and Maziar Ramezani ²

¹ Built Environment Engineering Department, School of Future Environments, Auckland University of Technology, Auckland 1010, New Zealand.

² School of Engineering, Computer, and Mathematical Sciences, Faculty of Design and Creative Technologies, Auckland University of Technology, Auckland 1010, New Zealand.

*Corresponding author: r.kalatehjari@aut.ac.nz

Abstract

Addressing the housing problem in New Zealand is a wicked problem that requires innovative multidisciplinary solutions. Facilitating small-scale construction firms – as a large part of the construction industry in New Zealand – with additive manufacturing can partially address this issue by bringing a sustainable, affordable, and superior construction technique to the market. 3D printing concrete is a rapidly growing technique because it reduces material waste and produces components with more flexibility in terms of design and faster than traditional methods. This multidisciplinary and advanced method engages computer, mechanical and construction experts. This paper initially discusses the steps required for a design-led approach to bring the advantages of additive manufacturing to the construction industry, and then focuses on the hardware and software developed and utilised by the authors for this purpose. The concrete mix designed and used in this study cures faster than regular construction concrete to enable the layers stacked vertically during the print. A robotic arm is used as the main hardware to which a concrete extruding nozzle is mounted. The concrete mixture is premixed and pumped with a grout pump through hosing to a modularly designed extruder nozzle with interchangeable nozzle shapes and sizes. A range of nozzle diameters and layer height are introduced to cater to different printing detail/ print times. Different software packages are used for modelling, slicing, and controlling purposes. Models are created by the modelling software, sliced into layers using slicer software, and imported into the controller of the robotic arm. Print speed, layer height, and extrusion rate are then fine-tuned to provide uniform curing and desired mechanical properties. The results obtained in configuring printable materials and printing design paved the way for further investigations on using this affordable and rapid construction method for a wide range of applications from small-scale to large-scale construction.

Keywords

3D printing; Additive manufacturing; Concrete; Construction; Robotic arm.

Introduction

Modernized 3D concrete printing began developing rapidly in 2008 and the first functional structure created by 3D Concrete Printing was revealed at Loughborough University (UK) in

2015. Currently, many companies and universities are focused on improving the process and parameters to produce components at high speed with good properties using concrete. There are several advantages and a small number of disadvantages recognised for concrete printing. Some advantages of using 3D printing techniques in the construction industry are reduced waste, low labour requirements, consistent and easily repeatable results, low cost, and rapid prototyping. On the contrary, a few disadvantages of this construction technique are risky transportation of the printers and a potential reduction in employee numbers in the construction industry which may result in increased unemployment. However, both mentioned disadvantages could be set off by proper design and implementation of this technique. Overall, the advantages of 3D concrete printing suppress the disadvantages listed previously, making this technique suitable and beneficial for the construction industry.

The residential construction sector is the primary aim for current 3D concrete printing companies. The compact sizing of the housing in residential areas allows for rapid construction using this manufacturing technique. Demand for construction-related occupations in New Zealand is projected to increase by 11 per cent between 2016 and 2022, by approximately 56,000 employees (including working proprietors) to a total of 571,300. This industry employed nearly 180,000 people only in the first quarter of 2021 (Ministry of Business, 2017). Labour dependency and cost reduction is the main benefit of this technology reducing the total cost of construction up to 80% (Elasad and Amirov, 2020). With the increasing demand for construction workers, the current shortage of workforce, and additional difficulties introduced by the Covid-19 pandemic, employing 3D concrete printing in construction looks a smarter option than ever.

Developing 3D concrete printing technology with local knowledge and materials would be a necessity for effective employment of this technology in New Zealand as the off-the-shelf commercial systems require large capital investment and do not usually provide enough flexibility in terms of material or design alteration. Table 1 shows the current pricing of industrial 3D concrete printers quoted by individual companies in NZD.

Table 1 – 3D concrete printers cost comparison

Manufacturer	Cost (NZD)	Type of 3D Concrete Printer	Country
Cobod	\$250 000	Gantry based Concrete Printer (no pump)	Denmark
CyBe	\$300 000	Mobile 3D Printer	Netherlands
Baumit	\$200 000	Extruding system only	Austria

Qorox (Hamilton) is the frontier company to obtain a 3D concrete printer in New Zealand after partnering with CyBe, a Netherlands-based company. Despite their recent development in acquiring local materials for 3D printing concrete, this technology has not been yet localised in New Zealand, and therefore, more research and development is required to develop and adapt it for New Zealand climate and market conditions (QOROX, 2021). A cost-effective and locally developed technology will allow material development and testing to suit the unique built environment of New Zealand. This research aims at the design, development, and testing of a full-scale 3D printing concrete system based on locally available materials and technology to facilitate the utilisation of this technology in the New Zealand construction industry with lower costs and more flexibility.

Research Background

A review of the existing literature was conducted on different versions of 3D concrete printing systems. The motion control system of a concrete printer can operate in several formats. The most common methods being, cartesian setups with 3 to 4 axes of motion (like conventional Fused Deposition Modelling (FDM) printers) and 5 to 6 axis of motion robotic arms which are extremely versatile and allow for complex geometries to be produced. The robotic arm motion control system was selected as the printing technology as the University-owned ABB IRB2600-12/1.85 robotic arm, thus, constraining the extruder design and software requirements tailored to this model of the robotic arm.

The remaining parts of the 3D concrete printing system consist of an extruder assembly, concrete hose management, and a concrete pump. With a key component being the final nozzle size. Nozzle size can be a constant variable with extrusion rate, print head speed and layer height being variable. These variables must be compared and adjusted for desirable mechanical properties. Variations of the main print parameters related to nozzle size are shown in Table 2.

Table 2 - Variations of the main print parameters related to nozzle size.

Study	Nozzle Size (mm)	Extrusion Rate (m^3/h)	Print Head Speed (mm/s)	Layer Height (mm)
(Malaeb <i>et al.</i> , 2019)	10 to 20 (Diameter)	0.324	87.6	NA
(Buswell <i>et al.</i> , 2018)	40 x 10	NA	30–35	6
(Lim <i>et al.</i> , 2016)	9 (Diameter)	NA	500–66	NA
(Ahmed <i>et al.</i> , 2016)	40 x 10	NA	NA	NA
(Lin <i>et al.</i> , 2018)	40 to 60 (Diameter)	0.09	40-80	12–18
(Weng <i>et al.</i> , 2018)	30 x 15	0.108	66.6	10

Research Methodology

This research follows an experimental approach by designing a controlled experimental environment in numerical models and practical laboratory experiments. By acquiring the ABB robotic arm for the research development, the research methodology of this project is comprised of four consequent steps including (i) the selection of suitable material to achieve a satisfactory mixture for extrusion; (ii) detailed finalised design appropriate for concrete extrusion; (iii) appropriate software integration with the ABB robotic arm; and (iv) testing and development. A concise description of each step is included in the following paragraphs.

The most basic concrete mix is composed of only cement, sand, and water. However, to achieve the desired mixture texture and workability different additives can be added to the mix. Different components can also influence the settling time, abrasion resistance and mechanical properties of concrete such as compression and tensile strength. The aggregate sizes used for the concrete mixture will also have an impact on the properties of concrete. For projects which require more compressive strength, the mixture will contain a larger number of smaller aggregates, such as fine sand, when compared to larger aggregates (Yu *et al.*, 2019).

The ratio of materials used for the concrete composition is also very important to achieve the ideal workability required for certain applications. This ratio can be determined experimentally as in every given situation, the proportion of each material used will differ. For this project,

this ratio was initially determined through standard Slump test and hand mixing and manual extrusion tests. For very dry mixtures, a slump of 0 to 25mm is expected while wet mixtures show slump results between 50 to 90 mm. For mixtures containing an average water content slump results of about 10 to 40 mm are anticipated. After achieving the ideal concrete workability for extrusion, the mixture was fine-tuned using hand printed tests with an in-house design and manufactured extruder, a motorised concrete mixer, and a grout pump. Figure 1 shows an expanded view of the designed extruder and the results of hand printing concrete with a 3D printed extruder assembly.



Figure 1 - (Left) Expanded view of the modular extruder assembly, (Right) Hand printing concrete using 3D printed extruder assembly with the nuzzle of 40 x 10 mm.

To run initial trial experiments the components were 3D printed due to the lead time of ordering and machining custom parts. The new design aimed to create a modular design capable of changing the nozzle extrusion diameter with ease. A groove was inserted at the base of each nozzle to accommodate an O-ring to ensure a good seal. The 3D printed nozzles were designed to be secured to a robotic arm mount with hose clamps. The final design for the nozzle is modular and directly connects with the concrete/mortar pump. Additional modifications were done to the initial design concepts after gathering further specifications from the locally available mixing and group pumps. Figure 2 shows an expanded view of the extruder assembly with the mounting plate, and the ABB robotic arm used in this research mounted with the manufactured extruder assembly.

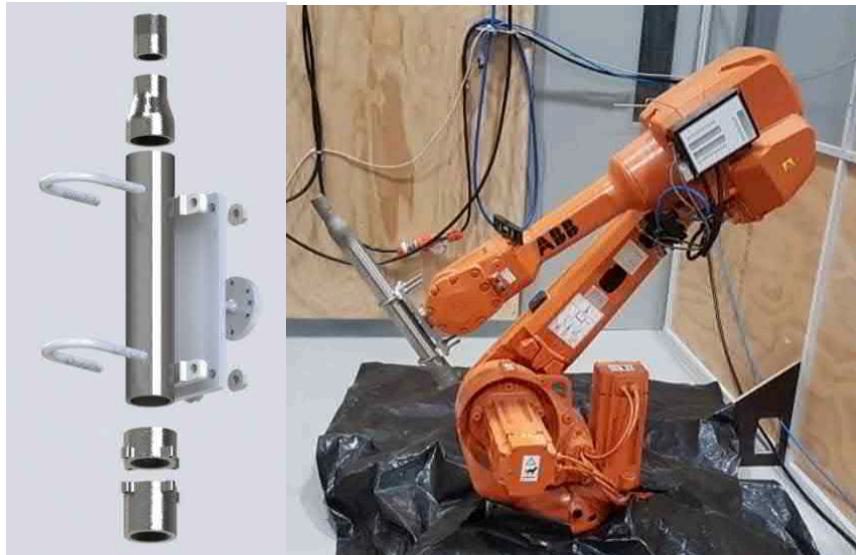


Figure 2 – (Left) Expanded view of the extruder assembly with the mounting plate, (Right) The ABB robotic arm mounted with the manufactured extruder assembly.

3D models of prints can be created using any 3D modelling software. 3D printers, generally convert the 3D models to G code which is generated with slicing software (e.g., Simplify 3D) to change independent parameters related to the printing process. The size of the nozzle, print speed, and layer height at which material is extruded are fundamental variables when printing concrete. As the initial extrusion tests were focused on the variable flow rate, a constant setting can be obtained and used for this parameter. All other variables can then be changed within the slicing software.

The object toolpath and printing parameters will be combined in the format of the RAPID code. RAPID code is the programming language associated with the ABB robotic arm. By using a virtual controller and running the RAPID code a virtual simulation of the complete 3D printing process can be done. This will show the travel movements of the robot arm to minimise any printing errors. Once the printing process for the specific component has been set up correctly the code can be uploaded to the robot.

Calibrating the extruder position with the printing platform will make the starting layer able to support the rest of the structure. Layers will be stacked vertically until the part is finished printing. RobotStudio environment was used for simulation of the robotic arm and calibration of the printing parameters with the components of the custom-designed system. Figure 3 shows a 3D model prepared in Solidworks software and converted to GCode in Simplify3D slicer, together with a simulation of 3D printing concrete by ABB robotic arm for the same model using the imported Gcode in Robotstudio.

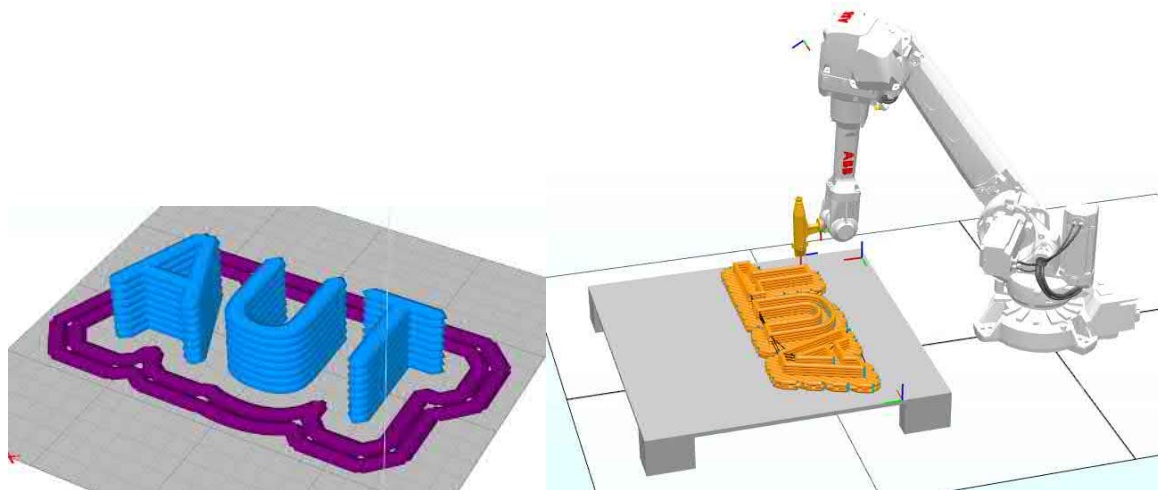


Figure 3 – (Right) a 3D model prepared in Solidworks software and converted to GCode in Simplify3D slicer, (Left) simulation of 3D printing concrete by ABB robotic arm for the same model using the imported Gcode in Robotstudio.

Findings and Discussion

The right concrete mixture is essential for a successful 3D print. To achieve the most suitable mix for 3D printing, a range of proportions of cement, water and sand were tested and the consistency and setting time of each different mixture was observed over a period. Tables 3 to 5 show three selected mixtures based on the results of the literature review for further investigations. Out of the three mixtures, mixture 1 requires the highest quantity of water due to its high cement composition which can lead to lower strength and durability. Mixture 2 contains less water and cement in comparison to the previous mixture which is an advantage as by lowering the amount of cement, the mixture cost is also reduced. Finally, the addition of larger particles of sand on mixture 3 resulted in the reduction of water content required for the mix as the third mixture required even less liquid water than the second.

Table 3 Mixture 1 with 3:1:1 ratio (cement: water: sand)

Cement (g)	Water (g)	Sand (g) NO.1 Sand
600	200	200
600	215	200
600	240	200

Table 4 Mixture 2 with 2:1:1 ratio (cement: water: sand)

Cement (g)	Water (g)	Sand (g) NO.1 Sand
500	157.5	200
500	177.5	200
500	187.5	200

Table 5 - Mixture 3 with 2:1:1 ratio (cement: water: sand)

Cement (g)	Water (g)	Sand (g) ½ NO.1 Sand / ½ Builders Mix
500	157.5	200
500	167.5	200
500	177.5	200

By further testing mixtures, 3 and 2 showed the best results for consistency and porosity. The materials used for each of these mixes bonded very well together, creating a smooth sample. In addition, no cracks appeared on the outer surface which shows that the mixture has good structural properties, to begin with. To test the workability of the concrete mixtures, a manual extrusion method using a plastic bag was used to prepare mixtures in small volumes and minimise waste. A range of tip sizes was tested using this technique starting from 10 mm to 40 mm. The results for a sample concrete mixture are shown in figure 4. Neither of the mixes extrudes well at 10 mm but they extrude smoothly at bigger cut sizes, especially 30mm and 40 mm. Three extra layers were extruded on top of the fresh first layer, resulting in a satisfactory final extrusion. It is important to highlight that the mixes used for the initial tests were hand-mixed, and more consistent mixtures were later produced with the use of a concrete mixer.



Figure 4 – (Right) Manually extrusion of a concrete mixture using a plastic bag for concrete workability test, (Left) Sample result for a mixture using different nuzzle sizes.

With acquiring a grout pump, samples containing a constant mixture were printed using different pumping speeds, from the lowest to the highest setting. Samples that were printed at higher pumping speeds showed smoother profiles than those samples that used low pumping speeds. At higher pumping speeds, it becomes very challenging for the operator to control the manual extrusion of concrete but that should not impact the extrusion quality if the ABB robot was used and set to the right speed configurations. In addition, higher pumping speed also caused the formation of air bubbles in the hose due to the batch size used for the experiment; however, this factor would not be an issue in bigger batch sizes. Figure 5 shows the concrete mixing and pumping machines used in this research, together with the operation of concrete consistency and flow test for calibration of the pumping speed.



Figure 5 – (Right) Concrete mixing and pumping machines used in this research, (Left) Concrete consistency and flow test for calibration of the pumping speed.

The addition of accelerant to the mixture aided the setting process of concrete, reducing the curing time of the mix. However, as the accelerators increase the hydration rate, it also causes high heat of hydration which consequently causes autogenous deformation and subsequent cracking in concrete (Safiuddin *et al.*, 2018). To prevent these cracks caused by plastic shrinkage, the use of a retarder is recommended as it prevents rapid loss of moisture from the surface of the concrete. The retarder should be added at the first stage of the process while the concrete is in the concrete mixer. Furthermore, the accelerator should be included in the mixture just before extrusion.

For the trials performed during this project, the used batches were scaled up by a factor of 40 from the original, experimental ratio. This ratio performed well during the extrusion; however, the mix did not fill the pump tank which, at times, resulted in the formation of air bubbles inside the hose. In addition, as the pump is rinsed before use, some of the pumped concrete would end up mixing with the remaining soapy water, altering the texture that is required for successful prints. Therefore, larger batches are recommendable to produce the best quality print as the first volume to leave the hose is often mixed with the remaining soapy water left on the pipe, thus if a large batch is produced this initial volume can be discarded which still leaves a good amount of concrete to be used in the actual print. Additionally, a higher concrete volume would result in fewer air bubbles which improve the quality and smoothness of the print.

Conclusion

The component design and initial testing of the concrete-printing system described in this research provide promising results for the use of computer modelling techniques and additive manufacturing processes to produce printable concrete structures in New Zealand. This technique promises a significant and positive impact on the current housing crisis experienced by New Zealand, especially in the Auckland and Wellington regions where the least affordable residential properties can be found. By providing a more sustainable, affordable, and rapid construction technique for a range of applications in the industry, the additive manufacturing of concrete structures could potentially replace traditional construction techniques currently utilised around the country with continuing research and improvements.

The presented research is progressing in different aspects including material development, material testing, and advancing the utilised printing technologies. Further tests on structural and mechanical properties of the printed materials including compression and tensile tests and

a stress and strain analysis will be needed to understand and quantify whether the concrete mixture is suitable for different applications. Furthermore, as it is known that concrete has a much larger compressive strength than the tensile strength, different additives might be needed to improve the way that the mixture behaves under tension to avoid ruptures and cracks due to rapid curing.

In addition to the experiments done on accelerant and retarder additives, different materials such as fibres and plasticizers may be added to the mixture to improve its mechanical properties and porosity. Further tests will also be needed to ensure the quality of concrete such as permeability and abrasion tests. The research team is pursuing such results that can be later used to validate whether the material would be suitable with the current extrusion method and can deal with local environmental conditions.

Combining the use of the control system with the current mixture will allow a reliable and repeatable process to be developed for 3D printing more complicated models. Nozzle size directly affects the extrusion rate and overall print time of components. A shorter print time will allow for a more cost-effective solution, allowing the New Zealand construction industry to be exposed to this novel additive manufacturing technique. The design and development of the presented full-scale 3D printing concrete system, based on locally available materials and technology, is expected to facilitate the utilisation of this technology in the New Zealand construction industry.

Acknowledgement

The authors would like to acknowledge the Faculty of Design and Creative Technologies at Auckland University of Technology (AUT) for providing financial support for this research.

References

- Ahmed, Z.Y., Bos, F.P., Wolfs, R.J. & Salet, T.A., 2016. Design considerations due to scale effects in 3D concrete printing.
- Buswell, R.A., De Silva, W.L., Jones, S.Z. & Dirrenberger, J., 2018. 3D printing using concrete extrusion: A roadmap for research. *Cement and Concrete Research*, 112, 37-49.
- Elasad, M. & Amirov, D., 2020. 3D printed construction and implementation in Cyprus: Discussion and overview. *International Journal of Advanced Engineering, Sciences and Applications*, 1, 26-32.
- Lim, S., Buswell, R.A., Valentine, P.J., Piker, D., Austin, S.A. & De Kestelier, X., 2016. Modelling curved-layered printing paths for fabricating large-scale construction components. *Additive Manufacturing*, 12, 216-230.
- Lin, J.C., Wang, J., Wu, X., Yang, W., Zhao, R.X. & Bao, M., Year. Effect of processing parameters on 3d printing of cement-based materials. eds. *E3S Web of Conferences* EDP Sciences, 03008.
- Malaeb, Z., Alsakka, F. & Hamzeh, F., 2019. 3D concrete printing: machine design, mix proportioning, and mix comparison between different machine setups. *3D concrete printing technology*. Elsevier, 115-136.
- Ministry of Business, I.a.E., 2017. *Projections from the National Construction Occupations Model*. New Zealand: Crown.
- Qorox, 2021. High Tech in Property Webinar with QOROX! In Relab (ed.) <https://www.facebook.com/relabpropertynz>: <https://www.facebook.com>.
- Safiuddin, M., Kaish, A., Woon, C.-O. & Raman, S.N., 2018. Early-age cracking in concrete: Causes, consequences, remedial measures, and recommendations. *Applied Sciences*, 8, 1730.
- Weng, Y., Li, M., Tan, M.J. & Qian, S., 2018. Design 3D printing cementitious materials via Fuller Thompson theory and Marston-Percy model. *Construction and Building Materials*, 163, 600-610.
- Yu, F., Sun, D., Wang, J. & Hu, M., 2019. Influence of aggregate size on compressive strength of pervious concrete. *Construction and Building Materials*, 209, 463-475.

The Influence of Real-Time Applications on the Performance of BIM-Enabled Projects

Bruno Lot Tanko¹, Cen-Ying Lee^{1*}, Mustafa Klufallah¹, and Wallace Imoudu Enegbuma²

¹University of Reading Malaysia, Malaysia.

²Victoria University of Wellington, New Zealand.

*Corresponding author: celine.lee@reading.edu.my

Abstract

Digital construction builds on diverse tools such as Building Information Modelling (BIM) for real-time project monitoring and data completion for asset management. BIM uptake presents positive productivity gains for measuring project performance. The significant contributions are attributed to various dimensions in the overall project performance which includes trust.

However, due to the increasing availability of BIM benefits, the influence of real-time applications on such benefits requires continuous exploration.

This study aims to examine the influence of trust on the real-time application of BIM in projects.

A survey was conducted on construction practitioners who utilised BIM and/or real-time applications to investigate the influence of trust in BIM on project performance. Two groups of data – respondents who did not apply real-time applications and those who applied real-time applications were analysed with partial least squares structural equation modelling (PLS-SEM).

The study revealed a significant relationship between trust in BIM and project performance in both groups. However, the findings also revealed that the respondents who applied real-time applications had more confidence in BIM physical attributes whereas the respondents who did not adopt real-time applications relied heavily on the BIM workflow that was reasonably designed and developed based on shared understanding to impact positive project performance.

Although the study has several limitations which include the types of real-time applications and the methods they connect to BIM could influence the results of the path models, the study provides important insights into the appropriate use of BIM and real-time applications for improving project performance.

Keywords

Building Information Modelling (BIM), Partial Least Square (PLS), Performance, Real Time, Trust

Introduction

Making informed decisions and completing a project within the parameters set forth at the outset require access to trustworthy information at the appropriate time and in the right location. Only when practitioners have timely access to relevant and appropriate project information can they produce a successful project. Even though technological advancements are accelerating, the construction industry is still a long way from implementing these new breakthroughs when

compared to other industries (Koseoglu and Nurtan-Gunes 2018). Nevertheless, due to the digital revolution, which integrates modern technology with the people involved in it, the construction sector is experiencing the Industrial Revolution (IR) 4.0 (Alaloul *et al.* 2020). As a result, academics have looked into a variety of evolving field data collection technologies to automate project inspections, either using a single tool or combining several (Asadi *et al.* 2021).

Digital applications such as Building Information Modelling (BIM) and real time applications in construction have been around for some years. These applications are important because they improve the performance of existing buildings and assets. Knowledge or information loss or distortion is a problem in construction projects since numerous contributors enter and exit at different periods during the design, construction, occupation, and operational stages (Araszkiewicz 2017). Using real-time applications with BIM is one technique to ensure efficient management of information and other processes to improve project performance.

According to Demian and Walters (2014), BIM-based solutions have dramatically improved project delivery efficiency by fostering more communication among construction stakeholders. It is proposed that rich 3D digital building models be used collaboratively at all stages of the project and building life cycle to enable and assist an integrated project flow and delivery (Xu *et al.* 2014). However, more research on the interrelationship between BIM and project alliance capacities is needed to examine the influence of BIM on project team members' collaboration, according to demand (Oti-Sarpong *et al.* 2020). BIM is a technology and process that allows a facility's building information to be presented virtually in a digital form throughout "the project lifecycle, which includes stages such as planning, design, manufacturing and construction, operation, maintenance, and demolition" (Alizadehsalehi *et al.* 2020). Koseoglu and Nurtan-Gunes (2018) defined BIM as "a digital representation of physical and functional attributes of a facility" in the National BIM Standard-USA. It is the process of creating and utilising three-dimensional (3D) representations of building objects, as well as their associated qualities and relationships to other elements in the structure. By employing numerous techniques, BIM improves productivity, efficiency, and quality in construction (Koseoglu and Nurtan-Gunes 2018); producing as-planned data, providing as-built data, and comparing the two together are all crucial components of progress monitoring (Machado and Vilela 2020). A virtual BIM model is generated using BIM technology based on the collective knowledge obtained from coordinated working activities and procedures (Rostam 2019). Additionally, the BIM model has multidimensional views that provide a clear representation of what will be built as well as detailed data information about that specific building (Akdag and Maqsood 2019). BIM technology allows for the creation of an exact intelligent 3D virtual model with precise geometry, as well as the integration of project data throughout the project delivery process (Jin *et al.* 2018). Hence, BIM is widely regarded as a platform for executing automatic project progress monitoring because it provides a rich and important data source (Kim *et al.* 2020).

For real-time applications, successful project delivery necessitates the administration of many diverse on-site and off-site tasks, access to vast amounts of information in various forms, and ongoing communication between the parties (Koseoglu and Nurtan-Gunes 2018). Construction management professionals, according to Hasan *et al.* (2021), use specialised software such as "document management software, project schedule management software, progress and quality checking software, defect management software, and cloud-based building information modelling (BIM) solutions". Real-time communication tools like virtual meeting tools, messaging apps, emails, and phones have an impact on how project team members share information and cooperate to improve project performance. Information such as the status of the 'As-Built' schedule can be gathered on-site and synchronised with a federated BIM using a real-time application. Handheld mobile devices are currently being used for a wide range of applications. This includes augmented reality (AR) in the construction environment, and the

portability and accessibility of portable mobile devices has spurred researchers to look into their possibilities for automating building site monitoring (Zaher et al. 2017). As a result, the progress of building operations may be tracked using smartphones and an Android application that allows end-users to track construction projects, update progress on-site, and facilitate real-time interactions and information sharing among project participants.

In this regard, recent studies have showed how combining virtual knowledge with the real world can be more efficient and successful (Zaher et al. 2017). Therefore, for the construction industry to reap the benefits, it is necessary to distinguish between BIM users who did not utilise real-time applications and those who did use real-time applications to improve the performance of their projects. However, due to the increasing availability of BIM benefits, the influence of real-time applications on such benefits requires continuous exploration. In particular, the effect of real-time application on trust in BIM and project performance remains unknown. Trust in BIM in the context of this study refers to the believe of the use of BIM that would bring benefits to the project outcomes. This study aims to examine the influence of real-time application on trust in BIM and project performance. Following is a review of related literature on real-time applications and BIM-enabled projects, as well as the methodology used to perform the study, findings, and discussion, as well as the study's conclusions.

Literature Review

Real-time Applications in BIM-enabled Projects

Traditional progress tracking relies on visual inspections and daily or weekly reports based on those inspections to ensure that work meets contract parameters and deadlines. This traditional approach mostly relies on the inspectors' personal judgement, observational ability, and expert weekly follow-up due to the high risk of incomplete and erroneous reports. BIM, on the other hand, is focused on structured data and allows access to multiple databases. However, in the construction industry, a large amount of unstructured data/information is communicated between team coordinators via speak or text (Motawa 2016). As a result, current BIM systems need be improved to include non-technical and non-geometric knowledge connected with construction practices.

Progress monitoring at construction sites is primarily accomplished using various technologies to track building components and materials, workers, and equipment, as well as capturing the as-built status of building components to compare it to the as-planned building information models, according to Guven and Ergen (2020). (BIMs). A smart and intelligent system that can continuously learn and update itself from various sources is required to gather, preserve, analyse, and manage huge and intricate data in order to offer a simple, accurate, quick, and real-time progress monitoring report (Boje et al. 2020). Thus, to validate the projected performance of construction projects, IoT technology and real-time apps measure and compare the progress of “as-built” and “as-planned” models (Alizadehsalehi and Yitmen 2021). By measuring and analysing project performance, the overarching purpose of monitoring is to ensure that project results and outputs are successfully controlled (Lin and Golparvar-Fard 2020). Construction project management relies heavily on the measurement of work in progress on construction sites, as this process has a direct impact on a project's timing, cost, quality, and safety.

Real-time applications provide a different technical environment in which infrastructure and projects are delivered using operating systems, software, servers, and services regardless of geographic location. They are increasingly being used to improve project performance during the design, construction, and operation phases. Having timely access to information on a

construction project's performance allows the design team and contractor to make better decisions, ensuring project deliverables are met (Matthew et al. 2015).

Although the advantages of using real-time applications in construction are evident, their greater acceptability is contingent not only on their advantages, but also on project team members' trust in the technologies' utilisation. While technology trust primarily refers to humans' trust in the use of technology (Ejdys 2018), the rapid development of technologies such as BIM in the construction industry, as well as increasing human reliance on these technologies, has piqued the interest of industry researchers in virtual technology trust (Krot and Lewicka 2016).

Trust in BIM

Trust in technology should be obtained from the viewpoints of its users (Nguyen et al., 2021). Trust in BIM refers to the believe of the use of digital modeling in construction which would impact positive project outcomes. As such, trust in BIM should be related to its attributes that could be accepted by the users who deploy BIM in the construction projects. These attributes could be extracted from the elements of BIM technology acceptance model - perceived usefulness and perceived ease of use of BIM (Lee et. al. 2015). An existing study has demonstrated that an intention to continue using BIM is influenced by both perceived usefulness and perceived ease of use (Cui et al., 2021).

This shows that trust in BIM could be possibly affected by these two elements. Examples of the constructs which could derive from these two elements include the believe of BIM that could improve project certainty (Crotty 2013), provide useful information (Kensek 2015), save the time of project delivery (Akinade et al. 2016), share information, improve understanding of the responsibilities, workflow and mutual understanding (Fan et al. 2018).

BIM and Project Performance

According to Hardin and McCool (2015), BIM has become one of the most popular technical improvements in the construction industry in the last decade, with roughly 74 percent of firms now utilizing this technology. It has gained in importance as more information about its benefits in general projects has become realized. BIM was created as a result of a lack of innovation and persistent inefficiencies in the construction industry, necessitating the use of automation and technology to integrate and improve on traditional construction techniques. From a holistic standpoint, BIM can address these inefficiencies by allowing a project to be completed virtually before it is carried out physically on site. (Crowther and Ajayi 2019).

BIM is frequently defined as a set of interconnected policies, processes, and technologies for managing critical building design and project data which are stored in a digital format throughout the life cycle of a project (Succar et al. 2013). As a result, many people consider BIM as "a solution to the many inefficiencies in the construction industry" (Zuppa et al. 2009). Organizations, in particular, hope to improve their performance in project delivery in terms of cost, time, and quality through the implementation of BIM (Bercerik-Gerber & Rice 2009). According to the National Building Specification (NBS) International BIM Report 2016, the BIM implementation rates in Canada, Denmark, and Japan were 67 percent, 78 percent, and 46 percent, respectively. (Chai et al. 2019).

Without a doubt, BIM will become a construction standard in the upcoming years. This can be seen in the implementation of BIM in some developed nations. According to the Building and Construction Authority in Singapore (2011), Hong Kong, South Korea, Finland, Denmark, the United Kingdom, and Norway are among the countries that have made BIM as a mandatory criterion for any construction proposal submission, either within public projects, specific

projects cost, as well as all projects in the country. Furthermore, Singapore mandated the use of BIM in projects with a gross floor area of more than 5,000 square metres in 2015. Furthermore, BIM is being improved so that it can be integrated into green initiatives to reduce the carbon footprint, as highlighted in The Green Star (New Zealand), Green Building Index (Malaysia), Green Mark (Singapore), Leadership in Energy and Environmental Design LEED (US), and the BRE Environmental Assessment Method (BREEM, in Europe; Usman et al. 2015; Ilhan & Yaman 2015; Liu et al. 2017).

Through the deployment and execution of BIM, it is possible to better monitor and enhance the performance of construction projects. According to Chan et al. (2019), the adoption of BIM in the AEC industry has resulted in increased collaboration and coordination across many disciplines and stakeholders, as well as a reduction in the industry's challenges to more manageable levels. BIM facilitates and supports productivity improvement on building projects by finding inefficiencies, establishing their source, and offering appropriate solutions by providing a platform for re-engineering the process (Nath et al. 2015). BIM is expected to aid the construction industry in a variety of ways, including improved project performance and quality (Succar 2009), a more efficient construction process (Abd Hamid et al. 2018), and better visualisation of project execution (Haron et al. 2015).

A number of case studies published in recent years have demonstrated the favourable positive impact of BIM on project outcomes. The Project Management Institute, which provides a high-level framework including numerous elements of project performance, is typically used to define project performance in these research (PMI, 2008). These include coordination, scope, time, cost, quality, organizations, communication (i.e., timely and appropriate generation, collection, distribution, storage, retrieval and disposition of project information), risk, and procurement. Examples of such studies include Barlish and Sullivan (2012) who calculated project cost (time performance) as the ratio of actual cost (duration) over budgeted costs (planned duration). This use of ratios immunizes the measures against the influence of absolute budget size and total project duration, thus facilitating cross-case comparisons. The study used this metric to measure BIM benefits in three cases of a tool installation department of a semiconductor manufacturing company, in which BIM and non-BIM projects in similar functional areas were compared. Results indicated a positive influence of BIM on cost and time performance (Smits et al. 2017).

As previously stated, most studies focused on BIM's impact on construction and identified important performance indicators like quality control, on-time completion, cost, and safety. Better cost estimates and control, expanded understanding of the design, decreased construction costs, better construction planning and monitoring, and improved project quality are among the top benefits of BIM implementation in Hong Kong, according to Chan et al. (2019). According to Diaz (2016), BIM adoption has several benefits for New Zealand construction projects, including improved project quality and performance, increased efficiency, reduced waste, faster delivery, and new revenue and business opportunities. Assessing BIM capability and a project's performance necessitates a full understanding of the true influence of the capability attributes under consideration on the project's chances of success (Mahamadu et al. 2017). As a result, identifying the underlying factors that drive construction performance, as well as developing measures to track and improve it, is crucial.

Research Methodology

A questionnaire survey was used to collect data for analysing the relationships among various variables. A survey questionnaire that included demographics, the use of real-time applications

and opinions of respondents about the project performance was distributed to construction professionals who were involved in BIM-enabled projects. As shown in Table 1, the indicators of trust in BIM and project performance used for the analysis were rated using five-point Likert scales. 93 responses were received, checked for missing data, and a total of 80 responses were selected for the data analysis. Table 2 demonstrates the primary nature of the firm that respondents worked with. Most of the respondents who filled out the survey worked with the construction firm (34%) and architectural design firm (20%). As the objective of the research is to explore the influence of real-time applications on trust in BIM to BIM-enabled project performance as shown in Figure 1, the data was divided into two sets and compared.

Table 1. Variables and indicators

Constructs	Indicators	References
Trust in BIM (TB)	1. We believed BIM could improve our project certainty (<i>TB_1</i>). 2. We believed BIM could provide useful information throughout the lifecycle of our project (<i>TB_2</i>). 3. We believed BIM software is robust in saving our time to deliver project outcomes (<i>TB_3</i>). 4. We felt secure to share the information in the Common Data Environment of our project (<i>TB_4</i>). 5. We believed a BIM workflow that is clear provides us with a better understanding of our responsibilities (<i>TB_5</i>). 6. We believed the BIM workflow was defined fairly (<i>TB_6</i>). 7. We believed the BIM workflow was developed based on our mutual understanding (<i>TB_7</i>).	Crotty (2013) Kensek (2015) Akinade et al. (2016) Fan et al. (2018) Fan et al. (2018) Fan et al. (2018) Fan et al. (2018)
Project Performance (PP)	1. In general, project team members were delighted with their work (<i>PP_1</i>). 2. The project outcome added business value to our firm (<i>PP_2</i>). 3. The rate of the project met the schedule as compared to other projects (<i>PP_3</i>). 4. The rate of the project met the budget as compared to other projects (<i>PP_4</i>). 5. The rate of the project met the quality of the produced work as compared to other projects (<i>PP_5</i>). 6. The rate of the project team interacted effectively as compared to other projects (<i>PP_6</i>). 7. The rate of the project met the health and safety expectations as compared to other projects (<i>PP_7</i>).	Thompson et al. (2007) Thompson et al. (2007) Thompson et al. (2007) Thompson et al. (2007) Thompson et al. (2007) Thompson et al. (2007) Thompson et al. (2007)



Figure 1: Relationship between trust in BIM and BIM-enabled Project Performance

PLS-SEM was used to investigate the relationship as this method is more appropriately used for examining an exploratory relationship (Hair et al. 2018). Although there was only one independent variable and one dependant variable used in this study which made it more sense of using single linear regression method, the study required a comparison between two sets of data – the respondents who applied real-time and non-real-time, where latent variables,

measurement model and structural model were needed in the path analysis. Hence, PLS-SEM is more appropriate to be applied in this case. To identify whether the data collected committed common method bias or not, the authors conducted a full collinearity assessment approach in PLS-SEM (Kock 2015). All variance inflation factors of the indicators were found to be less than 3.3 suggesting that the model is considered free of common method bias.

Table 2. Primary nature of the firm

Owner	6%
Architectural Firm	20%
Engineering Firm	8%
Quantity Surveying Firm	14%
Project Management Firm	9%
Construction Firm	34%
Subcontracting Firm	1%
Other	8%

Analysis and Findings

The study identified 52 samples that did not use real-time applications among the 80 samples collected, with a total of 28 samples using real-time applications. Table 3 displays the areas that have been updated in real time. The project schedule (43%) was the most frequently updated in real time, followed by design and specifications (33%) and project cost (15%).

Table 3. Areas that updated in real-time

Supply chain	6%
Project schedule	43%
Project cost	15%
Design and specifications	33%
Changes in works	3%

Outer loadings, construction reliability and validity, and discriminant validity are all used to evaluate the measurement model. Table 4 shows that the indicators that remained in trust in BIM for respondents who applied real-time applications were TB_1, TB_2, and TB_3, whereas the indicators that remained in trust in BIM for respondents who did not apply real-time applications were only TB_6 and TB_7. The outer loadings of the indicators in Table 4 were greater than 0.70, indicating that the indicators were highly satisfactory in contributing to the definition of the constructs. All of the composite reliability (CR)s exceeded 0.70, and the average variance extracted (AVE) was greater than 0.50, indicating that the measurement scale is reliable.

Table 4. Outer Loadings, Construct Reliability and Validity of Indicators

Constructs	Indicators	Real-time				Non-Real-time			
		Outer loadings	Cronbach's Alpha	CR	AVE	Outer loadings	Cronbach's Alpha	CR	AVE
Trust in BIM (TB)	<i>TB_1</i>	0.72	0.67	0.81	0.59		0.79	0.90	0.82
	<i>TB_2</i>	0.71							
	<i>TB_3</i>	0.87							
	<i>TB_6</i>						0.93		
	<i>TB_7</i>						0.89		
Project Performance (PP)	<i>PP_1</i>	0.92	0.86	0.90	0.70		0.80	0.88	0.71
	<i>PP_4</i>	0.86							
	<i>PP_5</i>	0.74							
	<i>PP_6</i>	0.87					0.92		
	<i>PP_7</i>						0.79		

As shown in Table 5, all Heterotrait-Monotrait Ratio (HTMT) values are less than 0.90, indicating that discriminant validity between the two constructs has been established.

Table 5. Heterotrait-Monotrait Ratio (HTMT) values

	Real-time		Non-Real-time	
	TB	PP		
TB	0.77		0.91	
PP	0.54	0.84	0.51	0.84

Table 6 shows that both real-time application and non-real-time application models have positive path coefficients and significant t-values and p-values for structural model assessment. The effect sizes f^2 for both models were greater than 0.35, indicating that the effect sizes on project performance were significant. Furthermore, values greater than zero for the coefficient of determination (R^2) and predictive relevancy (Q^2) in Table 7 indicate that both path models have predictive validity.

Table 6. Overall results of hypotheses testing

Type of effect	Path	Coeff.	t -value	p- value	Sig. level	Lower bound (5%)	Upper bound (95%)
Real-time	TB>PP	0.57	2.924	0.003	***	0.343	0.794
Non-Real-time	TB>PP	0.53	4.146	0.000	***	0.285	0.742

Note: *, **, ***, and ns indicate a significance level of $p < 0.1$, $p < 0.05$, $p < 0.01$, and no significance, respectively, based on bootstrapping of 5,000 subsamples and a significance level of 10%.

Table 7. Coefficient of Determination (R²) and predictive relevancy (Q²)

	Real-time		Non-Real-time	
Endogenous Latent Variable	R ²	Q ²	R ²	Q ²
PP	0.27	0.16	0.28	0.18

Table 8. Effect size f^2

	Real-time	Non-Real-time
	PP	PP
TB	0.415	0.40

Discussion and Conclusion

The study has demonstrated that trust in BIM has a positive influence on project performance despite there are real-time applications or not. However, through a detailed examination of measurement models, the study reveals that the respondents who used real-time applications have a higher trust of BIM physical attributes as compared with respondents who did not use real-time applications in their projects. This finding suggests that to improve positive project outcomes, construction projects which do not use real-time applications rely heavily on BIM workflow that promotes fair and mutual understanding among project participants. For participants who use BIM and real-time applications in construction projects, the physical attributes of BIM that improves project certainty, provide useful project lifecycle information and its robustness in saving the time of project delivery are proven could improve positive project outcomes. Another discovery is that there is a substantial effort that needs to be put by the industry to strengthen the security and privacy of BIM access so it could increase the confidence of practitioners to deploy BIM at a more advanced level.

This study provides several practical implications. For construction teams who do not use real-time applications in their projects, they must plan the BIM workflows that could promote mutual understanding to facilitate better work process among the project team. For project teams that use BIM and real-time applications to improve project efficiency, attentions should be paid on improving trust in BIM among project participants which include increasing project certainty and time of project delivery, providing useful lifecycle information and enhancing security and privacy access of the use of BIM.

There are several limitations identified in this study which includes the data sampling used to compare the group of respondents who used real-time applications and did not use real-time applications. 28 respondents stated that the real-time applications had been used whereas 52 respondents informed that they did not use real-time applications in the construction project that they responded in the survey. The significant difference between the sample size of these two groups could potentially experience a data bias despite several measures that have been taken to mitigate the potential data bias. Also, the types of real-time applications and the methods they connect to BIM could influence the results of the path models. Future research could focus on identifying the moderators and mediators for the paths analysed in this study and determining types of real-time applications and their connections with BIM models which could influence the structural models.

Acknowledgement

This work was supported by the Fundamental Research Grant Scheme (FRGS/1/2018/TK06/READING/03/1) and the Ministry of Higher Education Malaysia.

References

- Abd Hamid, A.B., Taib, M.M., Razak, A.A. and Embi, M., 2018. Building information modelling: challenges and barriers in implement of BIM for interior design industry in Malaysia. *IOP Conference Series: Earth and Environmental Science*, IOP Publishing, p. 012002.
- Akdag, S.G. and Maqsood, U., 2019. A roadmap for BIM adoption and implementation in developing countries: the Pakistan case. *Archnet-IJAR*, 14 (1), 112-132. doi: 10.1108/ARCH-04-2019-0081
- Akinade, O.O., Oyedele, L.O., Munir, K., Bilal, M., Ajayi, S.O., Owolabi, H.A., Alaka, H.A. and Bello, S.A., 2016. Evaluation criteria for construction waste management tools: towards a holistic BIM framework. *Int. J. Sustain. Build. Techno. Urban Dev.*, 7(1), 3-21.
- Alaloul, W.S., Liew, M.S., Wan Abdullah Zawawi, N.A. and Kennedy, I. B., 2020. Industrial revolution 4.0 in the construction industry: challenges and opportunities for stakeholders. *Ain Shams Engineering Journal*, 11(1), 225-230. doi: 10.1016/j.asej.2019.08.010
- Alizadehsalehi, S. and Yitmen, I., 2021. Digital twin-based progress monitoring management model through reality capture to extended reality technologies (DRX). *Smart and Sustainable Built Environment*, DOI 10.1108/SASBE-01-2021-0016
- Alizadehsalehi, S., Hadavi, A. and Huang, J.C., 2020. From BIM to extended reality in AEC industry. *Automation in Construction*, 116, doi: 10.1016/j.autcon.2020.103254
- Araszkiewicz, K. (2017). Digital technologies in facility management – the state of practice and research challenges. *Creative Construction Conference 2017, CCC 2017*, 19-22 June 2017, Primosten, Croatia. *Procedia Engineering* 196, 1034 – 1042.
- Asadi, K., Haritsa, V.R., Han, K. and Ore, J.-P., 2021. Automated object manipulation using vision based mobile robotic system for construction applications. *Journal of Computing in Civil Engineering*, 35 (1), doi: 10.1061/(ASCE)CP.1943-5487.0000946
- Authority, B.C., 2012. Building and Construction Authority Singapore. Design Concept for Precast System.
- Berckerik-Gerber, B., & Rice, S., 2010. The perceived value of building information modeling in the U.S. building industry. *ITCON*, 15, 185–201.
- Barlish, K., & Sullivan, K., 2012. How to measure the benefits of BIM—A case study approach. *Automation in construction*, 24, 149-159.
- Boje, C., Guerriero, A., Kubicki, S. and Rezgui, Y., 2020. Towards a semantic construction digital twin: directions for future research. *Automation in Construction*, 114, doi: 10.1016/j.autcon.2020.103179
- Chai, C., Mustafa, K., Kuppusamy, S., Yusof, A., Lim, C. S., and Wai, S. H., 2019. BIM integration in augmented reality model. *Civil Engineering*, 10 (7). DOI:10.14716/ijtech.v10i7.3278
- Chan, D.W., Olawumi, T.O. and Ho, A.M., 2019. Critical success factors for building information modelling (BIM) implementation in Hong Kong. *Engineering, Construction and Architectural Management*, 26 (9), 1838-1854.
- Crowther, J., and Ajayi, S. O., 2019. Impacts of 4D BIM on construction project performance. *International Journal of Construction Management*, 21(7), 724–737. doi.org/10.1080/15623599.2019.1580832
- Crotty, R., 2013. The impact of building information modelling: transforming construction. Routledge.

- Cui, Q., Hu, X., Liu, X., Zhao, L. and Wang, G., 2021. Understanding Architectural Designers' Continuous Use Intention Regarding BIM Technology: A China Case. *Buildings*, 11(10), 448.
- Doan, D. T., Ghaffarianhoseini, A., Naismith, N., Zhang, T., Tookey, J., & Ghaffarianhoseini, A. (2018). Examining the relationship between building information modelling (BIM) and Green Star. *International Journal of Technology*.
- Demian, P. and Walters, D., 2013. The advantages of information management through building information modelling. *Construction Management and Economics*, DOI:10.1080/01446193.2013.777754
- Diaz, P., 2016. Analysis of benefits, advantages, and challenges of building information modelling in construction industry. *Journal of Advances in Civil Engineering*, 2(1), 1-11.
- Ejdys, J., 2018. Building technology trust in ICT application at a university. *Int. J. Emerg. Markets*, ISSN: 1746-8809
- Fan, S.L., Lee, C.Y., Chong, H.Y. and Skibniewski, M.J., 2018. A critical review of legal issues and solutions associated with building information modelling. *Techno. Econ. Dev. Econ.*, 24(5), 2098-2130.
- Güven, G. and Ergen, E., 2020. Tracking major resources for automated progress monitoring of construction activities: masonry work case. *Construction Innovation*, 21(4), 648-667, DOI 10.1108/CI-05-2020-0081
- Hair, J.F., Risher, J.J., Sarstedt, M. and Ringle, C.M., 2019. When to use and how to report the results of PLS-SEM. *European business review*, 31 (1), 2-24.
- Hardin, B. & McCool, D. 2015. BIM and construction management: proven tools, methods, and workflows. 2nd ed. Indiana: Wiley.
- Haron, A.T., Marshall-Ponting, A.J., Zakaria, Z., Nawawi, M., Hamid, Z. and Kamar, K.A.M., 2015. An industrial report on the Malaysian building information modelling (BIM) taskforce: issues and recommendations. *Malaysian Construction Research Journal*, 17, 21-36.
- Hasan, A., Ahn, S., Rameezdeen, R. and Baroudi, B., 2021. Investigation into post-adoption usage of mobile ICTs in Australian construction projects. *Engineering, Construction and Architectural Management*, 28(1), 351-371. DOI 10.1108/ECAM-05-2019-0277
- Ilhan, B., & Yaman, H., 2015. IFC-based sustainable construction: BIM and green building integration. *Proc. of the 32nd CIB W78 Conference 2015*, 27th-29th 2015, Eindhoven, The Netherlands.
- Jin, R., Zou, P.X., Li, B., Piroozfar, P. and Painting, N., 2018. Comparisons of students perceptions on BIM practice among Australia, China and UK. *Engineering, Construction and Architectural Management*, 26 (9), 1899-1923. doi: 10.1108/ECAM-07-2018-0275
- Jóhannesson, E. I. (2009). Implementation of BIM. DTU Management Engineering.
- Kensek, K., 2015. BIM guidelines inform facilities management databases: a case study over time. *Buildings*, 5(3), 899-916.
- Koseoglu, O. and Nurtan-Gunes, E.T., 2018. Mobile BIM implementation and lean interaction on construction site. A case study of a complex airport project. *Engineering, Construction and Architectural Management*, 25(10), 1298-1321, DOI 10.1108/ECAM-08-2017-0188
- Kim, S., Kim, S. and Lee, D. E., 2020. 3D point cloud and BIM-based reconstruction for evaluation of project by as-planned and as-built. *Remote Sensing*, 12 (9), doi: 10.3390/rs12091457.
- Kock, N., 2015. Common method bias in PLS-SEM: A full collinearity assessment approach. *International Journal of e-Collaboration*, 11(4), 1-10.
- Krot, K. and Lewicka, D. (2016). Trust in an Innovative Organisation), C.H. Beck, Warsaw.
- Lee, S., Yu, J. and Jeong, D. 2015. BIM acceptance model in construction organizations. *Journal of Management in Engineering*, 31(3), 04014048.
- Lin, J.J. and Golparvar-Fard, M., 2020. Construction progress monitoring using cyber-physical systems. *Cyber-Physical Systems in the Built Environment*, 63-87, doi: 10.1007/978-3-030-41560-0_5.
- Liu, Z., Chen, K., Peh, L. & Tan, K. W., 2017. A feasibility study of building information modeling for green mark new non-residential building (NRB): 2015 analysis. *Energy Procedia*, 143, 80-87.
- Machado, R.L. and Vilela, C., 2020. Conceptual framework for integrating BIM and augmented reality in construction management. *Journal of Civil Engineering and Management*, 26 (1), 83-94, doi: 10.3846/jcem.2020.11803
- Mahamadu, A.M., Mahdjoubi, L. and Booth, C., 2017. Critical BIM qualification criteria for construction pre-qualification and selection. *Architectural Engineering and Design Management*, 13 (5), doi: 10.1080/17452007.2017.1296812.
- Matthews, J., Love, P.E.D., Heinemann, S., Chandler, R., Chris Rumsey, C. and Olatunji, O., 2015. Real time progress management: Re-engineering processes for cloud-based BIM in construction. *Automation in Construction*, 58, 38-47. doi.org/10.1016/j.autcon.2015.07.004
- Motawa, I., 2016. Spoken dialogue BIM systems – an application of big data in construction. *Facilities*, 35 (13/14), 787-800, DOI 10.1108/F-01-2016-0001

- Nath, T., Attarzadeh, M., Tiong, R. L. K., Chidambaram, C. & Yu, Z., 2015. Productivity improvement of precast shop drawings generation through BIM-based process reengineering. *Automation in Construction*, 54, 54-68.
- Nguyen, T.A., Pham, H.C., Dick, M. and Richardson, J., 2021. Trust Types and Mediating Effect of Consumer Trust in m-payment Adoption: An empirical Examination of Vietnamese Consumers. *Australasian Journal of Information Systems*, 25.
- Oti-Sarpong, K., Leiringer, R. and Zhang, S., 2020. A Critical Examination of BIM Policy Mandates: Implications and Responses. *Construction Research Congress 2020*, pp. 763-772, ASCE.
- Project Management Institute (PMI), 2008. A guide to the Project Management Body of Knowledge (PMBOK guide). Newton Square, PA: PMI.
- Rostam, D., 2019. Education needs to support architecture, engineering, and construction collaboration using building information modeling, *The Scientific Journal of Koya University*, 7(2), 54-62. doi: 10.14500/aro.10604
- Smits, W., van Buiten, M. & Hartmann, T., 2017. Yield-to-BIM: impacts of BIM maturity on project performance. *Building Research & information*, 45(3), 336-346.
- Usman, F., Khairulzaman, H. A. B. & Banuar, N. B., 2015. Implementation of Building Information Modelling (BIM) on Existing Multi-storey Residential Building in Achieving Better Thermal Comfort. *Conference Proceedings*, <http://dspace.uniten.edu.my/jspui/handle/123456789/10224>
- Succar, B., 2009. Building information modelling framework: a research and delivery foundation for industry stakeholders. *Automation in Construction*, 18 (18), 357-375.
- Succar, B., Sher, W. & Williams, A., 2013. An integrated approach to BIM competency assessment, acquisition and application. *Automation in Construction*, 35, 174-189.
- Thompson, R.L., Smith, H.J. and Iacovou, C.L. (2007). The linkage between reporting quality and performance in IS projects. *Information & Management*, 44, 196-205. doi:10.1016/j.im.2006.12.004
- Xu, X., Ma, L. and Ding, L., 2014. A Framework for BIM-enabled Life-cycle Information Management of Construction Project. *International Journal of Advanced Robotic Systems*, 11 (126). DOI: 10.5772/58445
- Zaher, M., Greenwood, D. and Marzouk, M., 2017. Mobile augmented reality applications for construction projects. *Construction Innovation*, 18 (2), 152-166. DOI 10.1108/CI-02-2017-0013
- Zuppa, D., Issa, R. R. & Suermann, P. C., 2009. BIM's impact on the success measures of construction projects. *Journal of Computing in Civil Engineering*, 503-512. DOI:10.1061/41052(346)50

Predominant Causes of Delays within the New Zealand Construction Industry: Residential vs Commercial

Adeside Sipaseuth* and Andries (Hennie) van Heerden

School of Built Environment, Massey University, Auckland.

*Corresponding author: a.vanheerden@massey.ac.nz

Abstract

There is a current need to understand the number and types of causes and their problematic underlying issues that can create delays within a construction project. Knowing these will enable them to be better delivered. While the causes of construction delays have been investigated extensively overseas, this is not the case in New Zealand.

The aim of this paper is to investigate what constitutes a construction delay in both residential and commercial projects in New Zealand with the objective of providing a better insight into their predominant causes. A cross-sectional survey was conducted with construction professionals. In addition to the survey, structured interviews with a delay analysis expert was conducted. This was done to gain specific insight into additional causes as a result of delaying factors that were shown to present themselves under COVID-19 conditions.

The survey results revealed that the most predominant causes of delays in residential projects included labour shortages, poor project planning and scheduling, and drawing changes. In commercial projects, the most critical causes included poor project planning and scheduling, project scope changes, unfinished and errors in drawing documents. Similar and different causes between the two types of project categories were identified and discussed. The findings were also backed up from published articles. The findings highlighted key problematic issues that are causing delays for residential and commercial construction projects in New Zealand during the current pandemic. The information can be used to inform industry and potentially be referenced by government should they choose to focus on providing guidance to improve the sector's construction practices.

Keywords

Construction Projects, COVID-19, New Zealand, Residential & Commercial

Introduction

Delay is one of the most common issues in the industry and occurs in all phases of every construction project. (Alaghbari et al., 2007; Alkass et al., 1996; Faridi & El-Sayegh, 2006; Yang & Wei, 2010). It is thus not surprising that the industry has been criticised for its recurring delay issues (Agyekum-Mensah & Knight, 2017) and especially for its inefficiency in resolving them (Aziz, 2013). The awareness of these adverse effects has motivated many researchers in several countries to seek for delay mitigation approaches and, inevitably, this is possible only after the delays are identified (Arditi & Pattanakitchamroon, 2006; Chang, 2002; Yang & Wei, 2010).

Different studies define the term “construction delay” differently (Zack, 2003; Assaf and Al-Hejji, 2006; Gündüz et al., 2013). In this research, delay is the variation between the time agreed between the parties to carry out a project, and the actual time spent on finishing the project. According to Maritz and Prinsloo (2016), there are two main types of construction delays: non-critical and critical delays. The former represents delays that do not extend a project’s completion date, whereas the latter refers to those that do.

Critical delays can be further categorised into two types: non-excusable and excusable delays. Non-excusable delays are those caused by the contractor. When this type of delay occurs, the contractor is obligated to pay liquidated damage. Excusable delays, on the other hand, are delays that are triggered by the client, or any contracting parties representing the client. Excusable delays also include delays that are beyond the control of both parties. In cases where the client, or those representing the client, are responsible for the delay, the contractor is usually entitled to an extension of time and payment of additional costs incurred as a result of the delay. In the case of an unforeseeable event, such as inclement weather, the contractor is usually granted only an extension of time, but not any additional payments to cover incurred expenses.

This research aims at identifying the predominant causes of delays in both residential and commercial construction projects in New Zealand, ranking the causes identified through a survey questionnaire, comparing the results between residential and commercial projects to identify similarities and differences.

Literature Review

Many researchers have investigated causal factors of construction delays in recent decades, as illustrated in Table 1.

Ahmed et al. (2002) employed a survey questionnaire to examine the causes of construction delays in Florida. The most critical factors are building permit approvals, change orders, drawing modifications, design progress, and law and regulation changes. Tafazzoli and Shrestha (2017), meanwhile, sought the opinions of experts in the U.S. construction industry on the causes of construction delays through a national survey. Change orders and slow decision-making are identified as the two most critical factors.

Agyekum-Mensah and Knight (2017), interviewing experienced construction practitioners in the UK construction industry, concluded that delays are mainly triggered by inadequacy in planning, poor communication, poor decision making, inefficient project management, insufficient project monitoring and control, clients’ financial issues, design changes, poorly defined project scope, and scope creep.

Wong and Vimonsatit (2012) carried out research to uncover delay causes in Perth (Western Australia) by using a survey questionnaire to seek opinions from clients, consultants, and contractors. The findings revealed ten predominant causes of construction delays: skill shortages, financial problems, insufficient labour, unrealistic project duration, unforeseen geotechnical conditions, contractor, and consultant’s poor

Table 1: Summary of Construction Delay Causes Identified in Previous Studies

AUTHOR	COUNTRY	CAUSES OF CONSTRUCTION DELAYS
AHMED ET AL. (2002)	US	<i>Building permit approvals, change orders, drawing modifications, design progress, law and regulation changes.</i>
TAFAZZOLI AND SHRESTHA (2017)		<i>change orders, slow decision making.</i>
AGYEKUM-MENSAH AND KNIGHT (2017)	UK	<i>Inadequate planning, poor communication, poor decision making, inefficient project management, insufficient project monitoring and control, clients' financial issues, design changes, poorly defined project scope, scope creep.</i>
WONG AND VIMONSATIT (2012)	Australia	<i>Skill shortages, financial problems, insufficient labour, unrealistic project duration, unforeseen geotechnical conditions, contractor and consultants' poor organisation, communication issues, unrealistic construction activity durations, slow decision making, design mistakes.</i>
SHAH (2016)		<i>Poor planning and scheduling, construction methodology, inefficiencies in project monitoring.</i>
CHAN AND KUMARASWAMY (1997)	Hong Kong	<i>Inadequate site management and supervision, uncertainty of ground conditions, slow decision making by contracting parties, changes ordered by clients, necessary variation orders.</i>
VACANAS AND DANEZIS (2018)	Cyprus	<i>Clients making changes, consultants making mistakes and omitting aspects in drawings, contractors' low productivity, consultants not possessing adequate experience, consultants</i>

		<i>providing slow responses, contractors' financial difficulties, inefficient project programming.</i>
MCCORD ET AL. (2015)	Northern Ireland	<i>Poor site management, inefficient communication strategies, poor coordination between project stakeholders.</i>
ARANTES ET AL. (2015)	Portugal	<i>Slow decision making, change orders, unrealistic project duration and specifications, contractors' financial difficulties, types of bidding and contract awarding.</i>
KOUSHKI ET AL. (2005)	Kuwait	<i>Change orders, clients' financial difficulties, clients lacking experience.</i>
ZIDANE AND ANDERSEN (2018)	Norway	<i>Inefficient planning and scheduling, slow decision making, organisations' bureaucratic and administrative issues, poor communication between parties within projects, completed works being inspected slowly, changes in designs during construction, unclear and undefined client objectives, issues in offices, slow design progression, end-user issues.</i>
GLUSZAK AND LEŚNIAK (2015)	Poland	<i>Design document errors, low-skilled workers, inclement weather, poor project management and supervision, contractors' internal issues, permit delays, unrealistic project duration expectations, inefficient planning and scheduling, funding issues, a lack of necessary construction equipment.</i>
FARIDI AND EL-SAYEGH (2006)	UAE	<i>Preparation and approval of drawings, slow client decision making, poor initial project planning, insufficient workers, skill shortages, low productivity, conflicts between consultants and contractors, issues related to communication and coordination.</i>
HWANG ET AL. (2013)	Singapore	<i>Site management issues, poor coordination between contracting parties, clients ordering design changes during construction, labour unavailability, material scarcity, insufficient staff to provide project management.</i>

YANG ET AL. (2013)	Taiwan	<i>Change orders, scope changes, slowness in handling construction sites, inclement weather.</i>
GUNDUZ AND ABUHASSAN (2016)	Qatar	<i>Slow decision making by clients or their representatives, poor site management and supervision, material shortages, clients requesting changes, labour shortages.</i>
EMAM ET AL. (2015B)		<i>Slow decision making, drawing and specification discrepancies, design changes during construction, slow resettlement of contractor claims, unrealistic project duration</i>
AL JURF AND BEHEIRY (2012)		<i>Change orders, changes in designs, a lack of skilled workers, material and equipment shortages, delays by subcontractors and suppliers, problems with designs, site accidents, poor construction methods.</i>
VENKATESH AND VENKATESAN (2017)	A review of many countries	<i>Inclement weather, unforeseeable ground conditions, subcontractor and supplier-related issues, design issues, change orders and scope changes, clients being slow to make decisions and to give approvals, slow permit approval, site condition problems, contractors' financial issues, slow payment from clients, force majeure.</i>
PRINSLOO AND VAN HEERDEN (2020)	A review of many countries	<i>Variation orders, slow approval of drawings, poor site management and supervision, poor design quality, slowness in information being received, poor communication between clients and consultants, slow decision making, clients demanding unrealistic project durations, planning and scheduling related issues, material shortages, contractors' cash flow issues, skilled and unskilled labour shortages.</i>
LESSING ET AL. (2017)	New Zealand	<i>Unforeseen ground conditions, delays in producing design documents, inadequate drawings, slowness in instructions being given.</i>

organisation, communication issues, unrealistic construction activity durations, slow decision making, and design mistakes. Another study carried out by Shah (2016) employed the same survey method and reported the three most prevalent delay factors in the Australian construction industry: poor planning and scheduling, construction methodology, and inefficiency in project monitoring.

Research with a similar aim has also been conducted in Hong Kong by Chan and Kumaraswamy (1997). Their research survey found the five most predominant delay causes in Hong Kong to be inadequate site management and supervision, uncertainty in ground conditions, slow decision making by contracting parties, changes ordered by the client, and necessary variation orders.

Vacanas and Danezis (2018), through a survey questionnaire, conducted research to simultaneously seek the opinions of nine experts (clients, consultants, and contractors) in the industry from four main cities in Cyprus-Larnaca, Limassol, Nicosia and Paphos-about causes of construction delays. The findings suggest that construction projects in Cyprus are delayed because of clients making changes; consultants making mistakes, omitting aspects in drawings, not having adequate experience, and giving slow responses; contractors' low productivity and financial difficulties; and inefficient project programming.

McCord et al. (2015) conducted a study to uncover the delay causes in a housing construction project in Northern Ireland. The research's survey and interviews with construction professionals (academics, clients, contractors, and consultants) suggest that poor site management, inefficient communication strategies, and poor coordination between project stakeholders are critical causes of construction project delays.

Arantes et al. (2015) examined delay factors affecting Portuguese construction project durations by distributing a survey questionnaire to developers, contractors, and consultants. The research report stated that the duration of construction projects in Portugal are extended due to slow decision making, change orders, unrealistic project duration estimates and specifications, contractors' financial difficulties, and the types of bidding and contract awarding.

In 2005, Koushki, Al-Rashid and Kartam studied residential projects in 27 metropolitan cities in Kuwait. The opinions of clients were sought through a survey questionnaire. The researchers found the most predominant delay causes to be change orders, clients' financial difficulties, and clients lacking experience.

Zidane and Andersen (2018) developed a survey questionnaire and conducted interviews with construction professionals to examine construction delay causes in Norway. The research participants included clients, consultants, contractors, and subcontractors. The respondents indicated eleven construction delay causes: inefficient planning and scheduling, slow decision making, organisations' bureaucratic and administrative issues, poor communication between parties, completed works being inspected slowly, changes in designs during construction, unclear and undefined clients' objectives, issues in offices, slow design progression, and end-user issues.

Głuszak and Leśniak (2015) investigated clients' opinions on construction delay factors in Poland. The data obtained through a survey questionnaire revealed that delays occur in Polish construction projects due to design document errors, low-skilled workers, inclement weather, poor project management and supervision, contractors' internal issues, permit delays,

unrealistic estimated project durations, inefficient planning and scheduling, funding issues, and a lack of necessary construction equipment.

Faridi and El-Sayegh (2006) conducted research adopting a survey questionnaire to extract contractors and consultants' opinions on delays in the United Arab Emirates's construction industry. The results revealed eight causes of construction delays: drawing preparation and approval, clients making slow decisions, poor project's initial planning, an insufficient workforce, skill shortages, low productivity, conflicts between consultants and contractors, and issues related to communication and coordination.

A similar study was conducted in Singapore by Hwang et al. (2013), who examined factors affecting construction schedules in Singaporean construction projects, including public housing projects. The data obtained from distributing a survey questionnaire to clients, consultants and contractors found that delays are caused by site management issues, poor coordination between contracting parties, clients ordering design changes while construction is in progress, labour unavailability, material scarcity, and insufficient staff to provide project management.

Empirical research by Yang et al. (2013) investigated the same issue in the construction industry in Taiwan. These researchers, however, adopted a unique investigation technique; they analysed construction cases that appeared in Taiwan's supreme court as a result of schedule disputes. The analysis discovered that delays in construction projects in Taiwan result mainly from change orders, scope changes, slowness in handling construction sites, and inclement weather.

Several studies have also been carried out in Qatar. Al Jurf and Beheiry (2012), focusing on residential projects, adopted a questionnaire to seek contractors' opinions. The results indicate that Qatar's predominant causes of construction delays include change orders, changes in designs, a lack of skilled workers, material and equipment shortages, delays by subcontractors and suppliers, other design-related problems, site accidents, and poor construction methods. Emam et al. (2015b) also used a survey questionnaire focusing on delay causative factors in large construction projects. The research indicates that slow decision making, drawing and specification discrepancies, design changes made during construction, slow resettlement of contractor claims, and unrealistic project duration estimates are causes of critical construction delays.

Gunduz and AbuHassan (2016) collected data using the same technique to investigate the perceptions of different construction-related professionals (clients, consultants, contractors, subcontractors, designers, and suppliers) on the most prevalent construction delay causes. The study concluded that Qatar's most critical construction delay causes are slow decision making by clients or clients' representatives, poor site management and supervision, material shortages, clients requesting changes, and labour shortages.

Venkatesh and Venkatesan (2017) examined the causes of construction delays, in developed and developing countries, in 53 research articles. In descending order, the predominant causes found in developed countries were inclement weather, unforeseeable ground conditions, subcontractor and supplier-related issues, design issues, change orders and scope changes, a client making slow decision and approval, slow permit approval, site condition problems, contractors' financial issues, slow payment from clients, and force majeure. For developing countries, the causes in descending order were client's slow payment, design errors, contractors' financial problems, poor planning and scheduling, materials supply delays, scope

changes and change orders, poor site supervision and management, political issues, slow decision making by clients, and supplier and subcontractor related issues.

Similarly, Prinsloo and van Heerden (2020) research investigated delay causes in 16 different countries. Change orders, construction material scarcity, and poor site management are the most predominant delay causes found. The data indicated that the critical delay factors in developed countries are variation orders, slow approval of drawings, poor site management and supervision, poor design quality, delays in information being provided, poor communication between clients and consultants, slow decision making, clients' unrealistic expectations regarding project duration, planning and scheduling related issues, and material shortages. The prevalent delay causes in developing nations included contractors' cash flow issues, variation orders, poor site management and supervision, material shortages, and both skilled and unskilled labour shortages.

Research Methodology

Data Collection

A survey questionnaire was developed to investigate the experience-based views of construction practitioners on the frequency of the occurrence of delay causes. The questionnaire had three main sections. The first section was designed to yield participants' demographic information. The second part listed all the delay causes derived from the research studies identified above. These delay factors were categorised into nine groups. Research participants were asked to rate the frequency of each delay factor using a five-point Likert scale. The scale ranges from 1: very low, to 5: very high. At the end of this part, there is an area that allows respondents to list any causes of construction delay in New Zealand not listed in the second section. The third section of the questionnaire is identical to the second, except that the third section concentrates on the causes of construction delays in commercial projects, and the second section concentrates on residential construction projects. Before the questionnaire was distributed, a pilot study was carried out with two construction project managers who have been working in the industry for more than ten years.

The link to the online questionnaire was thereafter distributed through the weekly newsletter of the New Zealand Institute of Quantity Surveyors (NZIQS). A second round of distribution was necessary to obtain more responses, and the questionnaire was re-distributed through Massey University's virtual learning system. The questionnaire was distributed to at least 80 Massey University's students who were pursuing master's degrees in the construction field. At the end of the processes, 24 responses were collected in total. However, one response was invalid because it was incomplete. The total number of responses received was thus 23.

A structured interview was conducted with a delay analysis expert. The interview aimed to gain insight into construction delays, especially regarding aspects related to the unprecedented COVID-19 situation. Hence, most of this interview's questions were formed to seek the expert's advice and opinion on queries related to construction delay triggered by the pandemic.

Data Analysis

The data obtained from the questionnaire were analysed to examine the frequency of each delay cause, as indicated by the respondents, by measuring the Frequency Index (FI). This approach has been adopted by many previous studies, including Assaf and Al-Hejji (2006), Shebob et al. (2012), Marzouk and El-Rasas (2014) and Gunduz and AbuHassan (2016). This method lends

a percentage numeric value to each delay factor, on which a frequency measurement can be based. To derive the FI of each delay cause, the following formula has been used:

$$FI(\%) = \frac{(\sum w) \cdot 100}{A \cdot N} \quad (1)$$

Where w is the weight of each cause rated by the questionnaire respondents, ranging from (1: very low – 5: very high), A is the highest weight on the rating scale (in this case, it is 5; $A=5$), and N is the number of total collected responses. The value derived from this calculation indicates which causative factor occurred more often than the others. Delay causes with a higher FI occur more often than those with a lower FI. Concerning the computed FI(s), causes of construction delays have been ranked accordingly.

The study's structured interview was conducted virtually and was audio recorded. The data obtained from this were manually transcribed and analysed, and all useful points were then integrated into other areas of the research.

Findings and Discussion

Demographic Background

The participants came from 11 different backgrounds, with over 50% being from three different backgrounds: Quantity Surveyors (6 participants: 26.08%), Civil Engineers (3 participants: 13.04%) and Construction Managers (3 participants: 13.04%). The other 11 participants are Clients (2 participants: 8.69%), Project Managers (2 participants: 8.69%), Senior Lecturers (2 participants: 8.69%), and one participant from each of the following backgrounds: Builder, Delay Claim Expert Witness, Director, Project Engineer and Project Planner (5 participants: 21.7%).

More than half (15) have worked in the industry for at least nine years, the majority of which (11) have been in the industry for a minimum of 12 years. This increases the reliability of the data as, by being in the industry for a long time, these participants are likely able to give a more holistic picture of what happens in the industry.

Eight respondents have participated in projects valuing a maximum of “5 million”, while seven and five participants indicated that they had been involved with projects worth “more than 50 million” and between “5-10 million” respectively. Fewer participants have worked on projects valuing “20-50 million”, and “5-10 million”.

When asked what percentage of construction projects they had been involved with had experienced delays, 11 participants responded with more than 40%. Of these, 4 responded with 41-60%, 2 with 61-80%, and 5 with 80% or more. A further 8 participants responded with 21-40%, and 4 with 20% or less.

Predominant Causes of Delay in Residential and Commercial Projects in New Zealand

There are seven identical predominant causes of construction delays for residential and commercial projects. These are: “poor project planning and scheduling”, “drawing changes”, “assigning unrealistic timeframes to project tasks”, “unfinished drawings and mistakes in drawing documents”, “design mistakes and discrepancies”, “consultants’ slowness in giving instructions and responses”, and “design changes during the construction phase”. The other

predominant causes of delay in residential projects are: “labour shortage”, “poor project management”, “insufficient data on ground conditions”, “permit delays from authority”, “slow design progression” and “lack of skilled labour”. For commercial projects, the other predominant causes of delay are “project scope changes”, “design document delays” and “unrealistic project duration”.

Labour shortages

“Labour shortages” is ranked as the most predominant cause of construction delay in residential projects (FI=90%). While it is not listed in the top ten predominant causes of delay for commercial projects, its Frequency Index is relatively high (FI=71.11%). “Lack of skilled labour”, meanwhile, is identified as a predominant cause of delays in residential projects (FI=85%), but not for commercial projects (FI=76.67%). This finding aligns with several studies identified in the literature review, which also identify insufficient labour as a predominant cause of construction delays. These include Koushki et al. (2005), Faridi and El-Sayegh (2006), Hwang et al. (2013), Gunduz and AbuHassan (2016), and, Prinsloo and van Heerden (2020). Of particular note is that this cause of delay is also considered significant in the New Zealand study by Lessing et al. (2017). This finding, however, is not consistent with the other identified studies.

A lack of skilled labour in the New Zealand construction industry has long been a recurrent problem. The reasons for this, as discussed by Lobo and Wilkinson (2008), Chang-Richards et al. (2017) and MBIE (2018), include fluctuations in construction activity leading to labour dispersing into other industries during quiet times. Partially because of this, and the fact that the industry is generally not perceived as having a good image or offering sufficient rewards, younger generations are not convinced to enter the industry in large numbers. The labour shortage becomes particularly apparent when there is an upturn in the industry as a result of situations such as higher demand for residential buildings and reconstruction after disasters, e.g., the Christchurch earthquakes.

Lobo and Wilkinson (2008)’s research participants shared various probable solutions to this issue, many of which are consistent with the solutions recommended by PWC (2016). One of the current solutions is relying on immigration, an approach that has helped fill gaps in the construction workforce in the past, especially in trade positions. This alone, however, is a short-term solution as the workforce inevitably returns to its previous situation once these workers leave. Thus, strategic workforce planning and effective training programmes should also be prepared and implemented. A dedicated effort is necessary to encourage people to join these programmes, and to improve the industry’s image. This could be partially done through a collaboration between the government and education institutions. The issue may also be eased by allowing students to work as apprentices in construction firms in their final year of study, to acquire skills before graduation. The government could further assist by subsidising construction-related training programmes, and by reducing the cyclical nature of the industry by introducing more projects when the industry is in a bust period. Lastly, construction firms’ policies should be improved to incentivise and motivate current construction professionals to perform with increased productivity, as discussed by Durdyev and Mbachu (2011).

Poor Project Management and Project Planning & Scheduling

“Poor project management” and “poor project planning and scheduling” are ranked separately in the data analysis, but it is reasonable to discuss these topics together since they are closely related. The FI analysis reveals that “project management” is a predominant delay cause in residential projects, but not in commercial projects (FI=86.67% and FI=74.12%, respectively). “Poor project planning and scheduling”, meanwhile, ranked as a very significant cause of delay

for both residential (FI=88.33%) and commercial (FI=83.53%) projects. This finding aligns with a considerable number of studies, e.g., Faridi and El-Sayegh (2006), Arantes et al. (2015), Głuszek and Leśniak (2015), McCord et al. (2015), Shah (2016), Agyekum-Mensah and Knight (2017), Lessing et al. (2017), Zidane and Andersen (2018) and Prinsloo and Van Heerden (2020).

The causes of poor project management and project planning and scheduling in New Zealand have been discussed extensively in a report by PWC (2016). According to this report, these delay factors are caused by practitioners not possessing sufficient management skills to manage projects. The report indicates that the industry does not seem to make formal education in this field necessary for those who have become managers of the projects. Clients do not often request that practitioners be highly skilled in project management.

PWC (2016) suggests that solutions include construction firms focusing on upskilling and training their workforces and clients, encouraging good project management. It is also recommended that BIM be employed when managing projects to avoid mistakes and improve productivity. Educational institutions, meanwhile, should seek to provide courses that grant project management qualifications.

Drawing and Design Issues

Both “drawing changes” and “unfinished drawings and mistakes in drawing documents” are identified by the participants to be predominant causes of delay in both residential (FI=88.33% and FI=85%, respectively) and commercial (FI=80% and FI=82.35%, respectively) construction projects. Several research reports also identify these as predominant causes, namely, Ahmed et al. (2002), Emam et al. (2015b), Arantes et al. (2015), Agyekum-Mensah and Knight (2017), Lessing et al. (2017) and Vacanas and Danezis (2018). “Design changes during construction phases” is also indicated by the respondents as a predominant cause of delay for residential and commercial construction projects (FI=85% and FI=78.82%). This result is consistent with the study of Emam et al. (2015b). While “Design document delays” are found to only be a predominant cause of delay in commercial projects (FI=82.35%), they are still significant in the residential field, the FI of which is relatively high: 83.33%. This is even a higher percentage than for commercial projects. An extensive number of research reports also identify this as a predominant cause of construction delays, including Ahmed et al. (2002), Al Jurf and Beheiry (2012), Wong and Vimonsatit (2012), Hwang et al. (2013), Yang et al. (2013), Głuszek and Leśniak (2015), McCord et al. (2015), Lessing et al. (2017), Tafazzoli and Shrestha (2017), Venkatesh and Venkatesan (2017), Zidane and Andersen (2018), and Prinsloo and van Heerden (2020). These studies further identify “slow design progression”, and “design mistakes and discrepancies” as predominant causes of delay. In the current study, “slow design progression” is found to be a predominant cause of delay for residential projects (FI=85%), but not for commercial projects (FI=72.94%). “Design mistakes and discrepancies”, on the other hand, is identified by the respondents to be a critical delay cause in both residential (FI=85%) and commercial projects (FI=80%).

Lessing et al. (2017) found that these problems partially result from procurement routes not allowing for synergy between contractors and design teams during design development. This study also finds that the quality of design documents can be harmed by clients not paying design costs separately but, rather, as an integrated portion of attendances. International research reports by Palaneeswaran et al. (2007) and Ren et al. (2008) find that errors in design are attributable to clients demanding design work be completed fast, and team members not being adequately experienced at drawing and design, both of which increase the chance of necessary information being omitted. The researchers also found that mistakes in drawings can occur when the same drawing standards are used for similar projects, which is often the case, without

due care and verification with the contractor on constructability. Similarly, ineffective leadership of a design team and a lack of coordination between team members in verifying work are also root causes of faulty drawings. The research reports of Love and Smith (2003), and Ebekozién et al. (2015) reveal that unfinished designs and drawings during the tender stage, a lack of thorough site investigation before design, clients demanding changes during the construction stage, and inexperienced clients not understanding construction processes, are also root causes of construction delay causative factors under this topic.

Love and Smith (2003), Arain et al. (2004), and Ebekozién et al. (2015) recommend that these problems can be mitigated by maximising clients' and contractors' involvement during the design phase of projects. This could allow clients to optimise their understanding of projects' requirements and conceptual aspects.

Unrealistic Timeframes

Both "assigning unrealistic timeframes to project tasks" and "unrealistic project duration", which are closely related, are found to be predominant causes of delay in commercial construction projects in New Zealand (FI=77.78% and 77.65%, respectively). However, only the former is a predominant cause of delay in residential projects (FI=86.67%). Several other studies have also found these factors to be significant causes of delay, namely, Al Jurf and Beheiry (2012), Wong and Vimonsatit (2012), Emam et al. (2015b), Arantes et al. (2015), McCord et al. (2015), Agyekum-Mensah and Knight (2017) and Lessing et al. (2017).

Several international studies have investigated the reasons behind unrealistic timeframes being set for project tasks and overall durations. These include Capka (2004), as cited in Son and Rojas (2011); Boyle (2014); and Mpofu et al. (2017). It is reported that these issues are generated by planning teams lacking careful consideration of the true nature of projects when creating construction plans which often overlook potential risks and uncertainties associated with the project. This increases the chance of not assigning an accurate time buffer to the durations of the tasks in the projects and, thus, accurate project duration cannot be achieved. It is also evident that the construction schedules developed in the early stages of the project are often not adequately prepared due to pressure from clients, who often set the finish date without consulting with the construction teams on feasibility.

Furthermore, some contractors rely solely on automatic resource levelling generated by software when creating schedules, which does not provide a realistic reflection of the availability of the actual resources, resulting in actual task durations deviating from plans. Contractors' teams are also often working on bidding documents for several projects at the same time. Usually, they have limited time to work (often for free) on updating bidding documents to facilitate scope changes. Under these circumstances, cost aspects are usually revised, but the time assigned to construction activities is rarely revisited by schedule experts.

Boyle (2014) suggests that it is important to assign realistic and accurate available resources when creating a schedule to achieve a realistically expected project duration. Also, when there is a variation between an activity's planned and actual time, a complete understanding of the root cause should be sought, and lessons should be learned to prevent future occurrences. The study also recommends that the contractor verify the time assigned to construction activities, since ultimately, the contractor is the party that carries out the work. There should be a discussion about the schedule's feasibility with the client.

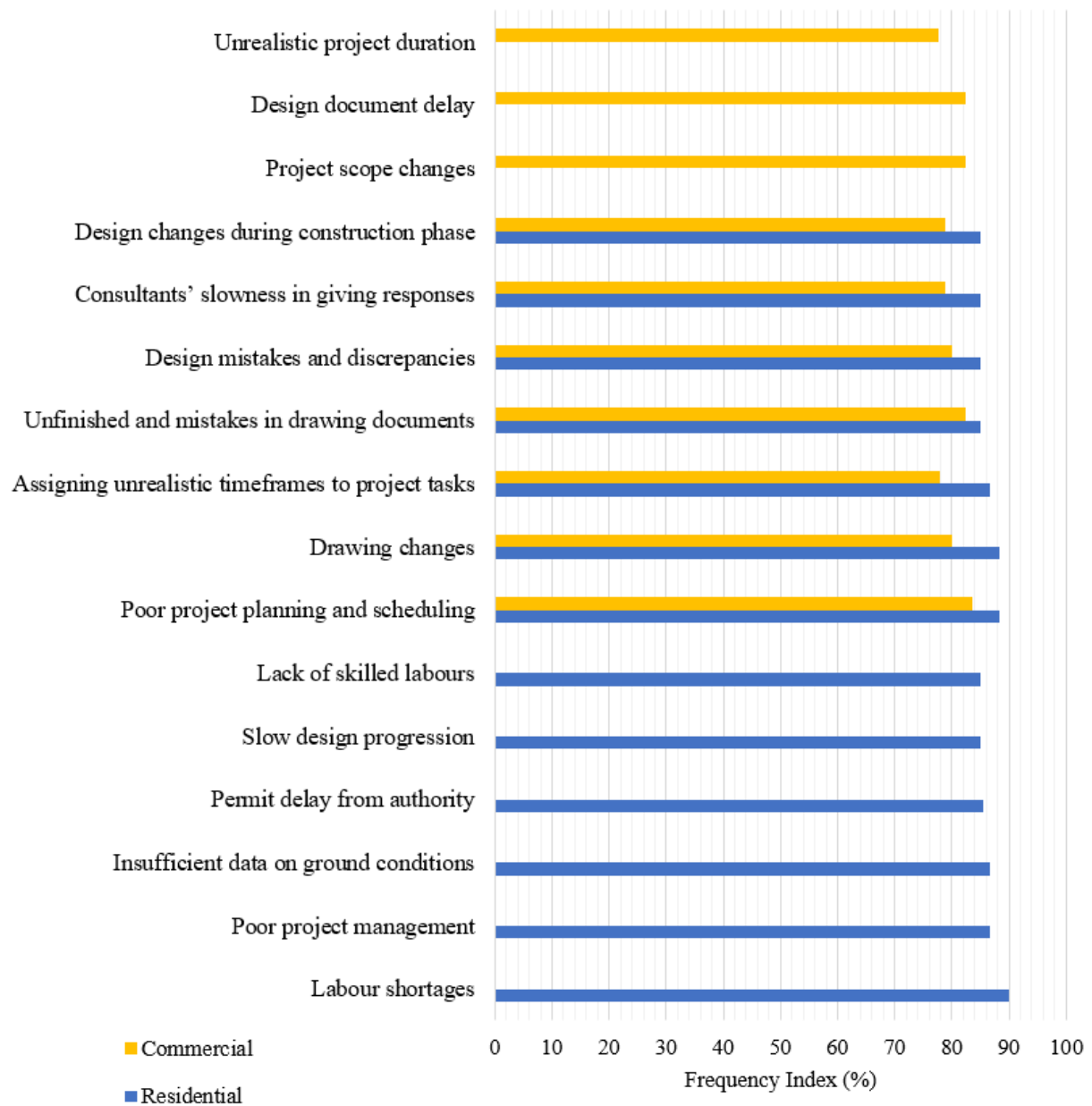


Figure 1: Predominant Causes of Delays in Residential and Commercial Construction Projects within New Zealand

Ground Conditions

Another predominant cause of delay in residential construction projects in New Zealand is “insufficient data on ground conditions” (FI=86.67%). Surprisingly, this is not found to be a predominant cause in commercial construction projects (FI=66.25%). Studies that identify “insufficient data on ground conditions” to be a predominant cause of delay include Chan and Kumaraswamy (1997), Wong and Vimonsatit (2012), Lessing et al. (2017) and Venkatesh and Venkatesan (2017).

A study delineating ground investigation specifications in New Zealand, led by Roberts (2017), pinpoints some of the main current practices in the industry that are the causes of this issue. According to the study, procuring ground investigation is often done in a single tender with initial studies and data interpretation. However, pricing in this manner does not create accurate cost estimations of each service. To propose a specific tender, the service provider needs to carry out preliminary studies of the construction site beforehand to understand the risks associated with the project. Another reason why many projects lack sufficient data on ground conditions because most geotechnical investigation tender selections focus mainly on price competitiveness. However, the tenders with the lowest prices usually limit the extent to which investigations can be carried out.

The same study suggests that single tenders (where work packages are combined) are only recommended for projects with low-risk levels, e.g., low-rise buildings. Projects that tend to encounter risks associated with ground conditions, such as tunnels, and medium to large projects, however, should carry out ground investigations as a separate procurement to prevent a reduction in investigation scope. When developing the tender document, the scope of the project should be defined with proper details, including criteria on which the selection of tender is based, to allow proper evaluation and pricing of the geotechnical investigation work. Likewise, when evaluating tenders of complex projects, advice from geotechnical experts should be sought. Lastly, the scope of geotechnical investigations should also embrace aspects that prevent project risks, not only aspects that facilitate design and analysis.

Authority approvals

Ahmed et al. (2002), Faridi and El-Sayegh (2006), Arantes et al. (2015), Głuszek and Leśniak (2015) and McCord et al. (2015) identify permit delays from authorities as one of the causative factors of construction delays. In the current study, the respondents identified this to be the case in residential projects (FI=85.45%) but not commercial projects (FI=72.94%). This goes against Provost’s (2015) study that found longer timeframes may be required to approve building permits for more complex projects.

In New Zealand, the time allowed for councils to assess and approve building consents is 20 working days, given that all information required is submitted before assessment and complies with all legal requirements. However, the 20-day timeframe is extended if a council requests a customer provide additional information. This is recognised as one of the main reasons why building consent approvals are delayed and, in such cases, additional costs ensue which are mostly paid for by home buyers (Duncan & Brunsdon, 2017; MBIE, 2016). A report by Provost (2015) (controller and auditor-general) on the results of an audit on the performance of Auckland Council, and another by Duncan and Brunsdon (2017) on the experiences of councils and industry practitioners regarding building consents, indicate that the reasons for permit delays are varied, but are mainly attributable to incomplete applications. Approximately 70% of applications submitted were found to lack necessary project details, meaning that authorities needed to request this information and put applications on hold. On top of this, it generally

took six weeks for customers to supply the necessary information, as they needed to gather it from relevant specialists and involved parties. The other reasons for permit delays found in these studies include insufficient staff, system errors, and the slow processing of applications due to most being heavily paper-based.

To solve the issue, Provost (2015) recommends that consent applications be processed online, reducing lodging times and costs. Councils should also improve website usability and application guidance, making them easier for customers to navigate. Any applications put on hold should be followed up by phone calls from the applicable authority to demystify any further requested information. Councils should also provide training to improve authorities' capacity to deal with customers. For complex projects, pre-application meetings should be carried out to discuss any concerns and advice to be sought (Duncan & Brunsdon, 2017).

Scope Changes

Participants recognised “project scope changes” as a predominant cause of commercial construction project delays (FI=82.35%), but did not for residential projects (FI=80%). Having said this, the value of the frequency index of this cause in residential projects is also quite high. Other studies that have found this to be a predominant cause of delay include Yang et al. (2013), Arantes et al. (2015), Gunduz and AbuHassan (2016), Agyekum-Mensah and Knight (2017), Lessing et al. (2017), Venkatesh and Venkatesan (2017) and Vacanas and Danezis (2018).

Many international research reports have found that the reasons for project scope changes are varied. Oyedele and Tham (2007) discovered that scope changes could occur when design teams do not fully realise clients' objectives. This results in designs being incomplete, and variations often ensue. There is also potential for the scope of a project to change if all the objectives are not properly defined (Mpofu et al., 2017). The root causes of such situations have been discussed extensively, among others, in a study by Ajmal et al. (2019).

It can be summarised from the study that the issue results from the inadequacies of many aspects during the initial phases of a project. Firstly, poor project scope can occur when there is no efficient communication between stakeholders, causing stakeholders' expectations and interests to be improperly managed or the project scope not satisfying stakeholders in an equal manner. Secondly, clients lacking “organisational business strategies” can be an issue. If a client finds it difficult to have a clear goal for a project, it can result in the specifications of the project's components being unclear. This, in turn, means design teams then carry out design work based on inexact specifications and assumptions. Lastly, achieving an adequately defined project scope is more of a challenge for complex projects.

Limiting project scope changes can be achieved by implementing various measures. Ajmal et al. (2019) state that scope changes can be reduced by managing a project's complexity. This can be done by implementing efficient methods to quantify the complexity and aid in dealing with any potential difficulties which arise. Accurate project scope can also be achieved by significantly involving the client in processes and developing a project plan that satisfies all involved stakeholders (Ajmal et al., 2019; Chan & Kumaraswamy, 1996; Chritamara et al., 2001).

Consultants

Interestingly, among the studies identified in the literature review, only Vacanas and Danezis (2018) found this cause of delay to be predominant. In contrast, the other predominant causes found in this research align with several studies. The current research finds that “consultants' slowness in giving instructions and responses” is one of the predominant causes of delay in both residential and commercial construction projects (FI=85% and FI=78.82%, respectively).

International studies by Ng (2004), and Al-Kharashi and Skitmore (2009) report that this issue stems from consultants not possessing the adequate experience, making it challenging for them to provide specific technical requirements. Janssens (1991), as cited in Ng and Chow (2004a), Thomas Ng and Chow (2004), Ren et al. (2008), Mydin et al. (2014) and Emam et al. (2015a), point out that inadequate resources and poor resource planning by consultants are also root causes of this issue. In some cases, a consultant's site engineer may not be capable of making ultimate decisions, meaning they have to wait for key team members, who are often assigned to multiple projects, to issue instructions for the contractor. These root causes, as discussed by Kasma (1987) and Sporrang (2011), may be attributable to clients selecting consulting firms based merely on their fees. That is, consultants offering the lowest prices get the jobs. When this is the case, there is a greater chance that consultants do not possess adequately qualified or experienced staff, as such staff cost more to employ.

Therefore, as Ng (2004) discusses, clients should investigate the previous performance of consultants before selections. This includes comparing the types of services provided by a consultant in previous projects, looking at their resource competence, assessing the frequency of disputes they have had with past clients, and gauging their overall efficiency and technical capacity.

Other Causes of Delays

A Lack of Accuracy of As-built Drawings for Underground Facility

The Department of Labour (2002) and the New Zealand Utilities Advisory Group (2013) have published guidelines for the construction industry on how to deal with underground utilities. Within these texts, causes for mistakes in as-built drawings are outlined. Firstly, mistakes in as-built plans can be due to draught persons reproducing plans from microfiche slides with inaccurate scales. Secondly, underground utilities may have been moved without the knowledge of the responsible authorities or the owner, resulting in differences between the actual position and the as-built drawings. Thirdly, new and old underground ducts are sometimes grouped in as-built drawings. That is, one line in a drawing may represent more than one duct. Fourthly, the depth of a utility indicated in an as-built drawing may become inaccurate over time since it may be disturbed by road construction activities or the land's owner, e.g., grading activities. Lastly, when utilities have to be constructed in areas that are already congested with existing ones or in areas that include public wastewater services, the depth of the newer utilities may be shallower than what is normally required.

The same guidelines recommend that consultations with owners of underground facilities (e.g., power, gas, and telecommunications) should be carried out before any excavation and that owners should ensure the availability of information. The importance of checking that the information received is the latest version is also emphasised.

COVID-19

Like in other countries, COVID-19 has impacted the New Zealand construction industry due to the imposition of "alert levels". Since 21 March 2020, restrictions that come with the alert levels have caused delays in construction projects. According to Stats NZ Tatauranga Aotearoa (04 September 2020), the Construction Sector Accord (2020), Building Performance (n.d.), Construction Health and Safety NZ (CHSNZ) (2020a), and CHSNZ (2020b), during periods of restriction (especially in alert level 2 and above), there are certain rules and protocols with which construction organisations and practitioners need to comply. Alert levels 2 and 3 allow construction activities to progress, but at a slower pace. This is because workers need to maintain minimum physical distances, the sharing of construction tools needs to be properly

managed, more processes are in place when entering and using facilities on construction sites, and construction practitioners moving to other regions-for some cases-was not permitted. Alert level 4, however, imposes greater restrictions, and most construction activities must be paused. During this alert level, buying construction materials is still possible, but only if they are being used for essential construction tasks, for example, works related to preventing the collapse of a section of a building. Therefore, most construction sites close. Additional work is then necessary when they reopen, such as reassessing the safety of sites and the health status of workers. A scarcity of construction materials can cause further delays during these periods. This occurs due to imported products taking longer to come into the country as a result of the pandemic. Bond (2020), and Pointon (2021) have reported that the supply of construction materials, which are mostly imported from China, has been disrupted by overseas ports being closed and extreme congestion at Auckland ports. This has delayed the shipment of many construction materials, including tiles, glass, ventilators, heating, plumbing and electrical materials. Furthermore, forward orders have often not been made by suppliers as some anticipated a downturn in construction activity.

Coping with the circumstances of the COVID-19 pandemic is particularly challenging as it is unprecedented, and there is no choice but to obey the new protocols imposed to stop the spread of the virus. It is, however, important for construction practitioners to carry out actions that help ensure the situation is not exacerbated. Deloitte (2020) recommends that contracting parties gain a good grasp on the contracts into which they have entered to prevent any possible disputes. The focus should be on relating provisions, such as *forces majeure*. Deloitte further recommends that, as the problem with supply scarcity still lingers, construction companies should closely monitor the availability of construction materials and look for other alternatives, which is consistent with a recommendation by Climo (2020). In such a difficult situation, it is also imperative that companies forecast future cash flow, and if the projection indicates financial difficulties, companies should seek additional capital to support future projects. Leys (2020) suggests that clients should consider alternatives in managing construction contracts. For example, changing retention systems may help the financial position of contractors to a certain extent. The researcher further suggests that workforces should be maintained to facilitate future work, and Brown (22 April 2020) notes the importance of taking measures to ensure the wellbeing of staff, especially their mental health, during the pandemic period.

Expert's Five Predominant Causes

The structured interview with the expert revealed five predominant causes of construction delays in commercial projects, based on the expert's career experience. The expert's view on residential projects was however limited as almost all the projects he has been involved with have been commercial. He stated that the most predominant cause of delays, based on his experience and research, is "changes by the owner of the project leading to change orders". This is due to the inability of clients to visualise the finished picture of projects. Therefore, after projects have commenced, clients start to realise the implications of a design and then change them. Secondly, he named "unforeseen site conditions" as a major cause of delays. Construction projects sometimes lack site investigations before construction. In cases where buildings already exist on a site, and there are no accurate as-built drawings, geotechnical testing can be limited, or even impossible. Thirdly, the expert named "design lacking details leading to design changes" as being another predominant cause. He postulated that one of the reasons for this is insufficient time spent on design. Construction projects these days are usually fast-paced which demands that designs be completed under pressure. Also, the involvement of several architects and engineers can lead to design clashes and constructability issues. Another predominant cause is "poor site management and supervision". Improper site management and

supervision, e.g., poor workforce management, often leads to low productivity. Although the reason for this can be country-specific, insufficient training seems to be the cause in many countries. Lastly, he named a “shortage of construction materials” as also being prevalent. This is a causative factor of delay, especially when there is a boom in the industry during which the competition for materials is always high. Of these five predominant causes of delay shared by the experts, two delay factors, i.e., “changes by the owner of the project leading to change orders”, and “design lacking details leading to design changes”, are consistent with the predominant causes of delays in commercial projects in New Zealand identified by the respondents of this study’s survey questionnaire.

Expert’s Anticipated COVID-19 Predominant Causes

The expert anticipated that during the pandemic, the predominant causes of construction delays would change from the five abovementioned. As illustrated in Table 2 below, the expert expected that the three most predominant causes of delays during such periods would be: “construction material availability”, “additional safety measures to mitigate the spread of COVID-19” which would affect the productivity of construction, and the “impact on health and safety of the construction workforce”.

While the above causes are based on the expert’s expectations of what will prove to be the predominant causes of delay due to the pandemic, they seem to be reflected in the reality of the New Zealand construction industry of the past year. These include the fact that a shortage of construction materials has disrupted the progression of construction activities in New Zealand. The construction industry has needed to embrace rules and protocols to help reduce the spread of the virus and ensure the health and safety of the construction workforce.

Table 2: Delay Causes During the COVID-19 Situation Identified by the Expert

No.	Delay causes during COVID-19 situation identified by the expert
1	Construction material availability
2	Additional safety measures to mitigate the spread of COVID-19
3	Impact on health and safety of the construction workforce

Conclusion

Delays are one of the most recurring and common problems in the construction industry. The consequences of these delays can be extremely detrimental to any country’s economy, the industry itself, the environment, and all stakeholders involved in construction projects. To solve delay issues, an important step is to identify what the causes of delays are. The findings from this research unfolded the predominant causes of delays in residential and commercial construction projects within New Zealand. The results of the survey questionnaire revealed that, in residential construction projects, the most predominant causes are, in descending order: labour shortages, poor project planning and scheduling, drawing changes, poor project management, assigning unrealistic timeframes to project tasks, insufficient data on ground conditions, permit delays from authorities, unfinished drawings and mistakes in drawing documents, slow design progression, design mistakes and discrepancies, consultants’ slowness at giving instructions and responses, design changes during construction phases, and a lack of skilled labour. For commercial construction projects, the predominant delay causes

included poor project planning and scheduling, project scope changes, unfinished drawings and mistakes in drawing documents, design document delays, drawing changes, design mistakes and discrepancies, consultants' slowness in giving instructions and responses, design changes during the construction phase, assigning unrealistic timeframes to project tasks, and unrealistic project durations. Seven identical causes between the two types of projects can be identified: poor project planning and scheduling, drawing changes, assigning unrealistic timeframes to project tasks, unfinished drawings and mistakes in drawing documents, design mistakes and discrepancies, consultants' slowness in giving instructions and responses, and design changes during the construction phase. The root causes of, and solutions to, these delay factors have also been discussed based on available, relevant research reports and articles.

The following recommendations should be considered to mitigate the existing causes of delays. Firstly, to solve workforce scarcity problems, the industry should ensure the solutions recommended have been implemented efficiently in a balanced and reasonable manner. Although training programmes have been widely recommended, several factors have deterred construction companies from implementing such programmes. Therefore, an in-depth study is necessary to investigate the root causes of this. There also seems to be a lack of agreement between New Zealand construction professionals and authorities as to why approvals for building permits are delayed. It is highly recommended that these two parties come together and discuss this issue to find solutions to help improve the speed at which future building permits are processed. Lastly, all sectors in the industry should rethink whether it is reasonable to blame project managers and labourers for not being sufficiently skilled when delays occur, when, in fact, the problem may stem from other factors. These could include clients being unwilling to pay for detailed designs and the consultants representing clients not providing sufficient information, which can affect how quantity surveyors prepare bills of quantity and how project managers create schedules. These, in turn, can affect how contractors, traders and labourers execute their work. Such incidents put stress on these construction professionals, which is a possible reason why so many leave the industry. It is therefore recommended that project managers and consultants educate clients on the importance of good planning from the initial stages of a project, the importance of creating construction contracts that equally allocate risks to all parties, and the consequences of not following these recommendations. A good start to this process would be to draw all parties to the attention to the Construction Accord.

While this research does contribute to filling in knowledge gaps regarding construction delay causes in New Zealand, it does have some limitations. The number of survey responses received, and the fact that participants have been randomised may render the findings to be biased. Thus, the results of this research may not be conclusive of the causative factors of delays in New Zealand residential and commercial construction projects. Furthermore, it should be noted that the discussions on the root causes of predominant delay factors which have been drawn from international research may not necessarily reflect the root causes in the New Zealand context, thus requiring further investigations.

References

- Agyekum-Mensah, G., & Knight, A. D. (2017). The professionals' perspective on the causes of project delay in the construction industry. *Engineering, Construction and Architectural Management*, 24(5), 828-841. <https://doi.org/10.1108/ECAM-03-2016-0085>
- Ahmed, S. M., Azhar, S., Castillo, M., & Kappagantula, P. (2002). Construction delays in Florida: An empirical study [Final report]. Department of Community Affairs, Florida, US. https://www.researchgate.net/publication/228584635_Construction_Delays_in_Florida_An_Empirical_Study
- Ajmal, M., Khan, M., & Al-Yafei, H. (2019). Exploring factors behind project scope creep –stakeholders' perspective. *International Journal of Managing Projects in Business*, 13(3), 483-504. <https://doi.org/10.1108/IJMPB-10-2018-0228>
- Al-Kharashi, A., & Skitmore, M. (2009). Causes of delays in Saudi Arabian public sector construction projects. *Construction Management and Economics*, 27(1), 3-23. <https://doi.org/10.1080/01446190802541457>
- Al Jurf, N., & Beheiry, S. (2012). Factors affecting cost and schedule in Qatar's residential compounds projects. *International Journal of Engineering Management and Economics*, 3(1-2), 117-134. <https://doi.org/10.1504/IJEME.2012.048608>
- Alaghbari, W. e., Kadir, M. R. A., Salim, A., & Ernowati. (2007). The significant factors causing delay of building construction projects in Malaysia. *Engineering, Construction and Architectural Management*, 14(2), 192-206. <https://doi.org/10.1108/09699980710731308>
- Alkass, S., Mazerolle, M., & Harris, F. (1996). Construction delay analysis techniques. *Construction Management & Economics*, 14(5), 375-394. <https://doi.org/10.1080/014461996373250>
- Araín, F. M., Assaf, S., & Pheng, L. S. (2004). Causes of discrepancies between design and construction. *Architectural Science Review*, 47(3), 237-249. <https://doi.org/10.1080/00038628.2000.9697530>
- Arantes, A., da Silva, P. F., & Ferreira, L. M. D. (2015). Delays in construction projects - causes and impacts. 2015 International Conference on Industrial Engineering and Systems Management (IESM), IEEE, pp. 1105-1110. <https://doi.org/10.1109/IESM.2015.7380293>
- Arditi, D., Akan, G. T., & Gurdamar, S. (1985). Reasons for delays in public projects in Turkey. *Construction Management and Economics*, 3(2), 171-181. <https://doi.org/10.1080/01446198500000013>
- Arditi, D., & Pattanakitchamroon, T. (2006). Selecting a delay analysis method in resolving construction claims. *International Journal of Project Management*, 24(2), 145-155. <https://doi.org/10.1016/j.ijproman.2005.08.005>
- Assaf, S. A., & Al-Hejji, S. (2006). Causes of delay in large construction projects. *International Journal of Project Management*, 24(4), 349-357. <https://doi.org/10.1016/j.ijproman.2005.11.010>
- Aziz, R. F. (2013). Ranking of delay factors in construction projects after Egyptian revolution. *Alexandria Engineering Journal*, 52(3), 387-406. <https://doi.org/10.1016/j.aej.2013.03.002>
- Bond, J. (2020). Coronavirus impact: Delays to construction projects feared. Retrieved 17 February 2021, from <https://www.rnz.co.nz/news/business/411094/coronavirus-impact-delays-to-construction-projects-feared>
- Boyle, J. B. (2014). A Performance-Based Solution to Avoid Schedule Failure on Construction Projects. *The Revay Rep*, 31(1), 1-8. <https://www.revay.com/wp-content/uploads/2020/10/v31no1en.pdf>
- Brown, C. (22 April 2020). Building resilience in 2020. *Build*, 178. <https://www.resorgs.org.nz/wp-content/uploads/2020/04/Build178-40-Feature-Resilience-Building-Resilience-In-2020.pdf>
- Building Performance. (n.d.). COVID-19: Building and construction sector guidance. Retrieved 04 February 2021 from <https://www.building.govt.nz/covid-19/>
- Capka, J. R. (2004). Megaprojects - they are a different breed. *Public Roads*, 68(1), 2-9. <https://trid.trb.org/view/741778>
- Chan, D. W., & Kumaraswamy, M. M. (1996). An evaluation of construction time performance in the building industry. *Building and Environment*, 31(6), 569-578. [https://doi.org/10.1016/0360-1323\(96\)00031-5](https://doi.org/10.1016/0360-1323(96)00031-5)
- Chan, D. W., & Kumaraswamy, M. M. (1997). A comparative study of causes of time overruns in Hong Kong construction projects. *International Journal of Project Management*, 15(1), 55-63
- Chang-Richards, Y., Wilkinson, S., Seville, E., & Brunsdon, D. (2017). Effects of a major disaster on skills shortages in the construction industry. *Engineering, Construction and Architectural Management*, 24(1), 2-20. <https://doi.org/10.1108/ECAM-03-2014-0044>
- Chang, A. S. T. (2002). Reasons for cost and schedule increase for engineering design projects. *Journal of Management in Engineering*, 18(1), 29-36. [https://doi.org/10.1061/\(ASCE\)0742-597X\(2002\)18:1\(29\)](https://doi.org/10.1061/(ASCE)0742-597X(2002)18:1(29))
- Chritamara, S., Ogunlana, S., & Bach, N. L. (2001). Investigating the effect of initial scope establishment on the performance of a project through system dynamics modelling. *Engineering, Construction and Architectural Management*, 8(5/6), 381-392. <https://www.emerald-com.ezproxy.massey.ac.nz/insight/content/doi/10.1108/eb021198/full/pdf>
- Climo, D. (2020). COVID and the new normal. *Build*, 179. <https://www.buildmagazine.org.nz/index.php/articles/show/covid-and-the-new-normal>

- Construction Accord. <https://www.constructionaccord.nz/>
- Construction Health and Safety NZ. (2020b). New Zealand COVID-19 - Alert Level 2 V&H Construction Protocols. <https://www.chasnz.org/covid19>
- Construction Health and Safety NZ. (2020a). COVID-19 Health and Safety Protocols for New Zealand Residential Construction Sites. <https://www.chasnz.org/covid19>
- Construction Sector Accord. (2020). COVID-19 – Standard for New Zealand Construction Operations. https://uploadssl.webflow.com/5b140388d0d5fed5b7f20f13/5e97fd843fc8a750a9292dfb_COVID19_Construction_Standard_v1.1_16Apr.pdf
- Deloitte. (2020). How the Construction Industry can take proactive steps to mitigate the impact of Covid-19 restrictions. Retrieved 24 February 2021, from https://www2.deloitte.com/content/dam/Deloitte/ie/Documents/FinancialServices/IE_RE_ConstructionIndustryCovid_0320_final.pdf
- Department of Labour. (2002). Guide for Safety with Underground Services. <https://worksafe.govt.nz/dmsdocument/1442-guide-for-safety-with-underground-services>
- Duncan, A., & Brunsdon, N. (2017). Perceived barriers to getting resource and building consents for medium-density housing (BRANZ Study Report SR381).
- Durdyev, S., & Mbachu, J. (2011). On-site labour productivity of New Zealand construction industry: Key constraints and improvement measures. *Australasian Journal of Construction Economics and Building*, 11(3), 18-33. <https://pdfs.semanticscholar.org/36a7/c15faecf75bc0b7c075f876d5341b009b658.pdf>
- Ebekozien, A., Uwadia, F., & Usman, D. (2015). The impact of design errors and incomplete drawings on construction project delivery in Nigeria. *Proceedings of the Academic Conference of African Scholar Publications & Research International on Sub-Sahara African Transformation and National Development*, Kaduna, Nigeria. <https://www.africanscholarpublications.com/wp-content/uploads/2016/03/THE-IMPACT-OF-DESIGN-ERRORS-AND-INCOMPLETE-DRAWINGS-ON-CONSTRUCTION-PROJECT-DELIVERY-IN-NIGERIA.pdf>
- Emam, H., Farrell, P., & Abdelaal, M. (2015a). Causes of delay on infrastructure projects in Qatar. *Proceedings of the 31st Annual ARCOM Conference*, Lincoln, UK, Association of Researchers in Construction Management, Nottingham, UK. <file:///S:/All%20downloads/Emam-2015-CausesofdelayoninfrastructureprojectsinQatar.pdf>
- Emam, H., Farrell, P., & Abdelaal, M. (2015b). Causes of Delay on Large Building Projects in Qatar. *The 2nd International Conference of Buildings, Construction and Environmental Engineering (BCEE2-2015)*. <file:///S:/All%20downloads/CausesofDelayonLargeBuildingProjectsInQatarfinal.pdf>
- Faridi, A. S., & El-Sayegh, S. M. (2006). Significant factors causing delay in the UAE construction industry. *Construction Management and Economics*, 24(11), 1167-1176. <https://doi.org/10.1080/01446190600827033>
- Głuszak, M., & Leśniak, A. (2015). Construction delays in clients opinion—multivariate statistical analysis. *Procedia Engineering*, 123, 182-189. <https://doi.org/10.1016/j.proeng.2015.10.075>
- Gonzalez, P., González, V., Molenaar, K., & Orozco, F. (2014). Analysis of causes of delay and time performance in construction projects. *Journal of Construction Engineering and Management*, 140(1), 04013027. [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0000721](https://doi.org/10.1061/(ASCE)CO.1943-7862.0000721)
- Gunduz, M., & AbuHassan, M. H. A. (2016). Causes of construction delays in Qatar construction projects. *International Journal of Civil and Environmental Engineering*, 10(4), 531-536. <file:///S:/All%20downloads/C15.pdf>
- Gündüz, M., Nielsen, Y., & Özdemir, M. (2013). Quantification of delay factors using the relative importance index method for construction projects in Turkey. *Journal of Management in Engineering*, 29(2), 133-139. [https://doi.org/10.1061/\(ASCE\)ME.1943-5479.0000129](https://doi.org/10.1061/(ASCE)ME.1943-5479.0000129)
- Hancher, D. E., & Rowings, J. E. (1981). Setting highway construction contract duration. *Journal of the Construction Division*, 107(2), 169-179. <https://doi.org/10.1061/JCCEAZ.0000953>
- Harris, C. (21 August 2017, para.13). Poor project management blamed for construction budget blowouts. Retrieved 21 August 2017 from <https://www.stuff.co.nz/business/property/95358391/poor-project-management-blamed-for-construction-budget-blowouts>
- Hwang, B.-G., Zhao, X., & Ng, S. Y. (2013). Identifying the critical factors affecting schedule performance of public housing projects. *Habitat International*, 38, 214-221. <https://doi.org/10.1016/j.habitatint.2012.06.008>
- Janssens, D. E. (1991). *Design-build explained*. Macmillan International Higher Education.
- Kasma, D. R. (1987). Consultant selection. *Journal of Management in Engineering*, 3(4), 288-296. [https://ascelibrary-org.ezproxy.massey.ac.nz/doi/pdf/10.1061/\(ASCE\)9742-597X\(1987\)3%3A4\(288\)](https://ascelibrary-org.ezproxy.massey.ac.nz/doi/pdf/10.1061/(ASCE)9742-597X(1987)3%3A4(288))
- Koushki, P. A., Al-Rashid, K., & Kartam, N. (2005). Delays and cost increases in the construction of private residential projects in Kuwait. *Construction Management and Economics* 23(3), 285-294. <https://doi.org/10.1080/0144619042000326710>

- Kraiem, Z. M., & Diekmann, J. E. (1987). Concurrent delays in construction projects. *Journal of Construction Engineering and Management*, 113(4), 591-602. <https://ascelibrary.org.ezproxy.massey.ac.nz/doi/pdf/10.1061/%28ASCE%290733-9364%281987%29113%3A4%28591%29>
- 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. *Journal of Management in Engineering*, 32(1), 04015032. [https://doi.org/10.1061/\(ASCE\)ME.1943-5479.0000391](https://doi.org/10.1061/(ASCE)ME.1943-5479.0000391)
- Lessing, B., Thurnell, D., & Durdyev, S. (2017). Main factors causing delays in large construction projects: Evidence from New Zealand. *Journal of Management, Economics, and Industrial Organization*, 1(2), 63-82. <file:///S:/All%20downloads/MaincausesofdelayNZ.pdf>
- Leys, J. (2020). The supply chain and recovery. *Build*, 178. <https://www.buildmagazine.org.nz/assets/ebooks/B178/Build178.html?>
- Lobo, Y. B., & Wilkinson, S. (2008). New approaches to solving the skills shortages in the New Zealand construction industry. *Engineering, Construction and Architectural Management*, 15(1), 42-53. <https://doi.org/10.1108/09699980810842052>
- Love, P. E., & Smith, J. (2003). Benchmarking, benchaction, and benchlearning: rework mitigation in projects. *Journal of Management in Engineering*, 19(4), 147-159. [https://doi.org/10.1061/\(ASCE\)0742-597X\(2003\)19:4\(147\)](https://doi.org/10.1061/(ASCE)0742-597X(2003)19:4(147))
- Mahamid, I., Bruland, A., & Dmaid, N. (2012). Causes of delay in road construction projects. *Journal of Management in Engineering*, 28(3), 300-310. [https://doi.org/10.1061/\(ASCE\)ME.1943-5479.0000096](https://doi.org/10.1061/(ASCE)ME.1943-5479.0000096)
- Maritz, T., & Prinsloo, H. F. (2016). A decision support framework for extension of time claims for the JBCC Principal Building Agreement. *Acta Structilia*, 23(2), 109-146. <file:///S:/All%20downloads/151804-Article%20Text-398189-1-10-20170217.pdf>
- Marzouk, M. M., & El-Rasas, T. I. (2014). Analysing delay causes in Egyptian construction projects. *Journal of Advanced Research*, 5(1), 49-55. <https://doi.org/10.1016/j.jare.2012.11.005>
- MBIE. (2016). Understanding the building consent process. Retrieved 02 January 2021 from <https://www.building.govt.nz/projects-and-consents/apply-for-building-consent/building-consent-process/>
- MBIE. (2018). Planning for 21st century construction skills. Retrieved 21 April 2020 from <https://www.mbie.govt.nz/assets/7b96257cf6/cabinet-paper-action-plan-construction-skills-strategy.pdf>
- McCord, J., McCord, M., Davis, P. T., Haran, M., & Rodgers, W. J. (2015). Understanding delays in housing construction: evidence from Northern Ireland. *Journal of Financial Management of Property and Construction*, 20(3), 286-319. <https://doi.org/10.1108/JFMPC-07-2015-0028>
- Mpofu, B., Ochieng, E. G., Moobela, C., & Pretorius, A. (2017). Profiling causative factors leading to construction project delays in the United Arab Emirates. *Engineering, Construction and Architectural Management*, 24(2), 346-376. <https://doi.org/10.1108/ECAM-05-2015-0072>
- Mydin, M. O., Sani, N. M., Taib, M., & Alias, N. M. (2014). Imperative causes of delays in construction projects from developers' outlook. *MATEC Web of Conferences*. <https://doi.org/10.1051/mateconf/20141006005>
- New Zealand Utilities Advisory Group. (2013). Your guide to working on the road and staying alive. <https://powernet.co.nz/uploads/2014/04/NZUAGRoadWorkersBookletWeb.pdf>
- Ng, S. T., & Chow, L. K. (2004a). Evaluating engineering consultants' general capabilities during the pre-selection process – a Hong Kong study. *Engineering, Construction and Architectural Management*, 11(3), 150-158. <https://doi.org/10.1108/09699980410535769>
- Ng, T. S. (2004). Factors pertinent to the selection of architectural and building services consultants. *HKIE Transactions*, 11(3), 42-49. <https://doi.org/10.1080/1023697X.2004.10667967>
- O'Brien, J. J. (1976). *Construction delay: Responsibilities, risks, and litigation*. Cahners Books International.
- Oyedele, L. O., & Tham, K. W. (2007). Clients' assessment of architects' performance in building delivery process: Evidence from Nigeria. *Building and Environment*, 42(5), 2090-2099. <https://doi.org/10.1016/j.buildenv.2005.06.030>
- Palaneeswaran, E., Ramanathan, M., & Tam, C. M. (2007). Rework in projects: Learning from errors. *Survey and Built Environment*, 18(2), 47-58.
- Pointon, N. (2021). Covid 19 coronavirus: Shortage of plumbing, electrical and glass supplies. Retrieved 17 February 2021, from <https://www.nzherald.co.nz/business/covid-19-coronavirus-shortage-of-plumbing-electrical-and-glass-supplies/AD2VDNUHJGTDAFC6VEE66PB7AQ/>
- Prinsloo, H., & Van Heerden, A. (2020). The Predominant Causes of Construction Delays. 6th New Zealand Built Environment Research Symposium (NZBERS 2020), 196-207. <https://nzbers.massey.ac.nz/index.php/2020-symposium/>
- Prinsloo, H. F. (2016). *Toward a decision framework for the analysis of construction claims* [Doctoral dissertation, University of Pretoria].
- Provost, L. (2015). Auckland Council: How it deals with building consents. <https://oag.parliament.nz/2015/auckland-building-consents/docs/auckland-building-consents.pdf>

- PWC. (2016). Valuing the role of construction in the New Zealand economy. <http://www.constructionstrategygroup.org.nz/downloads/PwC%20Report%20-%20Construction%20Sector%20Analysis%20Final%204%20Oct.pdf>
- Ren, Z., Atout, M., & Jones, J. (2008). Root causes of construction project delays in Dubai. *Procs 24th Annual ARCOM Conference*, (pp. 749-757).
- Roberts, R. (2017). New Zealand Ground Investigation Specification. <https://fl-nzgs-media.s3.amazonaws.com/uploads/2017/03/NZ-Ground-Investigation-Specification-Vol-0.pdf>
- Shah, R. K. (2016). An exploration of causes for delay and cost overrun in construction projects: A case study of Australia, Malaysia & Ghana. *Journal of Advanced College of Engineering and Management*, 2(1), 41-55. http://researchonline.ljmu.ac.uk/id/eprint/3974/1/JACEM_2016.pdf
- Shebob, A., Dawood, N., Shah, R., & Xu, Q. (2012). Comparative study of delay factors in Libyan and the UK construction industry. *Engineering, Construction and Architectural Management*, 19(6), 688-712. <https://doi.org/10.1108/09699981211277577>
- Son, J., & Rojas, E. M. (2011). Impact of optimism bias regarding organisational dynamics on project planning and control. *Journal of Construction Engineering and Management*, 137(2), 147-157. [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0000260](https://doi.org/10.1061/(ASCE)CO.1943-7862.0000260)
- Sporrong, J. (2011). Criteria in consultant selection: public procurement of architectural and engineering services. *Australasian Journal of Construction Economics and Building*, 11(4), 59-76. <file:///S:/All%20downloads/2297-Article%20Text-10015-1-10-20111212.pdf>
- Stats NZ Tataurangi Aotearoa. (04 September 2020). Impact of COVID-19 on building projects. <https://www.stats.govt.nz/news/impact-of-covid-19-on-building-projects>
- Tafazzoli, M., & Shrestha, P. (2017). Factor analysis of construction delays in the US construction industry. *International Conference on Sustainable Infrastructure 2017*, (pp. 111-122). <file:///S:/All%20downloads/FactorAnalysisofConstructionDelaysintheUSConstructionIndustry.pdf>
- Thomas Ng, S., & Chow, L.-K. (2004). Framework for evaluating the performance of engineering consultants. *Journal of Professional Issues in Engineering Education and Practice*, 130(4), 280-288. [https://doi.org/10.1061/\(ASCE\)1052-3928\(2004\)130:4\(280\)](https://doi.org/10.1061/(ASCE)1052-3928(2004)130:4(280))
- Vacanas, Y., & Danezis, C. (2018). An overview of the risk of delay in Cyprus construction industry. *International Journal of Construction Management*, 1-13. <https://doi.org/10.1080/15623599.2018.1541703>
- Venkatesh, P. K., & Venkatesan, V. J. M. C. R. J. (2017). Delays in construction projects: a review of causes, need and scope for further research. *Malaysian Construction Research Journal*, 23(3), 89-113. [file:///S:/All%20downloads/prasad_vasugi_MCRJ%20\(1\).pdf](file:///S:/All%20downloads/prasad_vasugi_MCRJ%20(1).pdf)
- Wilkinson, S. (2001). An analysis of the problems faced by project management companies managing construction projects. *Engineering, Construction and Architectural Management*, 8(3), 160-170. <https://www-emerald-com.ezproxy.massey.ac.nz/insight/content/doi/10.1108/eb021178/full/pdf>
- Wong, K., & Vimonsatit, V. (2012). A study of the factors affecting construction time in Western Australia. *Scientific Research and Essays*, 7(40), 3390-3398. <https://doi.org/10.5897/SRE12.138>
- Yang, J.-B., Chu, M.-Y., & Huang, K.-M. (2013). An empirical study of schedule delay causes based on Taiwan's litigation cases. *Project Management Journal*, 44(3), 21-31. <https://doi.org/10.1002/pmj.21337>
- Yang, J.-B., & Wei, P.-R. (2010). Causes of delay in the planning and design phases for construction projects. *Journal of Architectural Engineering*, 16(2), 80-83. [https://doi.org/10.1061/\(ASCE\)1076-0431\(2010\)16:2\(80\)](https://doi.org/10.1061/(ASCE)1076-0431(2010)16:2(80))
- Yates, J., & Epstein, A. (2006). Avoiding and minimising construction delay claim disputes in relational contracting. *Journal of Professional Issues in Engineering Education and Practice*, 132(2), 168-179. [https://doi.org/10.1061/\(ASCE\)1052-3928\(2006\)132:2\(168\)](https://doi.org/10.1061/(ASCE)1052-3928(2006)132:2(168))
- Zack, J. G. (2003). Schedule delay analysis; is there agreement? *Proc. PMI-CPM college of performance spring conf*, (Vol. 41)
- Zidane, Y., & Andersen, B. (2018). Causes of delay and their cures in major Norwegian projects. *Journal of Construction Engineering and Management*, 134(11), 831-841. [https://doi.org/10.1061/\(ASCE\)0733-9364\(2008\)134:11\(831\)](https://doi.org/10.1061/(ASCE)0733-9364(2008)134:11(831))

Mapping Supply Chain to Enhance Capability and Capacity of Prefabricated Housing Supply in New Zealand

Sanaz Nesarnobari * Wajiha Shahzad, Mostafa Babaeian Jelodar

School of Built Environment, Massey University, New Zealand.

* Corresponding author: S.nesarnobari@massey.ac.nz

Abstract

Long-term performance-related problems in the construction sector have caused a deficit in the housing supply in New Zealand. It is essential to enhance the capability and capacity of the residential sector of the construction industry for it to be able to tackle problems that are responsible for slow delivery of housing projects, high cost of construction, and generation of construction waste. Prefabricated construction has well-acknowledged tangible benefits, but it is relatively low in New Zealand. It is established that prefabricated housing supply chain management (SCM) in New Zealand needs improvement and integration to reap the full benefits of this technology and increase its uptake.

The focus of this study is to carry out a mapping of the prefabricated housing supply chain in New Zealand and identify the disruptions in the supply chain. For this purpose, a comprehensive analytical approach is followed integrating bibliometric search and qualitative discussion by objectively investigating: 1) recent prefabricated housing research keywords, pros & cons; to identify factors that are limiting prefabricated sector to deliver New Zealand housing supply requirements 2) study gaps in combining prefabricated housing sector with other new construction concepts, 3) prefabricated construction research directions in the future

There is no equivalency between the demand and supply of prefabricated housing. Trust among stakeholders, lack of workforce and a delay in the onsite assembly are significant issues in SCM. There are risks and disruptions through the whole supply chain, such as availability of imported raw material, freight delays, situations such as the Covid-19 pandemic are among other unprecedented disrupters. Moreover, the factories cannot manufacture and store bulky prefabricated components before the order and signing a contract due to lack of storage capacity. It is necessary to improve the capability and capacity of the residential sector to be able to tackle issues that are responsible for slow delivery of housing projects, high cost, and generation of construction waste.

Keywords

Supply Chain Management, Disrupters, review paper, Prefabrication, Housing, New Zealand.

Introduction

Housing demand in New Zealand (NZ) has risen dramatically over the last few decades. One of the primary sources of increased demand is accelerating an urbanisation plan led by a significant foreign population (Grimes, 2010). According to Statistics NZ, the country's ordinarily resident population increased by 10.8% between 2013 and 2018. However, the total number of dwellings increased by just 6.2 per cent. Between the 2013 and 2018 censuses, the population of Auckland increased by 156,168 (11%), although housing stock increased by just 6.5 per cent. According to the most recent census statistics, developing new residences has not kept pace with population growth. Much of the new construction has not taken place where it is most needed. As a result, there was a notable housing shortage compared to population growth.

Various issues and challenges in the building industry prohibited it from keeping up with the growing demand (Finnie, 2018). New Zealand's construction industry productivity is lower than other nations (PWC, 2016, Curtis, 2018, Allison, 2013). The NZ construction sector suffers from low productivity, high staff turnover, low skills, and a lack of innovation (Sutrisna, 2020).

This demonstrates that NZ has to build more homes and move toward more sustainable development to ensure that future generations have access to the resources they require and the opportunity to prosper (Moradibistouni M and Gjerde M, 2017).

Affordability, excellent quality, and quick-build were all factors that were necessary for NZ homes to meet demand, but they were not provided under the existing paradigm. As previously stated, home quality has been highlighted as a data system gap in NZ (Charlotte Brown, 2020), and it is a continuing concern in the building industry. Beyond the immediate housing crisis, it is necessary to reduce costs and move swiftly to enhance margins and reduce continuing skill shortages, contributing to lower quality and the need for rework (BDO, 2019, Gordon, 2018, Rotimi, 2015).

Researchers and working professionals in the construction industry have been trying to develop novel ideas and approaches that meet demands and requirements to respond to the sophisticated and growing needs to increase productivity in the industry. There were numerous options, some of which were eventually adopted. Offsite building, often known as prefabrication, has become increasingly popular (Goulding, 2013). According to construction industry practitioners, prefabrication technology is the construction industry's best hope for supplying a growing need for more affordable housing (Brandon, 2004, Tam et al., 2007).

Literature Review

Prefabricated Systems

The first prefabricated house in NZ was received by Te Pahi, the Maori chief, in 1806. The prefabrication business began in 1833 by importing prefabricated houses for individuals as kits and pre-cut frames from the United Kingdom, the United States, and Australia (Bergdoll, 2008, Toomath, 1996). The construction industry grew swiftly to meet the demands of a rapidly growing population and migratory population (Isaacs, 2008). In the last decade of the nineteenth century, the NZ Railways Department became the country's first producer of prefabricated houses (Bowron, 2007). Prefabricated building materials are divided into concrete-based and metal-based prefabricated products. Frames, partition panels, door and

window frames, metallic roof systems, formworks at various stages of construction, precast beams and façades, tunnel linings, bridge girders, and platforms for meteor works, sewage discharge units, and underground facilities, among other metal prefabricated components, are in high demand. According to Prefab (Prefab NZ, 2018a), prefabrication is primarily used in the production of concrete products, prefabricated timber structures, and prefabricated metal buildings. A successful adoption requires a deep understanding of industrial ideas and technology, as well as collaboration among supply chain players and full government support (Samarasinghe and Wood, 2021).

Eco-friendliness, safety, lower financial cost, greater flexibility in construction techniques, lower construction waste, short construction period, fewer construction defects, and increased health and safety levels are among advantages of prefabrication-based construction (Hao and Samarasinghe, 2020, Moradibistouni, 2017), more cost-effective housing alternative, greater control over manufacturing and building circumstances, resulting in a higher-quality product (Hashemi A and Hadjri K, 2014, Cook B, 2005). Houses, multi-story buildings, and highways and bridges are constructed using this method (Ngowi, 2005). To achieve this increased quality, closer coordination of labour, materials, equipment, and sub-trades in controlled circumstances is employed. Quality control and any required adjustments may be made before the product leaves the production floor.

When comparing prefabrication construction to traditional methods, it is evident that the speed of building delivery has risen. The use of prefabricated panels or modules reduces the requirement for external contractors and plastering and tiling (Poon CS, 2003, Jelodar et al., 2013). This might decrease staff management responsibilities (Roy R, 2003) and considerably boost the overall construction pace (Lu N and Korman T, 2010). Prefabricated buildings can assist to reduce the risk of construction delays due to poor weather in a manufacturing context. This can reduce the programme time component of typical construction process by 30 to 60%. The time saved onsite can help offset the increased expenses of new material development or pre-construction planning processes that involve large, prefabricated parts (Aburas H, 2011, Bildsten L, 2011). Prefabrication buildings, according to BRANZ, save 27% of the material, 18% of labor, 45% of the land, and 10% of other costs (profit, plant, fees), resulting in a 15% reduction in the constructed cost of new houses (Prefab NZ, 2014).

Prefabrication also has the advantage of tight quality controls and testing systems and prototypes within the facility. The defects liability period following occupancy can decrease the number of mistakes and subsequent repair work. Compared to typical construction, onsite noise, dust, transportation, and neighbourhood disruption will likely be reduced. Prefabricated houses can have a variety of appearances and are frequently indistinguishable from traditionally constructed homes. Cutting timelines and costs can be achieved by eliminating reliance on the weather for site-based construction, better in-house coordination of sub-trades, decreased transportation, and price advantages from bulk buying. Due to the cost savings inherent in the construction process, a prefabricated shell will often be less expensive than a site-built building of identical specifications, design, and quality (Buchanan M, 2004), through efficient ordering, indoor protection, pre-planning, and cutting, able to eliminate material waste. For example, in NZ, construction is the 'forty per cent industry', with buildings accounting for 40% of energy consumption, 40% of the waste stream, 35% of carbon dioxide emissions, and 40% of raw material use. Because prefabricated buildings require less transportation to the job site and use less energy during their lifetime, they reduce their carbon footprint. Modular construction can reduce delivery delays by as much as 60% to the worksite. The method provides a safe, healthy, and regulated working environment and increased worker

productivity and material efficiency. Site work has previously fallen up to 50% short of its potential, and an estimated 13–18% of resources allocated have been wasted owing to inefficient use. (Gorgolewski MT, 2005). Prefabrication technologies can also assist challenges in the construction industry, such as low-skilled labour, growing market demands for higher-quality homes, and more regulatory oversight.

Barriers to Adoption of Prefabricated Systems

Despite the significant advantages of prefabrication construction projects, prefabrication has numerous limitations in NZ. It is challenging to expand prefabricated building components in NZ since the capacity of manufacturing companies is limited. As a result, prefabricated construction elements are pretty expensive. The expense of crane logistics is a crucial barrier for prefabrication applications in NZ due to a lack of technology and suitably robust cranes (Shahzad, 2011).

China International Marine Containers (CIMC) Modular thinks that contemporary NZ modular buildings are still in the early phases of development, notably in terms of international module suppliers. According to CIMC Modular Systems (2016), the level of local acceptability and acknowledgement of modular structures is still relatively low, ranging from local governments to end-users. They think NZ's approval procedure is more complex and time-consuming than Australia and the United Kingdom. Second, there is a labor shortage in the building industry. The multi-domain collaborative content included in modular structures is different from traditional construction processes (China International Marine Containers (CIMC)Group, 2016). All consultants, construction teams, and modular supply teams must collaborate to guarantee an efficient and cost-effective modular design and to achieve industrial factory production in modular building projects. Because there are few engineering consultancy firms familiar with specific modular building systems in NZ, such as architectural design consultants, structural consultants, fire consultants (including fire engineers), energy efficiency consultants, sound insulation consultants, and mechanical, electrical, and public health consultants, modular construction is difficult to implement. (Prefab NZ, 2018b, Shahzad, 2011). According to Scofield et al. (2009), the main obstacle in bringing modular construction to NZ is the lack of understanding about prefabricated building technologies among experts providing consultancy services (Scofield, 2009a). In addition to the problem of a small talent pool within the industry, no bank mortgage policy embraces prefabricated houses. Prefab NZ (2018) says that banks have a direct system to assess the loan risk of onsite construction, but if the home is produced in advance at the factory, they need an additional assessment mechanism (Prefab NZ, 2018). At present, financial institutions have doubts about loans, which are all related to risks.

The Supply Chain Network

The supply chain (SC) is a web of interconnected companies and relationships of various suppliers and distributors (Mostafa, 2014a). The SC is a product transformation method that changes items from raw materials to inventory, work-in-progress, and completed goods. To put it another way, supply chain management (SCM) is the notion of collaborating and integrating the value chains of many businesses. The strategic management of these chains has one main goal: to create value for customers and chain members in higher profitability (Speller T, 2007). These advantages would be utilised to their full extent only if growth could be generated and sustained. Identifying, measuring, and modelling value across all stakeholders in the prefabrication manufactured supply chain (PM SC) is paramount to increasing the adoption of PM buildings.

There are unique features like the supply chain for offsite construction (OSC) compared to traditional SCs. These features include design, manufacturing, factory inventory, delivery, onsite inventory, construction site, and end-project (Figure 1) (J. Ikonen, 2013). The OSC-SC is a multi-tiered SC that begins with the creation of comprehensive design and shop drawings for structural components that will be constructed in a prefabricated factory. The components are then stored and transferred to building sites where they will be installed. These components are made to order to meet the needs of each project. As a result, prefabricators cannot manufacture certain parts before receiving orders. Contractors cannot retain huge buffer stockpiles of these components to hedge against supply delays because they are heavy and bulky (Hsu et al., 2018).

Furthermore, the OSC-SC is rife with risks dispersed throughout its stages (design, production, logistics, and onsite building) (Wang et al., 2018). Any disruption at the top of the OSC-SC impacts the following stages, resulting in an inefficient SC. As a result, researchers have used a variety of modelling methodologies to investigate the OSC-SC and improve its performance and long-term viability. Compared to the manufacturing supply chain, the primary distinction is that the product is assembled onsite, and a greater portion of the supply chain is completed during production (Stroebele and Kiessling, 2017).



Figure 1. The manufacturing process of Prefabrication in NZ (Sooriyamudalige, 2020)

According to previous research, there has not been an adequate understanding of supply chain management and the growth in its performance in residential construction in NZ.

Research Methodology

The research method is based on an in-depth review of relevant literature. The research methodology for literature review is chosen from related survey studies by Chan & Yi (2014), W. Zhou et al. (2012), Hassan Ibrahim (2013), Ibem & Laryea (2014), and Guo et al. (2017). This involves the de-contextualisation and recontextualization of the examined articles (Jelodar et al., 2016). The selection of this approach offered the benefit of bringing together proof from various research on the topic to inform practice. The analysis related to supply chain research is divided into two main perspectives: SCM for prefabricated elements and barriers to adopting prefabricated components. A three-stage literature search refined the desktop investigation to present an analysis of relevant journal papers. SCM of prefabricated elements has gained traction from practitioners over the last two decades. Hence for the study, authors selected articles published using Scopus as the primary source of literature. Scopus has a wide range of journal indexes and unique features in keyword searching and citation analysis compared to other databases like Google Scholar, Science Direct and Web of Science.

Stage 1 – Search by keywords, title, and abstract

A search criterion was designed to select emerging developments on the subject of interest, i.e., application of supply chain in NZ and links to prefabricated housing contained in article keywords, title, and abstract. Articles were searched by rearranging key phrases under the 'TITLE-ABS-KEY' menu.

Stage 2 – Selection by journal impact

This survey is based on selected top-ranked, peer-reviewed to obtain related developments.

Stage 3 – Selection by visual screening

The papers collected from stage 2 were considered to ensure that the search is concentrated on the relationship between the supply chain and prefabricated housing. This stage is designed to achieve the research objective of finding key supply chain functions and linking them to prefabrication in NZ. Screening involved reading the abstracts, findings, and conclusions. The criteria for selection were to find related work in NZ.

Findings and Discussion

Residential Housing in New Zealand

The residential construction sector in NZ is uniquely positioned to benefit from decades of international expertise and adapt knowledge and techniques to the local situation. NZ's home building sector has a lot of room to develop aspirational industry, quality standards or labels that help customers understand the quality of what they are buying (Buckett, 2014). In NZ, detached housing makes up the majority of new construction (PAGE, 2013). The disparity between the rate of new house building and population growth in several of NZ's major cities is causing considerable worry. Auckland is particularly heavily afflicted with over a third of NZ's population (Quickstats, 2013). In Auckland, in particular, rising property prices and rents have become a significant source of worry (Buckett, 2014). The average business size is expected to rise, resulting in a dramatic shift in new housing features, perhaps resulting in higher quality, more affordable housing, and increased sustainability (PAGE, 2013).

Prefabricated house-building (PHB) is a natural synthesis of the manufacturing and construction sectors, with techniques that overlap (Gann, 1996). However, this is a minor part of the entire house-building sector (Linner, 2012), with space to move and market intervention a CIB report on offshore manufacturing and production (Goulding, 2013). Studies have shown that industrialising businesses may be an efficient way to increase construction capacity and capability while also increasing productivity. However, because of cost obstacles, a lack of design flexibility and opposing views, the industry's adoption of new prefabricated building technologies has been limited (Mostafa, 2014a, Goodier, 2012, Pan, 2011a). Poshdar et al. (2019) found out that most SMEs (small and medium enterprises) in NZ housing is trailing behind in new business methods. Building contractors, also continue to be hesitant to use prefabrication, which is necessary to stay competitive and improve organisational performance (Poshdar, 2019).

As a result, these constraints respond slowly to the house-building SC, demonstrating the need of managing and improving the whole supply chain's efficiency (Bankvall, 2010). SCM is critical for projects that employ prefabricated house-building parts to achieve sustainability. Improved prediction of under-capacity or overcapacity, as well as greater evidence-based decision-making, would eliminate waste. Furthermore, the delivery uncertainty would be reduced by prioritising the project through SCM.

Because offsite business is considered a specialised industry with a variety of offerings, it generates a dynamic and competitive environment for firms participating in it ((Lessing, 2015a). However, as the construction operations have been moved offsite, supply chains have become critical for PHB (Vrijhoef, 2000). This contrasts with typical techniques, which require suppliers to have previous knowledge of other parts of the supply chain (Walker, 2012, p. 137).

Regardless of the stage or phase of the house-building project, relying on supply chains is critical for achieving offsite advantages (Pan, 2012b, Pan, 2012a). PHB projects are confronting existing firms (e.g., suppliers) adjusting to industrialisation and their level of engagement in supply chains to PHB projects. Due to the unique nature of prefabricated house-building elements compared to typical supply chains, managing supply chains to achieve sustainability is a crucial topic for projects utilising prefabricated house-building parts. According to Shahzad (2011), a lack of supply chain capacity is a key obstacle to prefabrication adoption in NZ (Shahzad, 2011). Also, Almughrabi stated that complexity and fragmentation in NZ's prefabricated construction supply chain is one of the barriers of prefab uptake in NZ (Almughrabi et al., 2021).

Residential Supply Chain

The traditional construction supply chain that developed according to relations of the construction project's participants in 2000 aligned the information and material flows among the participants within the construction process (Vrijhoef, 2000). The timeframe was developed in 2009 for a conventional industrialised house-building project to recognise the errors in the projects (Johnsson, 2009). However, because of crucial factors such as high expectancy, small economic size, and physical isolation, construction supply chain procedures in NZ are at a tactical level (Ying, 2015). Supply chain challenges include a lack of foreign strategic alliance partnerships, information exchange, and trade partnering (Basnet, 2003, D. Mollenkopf and G. P. Dapiran, 2005). Also, interdisciplinary problems existed, such as the connection between the building supply chain and sustainability (J. E. McDevitt, 2012). The home construction supply chain is fragmented by nature, causing management issues and stifling inventiveness, so construction prices increase and building quality decreases (NZPC, 2012). Moreover, contractors were indifferent in collaborating with other parts (Samarasinghe A, 2013). In construction, advanced technologies such as BIM software and supply chain planning and management are not taken into account (V. Tran, 2012).

Under corporate social responsibility, all stakeholders in the building supply chain are responsible for affordable housing. Still, reduced industry productivity and tight government restrictions add to the complexity (M. M. Bassett, 2015). Affordable housing is impossible without the engagement of contractors (who are the primary actors in the building supply chain) through incentive programmes (A. J. Cullen, 2005). Government initiatives such as those made by the Construction Strategy Group (CSG., August 1, 2015) to decrease material and labor costs by 20% through Productivity Partnership are insufficient unless the industry is involved at both the micro and macro levels to achieve affordable housing. For this purpose, the report suggested: introducing and integrating specialised subcontractors to increase SC flexibility; and effective subcontractor management to restrict coordination issues and rework. To minimise disputes, subcontractors should be more involved in achieving project goals, implementing standardised housing to boost scalability and production, and integrating project delivery via SC members' cooperation during the design and construction phases for the supply chain of affordable houses. Also, aspects of trade partners to achieve external emphasis (D. Mollenkopf and G. P. Dapiran, 2005) and effective logistics management (Y. Fei, 2014) are suggested. Auckland council report (C. Parker, 2015) indicated factors have been considered for reforming the supply chain: 1) fewer licensed building practitioners 2) inconsistent design and manufacturing processes 3) low scale economies and limited scope economies 4) quality risk of construction and design 5) poor quality assurance 6) project management practices 7) more essential, supply chain participants should collaborate to increase overall productivity through innovative manufacturing technology. Facilitating international supply chain members

will result in innovative housing solutions while also reducing market power. Affordable housing has been related to issues in building SCM such as alliancing, partnering, and collaboration among housing supply chain participants (Basnet, 2003, D. Mollenkopf and G. P. Dapiran, 2005, NZPC, 2012). These issues have to do with the relationships and coordination of supply chain participants.

Construction supply chain management needs to investigate a link between primary and particular difficulties with generic problems. Researches have explained general main obstacles to coordination, subcontractor or supplier integration, legality, stakeholder management, and corporate social responsibility.

Literature review explains specific issues: insufficient information exchange among supply chain participants, a lack of Building Information Modelling adoption by construction parties (DBHNZ, 2012), which facilitates collaboration among partners (M. Khosrow-Pour, 2013). Also, material logistic management is a critical component of SCM from a business viewpoint (Barriga, 2005). Offsite manufacturing helps customise construction elements, resulting in increased efficiency (Barriga, 2005). Furthermore, industrialisation can assist in integrating the construction supply chain (A. R. Dainty, 2001).

Construction supply chain integration

Integration of the supply chain concentrates on reaching a reliable, valid, and timely flow of material, information and finance over the whole network to provide consumers value for money. Beneficiaries of reduction in cost and time for constructing order were drawn by integrating the key business functions over the supply chain (Power, 2005). Despite the one-off product is assembled onsite through temporarily set up supply chains (Vrijhoef, 2000), it seems that the essence of construction supply chains is far from a production viewpoint (Fearne, 2006). However, combining the processes and products in the construction sector to gain profit for the customer is suggested (Egan, 1988, Dubois, 2000). Supply chain integration has been offered for the potential to improve efficiency and effectiveness.

Nonetheless, there are barriers linked with implementation. Awad (2010) has recognised perspectives including technical, managerial, and relationship, (Awad, 2010). Technical relates to the obstacles that appear among the SCM systems and strategies; managerial refers to the restrictions that occur in planning and performance of the strategy, and relationship describes the obstacles that influence the organisation of the whole relations (Awad, 2010). Numerous investigations like Akintoye & McIntosh & Fitzgerald 2000, Vrijhoef & Koskela & Howell, 2001, Barratt 2004, Briscoe & Dainty 2005, have been carried out to recognise the obstacles to supply chain integration in the construction industry (Vrijhoef, 2001, Barratt, 2004, Briscoe, 2005, Mbachu, 2017). Results illustrate different barriers: lack of senior management responsibility, lack of understanding of SCM, unequal organisational structure to support the SCM system, low commitment of partners, uncertain strategic advantages. One of the other critical factors for any integration process in construction projects are the availability of information technology support and infrastructure (Eliwa et al., 2018). Often these barriers and critical factors to SCI were not accurately classified and discussed regarding the nature of the project.

The supply chain of prefabricated houses

Production planning and inventory control and logistics and distribution are two activities that make up a supply chain (Beamon, 1988). The prefabricated housing supply chain is divided into four categories, first design consent, second manufacturing of modules/components off-

site, third transportation of modules to site and the last gathering of modular units to form the complete building. Different business entities, such as manufacturers, suppliers, developers, contractors, and distributors, are directly and indirectly involved in the prefabricated house building supply chain to deliver the house to the customer (Mostafa, 2014a), to process forward flow of materials and a backward flow of information (Beamon, 1988). Prefabricated houses' supply is done in two steps: pre-assembly and onsite construction that both have diverse demands on the supply chain. Pre-assembly includes designing, material handling, manufacturing, transportation to the place, and onsite construction involves procurement for installation and foundation (Vrijhoef, 1999, Lessing, 2015b). Design and planning stages involve design freezes, expense planning, methods of procurement, and project planning and scheduling, which are crucial milestones. It is essential to have an exhaustive understanding of the basic requirements to improve the design for following consents and reduce the construction stage's complexities (Amirtash *et al.*, 2021). Numerous studies associated with the construction supply chain have investigated and improved the supply chain's network. However, there is little investigation on the integration of supply chains of prefabricated elements. The obstacles to using this innovative method have restricted its broader uptake, particularly in the housing sector.

According to the research, the prefabricated home construction process was shown to be very complicated and unique in each project. The main phases and critical stakeholders are analysed to determine the interfaces, followed by difficulties since the prefabricated home building process is not standardised. As a result, it is essential to map the exact and accurate supply chain of prefabricated housing buildings to maximise their use.

Supply chains of prefabricated housing buildings are represented in different ways in the construction and manufacturing literature and industry reports: For instance, the producers (Prefabroad map, 2014), manufacturers/suppliers (Liu, 2020), supply network acting as suppliers at different tiers (Steinhardt, 2020), offsite companies in the organisational perspective (Manley, 2019), industrialised house-building companies (Lessing, 2015a), or offsite manufacturing SME supply chains to PHB projects (Pablo, 2020). These supply chains are explained further by Pan and Goodier (2012) as business models based on process, risk, and financial features of offsite construction divided by the amount of offsite work and material (Pan, 2012b).

Also, studies have been conducted to investigate: the benefits of prefabrication (Pasquire, 2002, Lawson, 2010, Pan, 2012b), the improvement of the prefabrication supply chain (London, 2001, Naim, 2003, Doran, 2011, Stroebele and Kiessling, 2017), prefabrication and lean manufacturing (Mostafa, 2014a, Mostafa, 2014b, Lessing, 2015b), the integration of supply chain strategies to prefabrication (Mostafa, 2014a, Lessing, 2015b). However, there has been little research considering the nature and the constraints in the prefabricated housing supply chain. Most of the barriers of prefabrication are aligned with the supply chain of prefabricated housing buildings. Therefore, managing and developing the performance of the complete supply chain is necessary (Bankvall, 2010). Briefly, some of the barriers: Partnering between builders and manufacturers, public perception, cost barriers, less flexibility in design and negative perceptions (Bildsten, 2011b, Pan, 2011a, Goodier, 2012, Mostafa, 2014a), extensive project planning from an early stage, lack of coordination and communication, and transportation constraints are found to be other barriers in prefabricated house building (Pan, 2007, Kamali, 2016). This led to low uptake of prefabrication in NZ. Many studies have been conducted on the construction supply chain to investigate and improve networks. In the NZ

building sector, however, such a detailed examination of different elements of prefabrication construction, including SCM and hazards, has not been conducted.

Shortage of Procurement Innovation in Supply Chain

Even though the construction and operation of prefabrication need considerable innovation in resources and technical support (Tam *et al.*, 2007), prefabrication of NZ lacks resources and technical assistance and lacks innovation in the supply chain which leads to insufficient production potential (Scofield, 2009a, Konukcu, 2011). This causes fundamental challenges for contractors. Finnie *et al.* stated that traditional purchasing systems are used for imports needed for prefabrication (Finnie, 2018). Hence, this problem (lack of innovation) makes limitations to adopt prefabrication.

Prefabrication Supply Chain Integration

All the processes included in project shipment, from procuring essential components to delivering the project to the customer, are Construction Supply Chain Management (CSCM) (Behera, 2015). It is described as managing the flow of information, materials, processes, and activities between whole employees of organisations to deliver high quality and reliable products to the customer efficiently (Akintoye, 2000). Various authors have continuously revised the definition of CSCM in several industries and different cases (Tan, 2001). However, the substantial premise of SCM can be established in systems thinking, which magnifies the significance of viewing all single parties included in the cycle of delivering a product (or service) as an essential contributor to a more robust system (Cai, 2010). Lack of collaboration and coordination amongst stakeholders is one of the barriers to the supply chain (Stadtler, 2002). Unfit integration of all supply networks inside an organisation prevents the adequate flow of orders and products among suppliers and end-user (Lambert, 2000). Other challenges of SCM systems are low transparency, traceability, and lack of trust ((Mentzer, 2001). Favoured SCM demanded a qualification from specific roles to integrate key SC processes (Lambert, 2000). The solution for SCM is Supply Chain Integration (SCI) (Konukcu, 2011). Implementing an effective and powerful SCM needs a combination of processes and flows (Cooper, 1997). The regularity of project delivery systems and collaborative relationships with sufficient flows are described as integration (A. R. Dainty, 2001).

The prefabrication is identified as leverage for reducing the shortcomings of traditional construction systems. Nevertheless, the construction industry is lingering in supply chain integration (Segerstedt Olofsson Anders, 2010, Zhai, 2013, Shahzad, 2016). The complication in prefabrication supply chains is high because of broken working sites (Mostafa, 2014a); this shows that better collaboration and more transparent communication is needed. Furthermore, managing the flows of information and materials and reacting speedily to any modification in customers' demands or design requires dynamic concurrent management strategies as well as the flexibility of supply chain partners to guarantee that the efficient integration of prefabrication supply chain is maintained (Gibb, 2010 , Mostafa, 2014b)

A comprehensive review has been accomplished for identifying the modular barriers and enablers for supply chain integration in module manufacturing. The identified obstacles for wall panel and bathroom pods manufacturing companies in NZ are lack of trust among stakeholders, lack of technology and automation, lack of clear direction and guidance, transportation of models, lack of understanding of SCM (Sooriyamudalige, 2020).

Supply Chain Management

As mentioned, a study in the supply chain of prefabricated housing buildings is rare. One of the latest researches was conducted on significant supply chain barriers for the modular component. As shown in Table, it is demonstrated that automation and trust among stakeholders are substantial barriers to the prefabrication supply chain. Prefabricated home construction is further hampered by significant project planning from the start, a lack of collaboration and communication, and transportation restrictions (Pan, 2011b, Bildsten, 2011a). Contractors may use several methods and essential aspects to reduce or remove the disadvantages while building empirical capacity and competence. These constraints respond slowly to the house-building supply chain, demonstrating the need of managing and improving the whole supply chain's efficiency (Goodier, 2012). Managing supply chains to gain sustainability due to the novel nature of prefabricated house-building elements instead of regular supply chains is essential for projects utilising prefabricated house-building parts. Integration of the supply chain should be from the beginning of the design phase and need strong coordination among stakeholders to arrange labor, materials and equipment resources (Čuš-Babič, 2014).

This coordination requires regular communication and collaboration among stakeholders to convey valuable and up-to-date information (Abedi, 2014). In this study, the latest research on the prefabricated housing supply chain in NZ has been mapped and the disruptions in the supply chain have been identified. Improved prediction of under-capacity or overcapacity, as well as more excellent evidence-based decision-making, would eliminate waste.

Conclusion

This research focuses on prefabrication supply chains within the New Zealand construction sector, specifically housing development. The obstacles and barriers leading to the sector's current flawed status were discussed. Solving offsite construction's complexity/uncertainty challenges is required to improve the industry and increase capacity and capability. This also alleviates the housing shortage. It was shown that the uptake of prefabrication was too low because of supply chain barriers.

Consequently, various influential factors from the literature that hinder its uptake were discussed, indicating the direction of future research to tackle those issues leading to the enhancement of prefabrication. SCM requires extensive investigation first to identify its barriers, disruptions and risk controls and second to employ new approaches to rectify those. Furthermore, lack of trust among stakeholders, lack of understanding of SCM, lack of information sharing, lack of innovation (lack of technology and automation), low coordination, collaboration and partnership, transportation constraints, lack of commitment of managers and experts, vague regulations and strategic legislations, hinder building capacity and capability in the prefabricated manufacturing housing construction sector in NZ. There are risks via the entire supply chain, such as the availability of imported raw material, freight delays, and situations such as the Covid-19 pandemic, among other unprecedented disrupters. Furthermore, the factories cannot manufacture and store bulky prefabricated components before the order and signing a contract due to lack of storage capacity. Hence, future research should target SCM so the housing sector will flourish and thrive gradually. The current study limited its scope because it is based on NZ studies and research literature. Classification of the research problems in the construction supply chain related to prefabricated housing will lead to a more appropriate research approach for further investigation.

References

- A. J. CULLEN 2005. Urban intensification and affordable housing in Auckland. Unpublished Masters, University of Otago, Dunedin.
- A. R. DAINTY, S. J. M., AND G. H. BRISCOE, 2001. New perspectives on construction supply chain integration. *Supply Chain Management: An International Journal*, 6, 163-173.
- ABEDI, M., RAWAI, N. M., FATHI, M. S., AND MIRASA, A. K. 2014. Cloud Computing as a Construction Collaboration Tool for Precast Supply. *Jurnal Teknologi*, 10 70(7), 1-7.
- ABURAS H 2011. Off-site construction in Saudi Arabia: the way forward. *J Archit Eng*, 17, 122-124.
- AKINTOYE, A., MCINTOSH, G & FITZGERALD, E 2000. A survey of supply chain collaboration and management in the UK construction industry. *European Journal of Purchasing & Supply Management*, 6, 159-68.
- ALLISON, N., & PARKER, C. . 2013. *Construction industry study*.
- ALMUGHRABI, F. M., SAMARASINGHE, D. A. S. & ROTIMI, F. E. 2021. Analysis of skill shortages in prefabricated residential construction: A case for new zealand. *C J (Eds) Proceedings of the 37th Annual ARCOM Conference, 6-7 September 2021, UK, Association of Researchers in Construction Management*, 481-490. Scott, L and Neilson, .
- AMIRTASH, P., PARCHAMI JALAL, M. & JELODAR, M. B. 2021. Integration of project management services for International Engineering, Procurement and Construction projects. *Built Environment Project and Asset Management*, 11, 330-349. Available: 10.1108/BEPAM-06-2020-0106
- AWAD, D. 2010. A broader view of the supply chain integration challenges. *International Journal of Business Performance and Supply Chain Modelling*, 2, 282-303. Available: <https://doi.org/10.1504/IJBPSM.2010.036203>
- BANKVALL, L., BYGBALLE, L.E., DUBOIS, A., & JAHRE, M. 2010. Interdependence in supply chains and projects in construction. *Supply Chain Management: An International Journal*, 15, 385-393. Available: <https://doi.org/10.1108/13598541011068314>
- BARRATT, M. 2004. Understanding the meaning of collaboration in the supply chain. *Supply Chain Management: An International Journal*, 9, 30-42. Available: <https://doi.org/10.1108/13598540410517566>
- BARRIGA, E., J. JEONG, M. HASTAK, AND M. SYAL. 2005. Material control sys tem for the manufactured housing industry. *Journal of Management in Engineering*, 21. Available: [https://doi.org/10.1061/\(ASCE\)0742-597X\(2005\)21:2\(91\)](https://doi.org/10.1061/(ASCE)0742-597X(2005)21:2(91))
- BASNET, C., CORNER, J., WISNER, J., & TAN, K.-C. 2003. Benchmarking supply chain management practice in New Zealand. *Supply Chain Management: An International Journal*, 8(1), 57-64. Available: <https://doi.org/10.1108/13598540310463369>
- BDO. 2019. *The Construction Survey Report*. Retrieved from. <https://www.bdo.nz/ennz/industries/construction-and-real-estate/2019-construction-survey-results>.
- BEAMON, B. M. 1988. Supply chain design and analysis: Models and methods. *International Journal of Production Economics*, 55, 281-294. Available: [https://doi.org/10.1016/S0925-5273\(98\)00079-6](https://doi.org/10.1016/S0925-5273(98)00079-6)
- BEHERA, P., R. P. MOHANTY, AND A. PRAKASH. 2015. Understanding construc tion supply chain management. *Prod. Plann. Control*, 26, 1-19.
- BERGDOLL, B. A. C., P. 2008. *Home Delivery: fabricating the modern dwelling, ed.,* The Museum of Modern Art, New York.
- BILDSTEN, L. 2011a. Exploring the opportunities and barriers of using prefabricated house components. *19th Conference of the International Group of Lean Construction (IGLC)*. Lima, Peru.
- BILDSTEN, L. 2011b. Exploring the opportunities and barriers of using prefabricated house components. . *Paper presented at the 19th Conference of the International Group of Lean Construction (IGLC), July 13-15, Lima, Peru*.
- BILDSTEN L 2011. Exploring the opportunities and barriers of using prefabricated house components. *Proceedings 19th conference of the international group of lean construction(IGLC)*. Lima, Peru.
- BOWRON, G. A. M., T. 2007. State Housing: A Thematic Survey. *Housing NZ Corporation, Wellington, New Zealand*.
- BRANDON, K. D. H. A. P. 2004. Construction 2020: A Vision for Australia's Property and Construction Industry. *CRC Construction Innovation*.
- BRISCOE, G., & DAINTY, A. 2005. Construction supply chain integration: an elusive goal? . *Supply Chain Management: An International Journal*, 10, 319-326. Available: <https://doi.org/10.1108/13598540510612794>
- BUCHANAN M 2004. Prefab home. Gibbs Smith, Salt Lake City.

- BUCKETT, N., MARSON, N., SAVILLE-SMITH, K., JOWETT, J. & JONES, M. . 2014. *Advanced Residential Construction Techniques – Opportunities and Implications for New Zealand*. . Study Report SR311, BRANZ Ltd, Judgeford, New Zealand.
- C. PARKER. 2015. *Housing supply, choice and affordability: Trends, economic drivers and possible policy interventions*.
- CAI, S., JUN, M., & YANG, Z. 2010. Implementing supply chain information integration in China: The role of institutional forces and trust. 28, 257-268. Available: 10.1016/j.jom.2009.11.005
- CHARLOTTE BROWN, E. A. 2020. *Construction sector performance measurement: Learning lessons and finding opportunities*. Project LR12087 Resilient Organisations, Kin Strategy, University of Cambridge, funded by the Building Research Levy(BRNZ).
- CHINA INTERNATIONAL MARINE CONTAINERS (CIMC)GROUP. 2016.
- COOK B 2005. An assessment of the potential contribution of prefabrication to improve the quality of housing. *Constr Inf Q* 7(2):50–55Cook B (2005) . *Constr Inf Q* 7(2):50–55.
- COOPER, M. C., LAMBERT, D. M., & PAGH, J. D. J. T. I. J. O. L. M. 1997. Supply chain management: more than a new name for logistics. 8, 1-14.
- CSG. August 1, 2015. *Housing Affordability Workshops*. .
- CURTIS, M. 2018. *Productivity in the construction industry 2017 (Study Reports No. SR388)*. . Porirua, NZ.Retrieved from <https://nzier.org.nz/publication/construction-productivity-an-evidence-base-forresearch-and-policy-issues>.
- ČUŠ-BABIČ, N., REBOLJ, D., NEKREP-PERC, M., AND PODBREZNIK, P. 2014. Supply chain transparency within industrialised construction projects. *Computers in 15 Industry*, 65(2), 345–353.
- D. MOLLENKOPF AND G. P. DAPIRAN 2005. The importance of developing logistics competencies: A study of australian and New Zealand Firms. *International Journal of Logistics Research and Applications*, 8.
- DBHNZ. 2012. *Productivity roadmap*. Department of Building and Housing Wellington, New Zealand
- DORAN, D., & GIANNAKIS, M. 2011. An examination of a modular supply chain: A construction sector perspective. *Supply Chain Management: An International Journal*, 16, 260-270. Available: <https://doi.org/10.1108/13598541111139071>
- DUBOIS, A., & GADDE, L.-E, 2000. Supply strategy and network effects-purchasing behaviour in the construction industry. *European Journal Of Purchasing & Supply Management*, 6, 207-215. Available: [https://doi.org/10.1016/S0969-7012\(00\)00016-2](https://doi.org/10.1016/S0969-7012(00)00016-2)
- EGAN, J. 1988. *Rethinking construction: Department of Environment, Transport and the Region*.
- ELIWA, H., JELODAR, M. B. & POSHDAR, M. 2018. Information technology and New Zealand construction industry: an empirical study towards strategic alignment of project and organisation. *18th International Conference on Construction Applications of Virtual Reality (CONVR2018)*. Auckland. New Zealand.
- FEARNE, A., & FOWLER, N. 2006. Efficiency versus effectiveness in construction supply chains: the dangers of "lean" thinking in isolation. *Supply Chain Management: An International Journal*, 11, 283-287. Available: <https://doi.org/10.1108/13598540610671725>
- FINNIE, D., ALI, N. A., & PARK, K 2018. Enhancing off-site manufacturing through early contractor involvement (ECI) in New Zealand. *Proceedings of the Institution of Civil Engineers- Management, Procurement and Law*, 171(4) 176 – 185.
- GANN, D. M. 1996. Construction as a manufacturing process? Similarities and differences between industrialised housing and car production in Japan. *Construction Management and Economics*, 14, 437–450.
- GIBB, A. I., F 2010 Re-engineering through pre-assembly: client expectations and drivers. *Building Research & Information*, 31, 146-60.
- GOODIER, P., W 2012. Briefing: Future trends in UK housebuilding. *Municipal Engineer* Available: <https://doi.org/10.1680/muen.11.00001>
- GORDON, G. C., M. 2018. *Building-quality issues: A literature review*. BRANZ Study Report SR375.Judgeford, New Zealand: BRANZ Ltd.
- GORGOLEWSKI MT 2005. The potential for prefabrication in United Kingdom housing to improve sustainability. *Yang J, Brandon PS, Sidwell AC. Smart and sustainable built environments.Blackwell, Oxford*.
- GOULDING, J. S., & ARIF, M. 2013. Offsite production and manufacturing – research roadmap report. W. Bakens (Ed.), p. 43. International Council for Research and Innovation in Building and Construction (CIB), Publication 372.
- GRIMES, A., HOLMES, M. J., & TARRANT, N 2010. New Zealand housing markets: Just a bit-player in the A-league. *Motu Economic and Public Policy Research Working Paper* 10-07.

- HAO AND SAMARASINGHE 2020. The Factors Constraining the Adoption of Prefabrication in the New Zealand Residential Construction Sector: Contractors' Perspective.
- HASHEMI A & HADJRI K 2014. Offsite construction, a potential answer to the Iranian housing shortages. *In: Proceedings construction technology and management (CTM) 2014 international scientific conference*. Bratislava, Slovakia.
- HSU, P.-Y., ANGELOUDIS, P. & AURISICCHIO, M. 2018. Optimal logistics planning for modular construction using two-stage stochastic programming. *Autom. Constr.*, 90, 47–61.
- ISAACS, N. 2008. House assembly – prefabrication and factory manufacture. *Build Magazine*, 94-95.
- J. E. MCDEVITT, D. M., F. LAMM, AND N. MCDONNELL, 2012. Estimating injurious impact in construction life cycle assessments: A prospective study. *Supply Chain Management*, 2.
- J. IKONEN, A. K., H. HÄMÄLÄINEN, M. IHONEN, J. PORRAS, T. KALLONEN. 2013. Use of embedded RFID tags in concrete element supply chains, *J. Inf. Technol. Constr.* 18 (7) (2013) 119–147.
- JELODAR, M. B., JAAFAR, M. & YIU, T. 2013. In Search of Sustainability: Constructability Application and Contract Management in Malaysian Industrialized Building Systems. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, 5, 196-204. Available: doi:10.1061/(ASCE)LA.1943-4170.0000121
- JELODAR, M. B., YIU, T. W. & WILKINSON, S. 2016. A conceptualisation of relationship quality in construction procurement. *International Journal of Project Management*, 34, 997-1011. Available: <https://doi.org/10.1016/j.ijproman.2016.03.005>
- JOHNSON, H., & MEILING, J.H. 2009. Defects in offsite construction: timber module prefabrication. *Construction Management and Economics* 27, 667-681. Available: <https://doi.org/10.1080/01446190903002797>
- KAMALI, M., & HEWAGE, K. 2016. Life cycle performance of modular buildings: A critical review. *Renewable and Sustainable Energy Reviews*, 62, 1171-1183. Available: <https://doi.org/10.1016/j.rser.2016.05.031>
- KONUCCU, S. 2011. *A knowledge chain framework for construction supply chains*.
- LAMBERT, D. M., & COOPER, M. C. 2000. Issues in Supply Chain Management. *Industrial Marketing Management*, 29, 65-83. Available: [https://doi.org/10.1016/S0019-8501\(99\)00113-3](https://doi.org/10.1016/S0019-8501(99)00113-3)
- LAWSON, R., & OGDEN, R. Sustainability and process benefits of modular construction. . Paper presented at the Proceedings of the 18th CIB World Building Congress, , 2010 TG57-Special Track, Salford, UK.
- LESSING, J., & BREGE, S. 2015a. Business models for product-oriented house-building companies– Experience from two Swedish case studies. *Construction Innovation*, 15 449–472.
- LESSING, J., STEHN, L., & EKHOLM, A 2015b. Industrialised house-building-development and conceptual orientation of the field. *Construction Innovation*. 15(3), 378-399.
- LINNER, T., & BOCK, T. 2012. Evolution of large-scale industrialisation and service innovation in Japanese prefabrication industry. *Construction Innovation*, 12, 156–178.
- LIU, Y., DONG, J., & SHEN, L. 2020. A conceptual development framework for prefabricated construction supply chain management: An integrated overview. *Sustainability*, 12
- LONDON, K. A., & KENLEY, R. 2001. An industrial organisation economic supply chain approach for the construction industry: A review. *Construction Management & Economics*, 19, 777-788. Available: <https://doi.org/10.1080/01446190110081699>
- LU N & KORMAN T 2010. Implementation of building information modeling (BIM) in modular construction: Benefits and challenges. . *Construction research congress 2010: Innovation for reshaping construction practice*.
- M. KHOSROW-POUR 2013. Managing Information Resources and Technology: Emerging Applications and Theories: Emerging Applications and Theories,. *Information Science Reference*.
- M. M. BASSETT 2015. Priced out: How New Zealand lost its housing affordability. *The New Zealand Initiative Wellington, New Zealand*.
- MANLEY, K., & WIDEN, K. 2019. Prefabricated housing firms in Japan and Sweden: Learning from leading countries. *People, process and technology UK: Routledge*, 1, 399–418.
- MBACHU, J., EGBELAKIN, T., RASHEED, E.O., & SHAHZAD, W.M. 2017. Influence of key role players on productivity outcomes in the residential building lifecycle. *Journal of Engineering, Design and Technology*, 15, 528-551. Available: <https://doi.org/10.1108/JEDT-02-2017-0014>
- MENTZER, J. T., DEWITT, W., KEEBLER, J. S., MIN, S., NIX, N. W., SMITH, C. D., & ZACHARIA, Z. G. 2001. Defining supply chain management. *Journal of Business logistics*, 22, 1-25.
- MORADIBISTOUNI, M. 2017. Prefabricated secondary units for overcoming the shortage of houses: A case study of new zealand. *International Conference on Smart Infrastructure and Construction 2019 (ICSIC)*. Driving data-informed decision-making.

- MORADIBISTOUNI M AND GJERDE M 2017. Potential for Prefabrication to Enhance the New Zealand Construction Industry. *51st International Conference of the Architectural Science Association (ANZAScA)*
- MOSTAFA, S., CHILESHE, N., & ZUO, J 2014a. Enhancing Australian Housing Affordability: Off-site Manufacturing Supply Chain Strategies. *Akademika forlag*.
- MOSTAFA, S., DUMRAK, J., CHILESHE, N., & ZUO, J. 2014b. Offsite manufacturing in developing countries: current situation and opportunities. . *Paper presented at the The 5th International Conference on Engineering, Project and Production Management* .
- NAIM, M., & BARLOW, J. 2003. An innovative supply chain strategy for customised housing. *Construction Management and Economics*, 21, 593-602. Available: <https://doi.org/10.1080/0144619032000134129>
- NGOWI, A. B., PIENAAR, E., TALUKHABA, A., & MBACHU, J 2005. The globalisation of the construction industry. *Building and Environment*, 40(1), 135 – 141. Available: <https://www.researchgate.net/deref/http%3A%2F%2Fdx.doi.org%2F10.1016%2Fj.buildenv.2004.05.008>
- NZPC. 2012. *Housing affordability inquiry*. New Zealand Productivity Commission Wellington, New Zealand.
- PABLO, Z., & LONDON, K. A. 2020. Stable relationality and dynamic innovation: Two models of collaboration in SME-driven offsite manufacturing supply chains in housing construction. *Engineering Construction & Architectural Management*. Available: <https://doi.org/10.1108/ECAM-07-2019-0346>.
- PAGE, I. S. K., K. MANLEY, & K. HAMPSON (CHAIR), 2013. New Zealand new housing characteristics and costs. *Symposium conducted at the meeting of the 19th CIB World Building Congress: Construction and Society*. Brisbane, Australia: Queensland University of Technology, Australia.
- PAN, W., & SIDWELL, R 2011a. Demystifying the cost barriers to offsite construction in the UK. *Construction Management and Economics*, 29(11), 1081-1099. Available: <https://doi.org/10.1080/01446193.2011.637938>
- PAN, W., & SIDWELL, R 2011b. Demystifying the cost barriers to offsite construction in the UK. *Construction Management and Economics*, 29(11), 1081-1099. Available: 10.1080/01446193.2011.637938
- PAN, W., DAINITY, A. R., & GIBB, A. G. F. 2012a. Establishing and weighting decision criteria for building system selection in housing construction. *Journal of Construction Engineering and Management*, 138, 1239–1250. Available: [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0000543](https://doi.org/10.1061/(ASCE)CO.1943-7862.0000543)
- PAN, W., GIBB, A. G. F., & DAINITY, A. R. J. 2012b. Strategies for integrating the use of off site production technologies in house building. *Journal of Construction Engineering and Management*, 138, 1331–1340. Available: [https://doi.org/10.1061/\(asce\)co.1943-7862.0000544](https://doi.org/10.1061/(asce)co.1943-7862.0000544)
- PAN, W., GIBB, A.G., & DAINITY, A.R 2007. Perspectives of UK housebuilders on the use of offsite modern methods of construction. *Construction Management and Economics*, 25(2). Available: <https://doi.org/10.1080/01446190600827058>
- PASQUIRE, C. L., & GIBB, A G. 2002. Considerations for assessing the benefits of standardisation and pre-assembly in construction.
- POON CS, A. T., NG LH. 2003. Comparison of low-waste building technologies adopted in public and private housing projects in Hong Kong. *Eng Constr Archit Manage* 10, 88–98.
- POSHDAR, M., GONZALEZ, V. A., ANTUNES, R., GHODRATI, N., KATEBI, M., VALASIUK, S., ... TALEBI, S. 2019. Diffusion of lean construction in small to medium-sized enterprises of housing Sector. *Paper Presented at the 27th Annual Conference of the International Group for Lean Construction (IGLC)*. Dublin, Ireland.
- POWER, D. 2005. Supply chain management integration and implementation: a literature review. *Supply Chain Management: An International Journal*, 10, 252-263. Available: <https://doi.org/10.1108/13598540510612721>
- PREFAB NZ. 2018. *Levers for PREFAB How offsite construction can deliver better cost-effective housing to more New Zealanders*.
- PREFAB NZ. 2014. *year impact report*.
- PREFAB NZ. 2018a. *levers for prefab how offsite construction can deliver better cost-effective housing to more new zealanders*.
- PREFAB NZ. 2018b. *Prefabrication: A solution for a NZ housing shortage? Literature review*.
- PREFABROAD MAP. 2014. *Prefb roadmap: A way forward for prefabrication in New Zealand*
- PWC. 2016 *Valuing the role of construction in the New Zealand economy*. Construction Industry Council BRANZ <https://www.pwc.co.nz/pdfs/CSG-PwC-Value-of-Construction-Sector-NZ.pdf>.
- QUICKSTATS, C. 2013. *Census QuickStats about a place: Auckland Region*. [Online]. [Accessed 2017].

- ROTIMI, F., TOOKEY, J. & ROTIMI, J 2015. Evaluating defect reporting in new residential buildings in New Zealand. *Buildings*, 2015(5), 39–55. Available: <https://www.researchgate.net/publication/272641959>
- ROY R, B. J., GAZE C 2003. Re-engineering the construction process in the speculative house-building sector. *Constr Manage Econ*, 21, 137–146.
- SAMARASINGHE A, J. T., AND J. O. B. ROTIMI, 2013. Supply chain collaboration in New Zealand house construction. *Australasian Universities Building Education Association*.
- SAMARASINGHE, D. A. S. & WOOD, E. 2021. Innovative digital technologies, In: J Underwood and M Shelbourn (Eds.) *Driving Transformational Change in the Built Environment*, IGI Global.
- SCOFIELD, R., WILKINSON, S., POTANGAROA, R., & ROTIMI, F. 2009a. Driving innovative offsite construction techniques in New Zealand. In *Global Innovation in Construction Conference* Loughborough University, UK.
- SEGERSTEDT OLOFSSON ANDERS, T., & BANKVALL BYGBALLE DUBOIS JAHRE LARS LENA, E. A. M. 2010. Interdependence in supply chains and projects in construction. *Supply Chain Management: An International Journal*, 5. Available: 10.1108/13598541011068314
- SHAHZAD, W. M. 2011. *Offsite manufacturing as a means of improving productivity in New Zealand construction industry: Key barriers to adoption and improvement measures*. Massey University.
- SHAHZAD, W. M. 2016. *Comparative analysis of the productivity levels achieved through the use of panelised prefabrication technology with those of traditional building system*. Massey University, Albany, New Zealand (Doctoral dissertation, Massey University).
- SOORIYAMUDALIGE, N., DOMINGO, N., SHAHZAD, W., & CHILDHOUSE, P 2020. Barriers and enablers for supply chain integration in prefabricated elements manufacturing in New Zealand. *International Journal of Construction Supply Chain Management*, Vol. 10, No1, 73-91. Available: 10.14424/ijscsm100120-73-91.
- SPELLER T, R. L., JONES A. 2007. Value chain modelling using system dynamics. *Int J Man Technol Manage.*, 11, 135–156.
- STADTLER, H., & KILGER, C. 2002. Supply chain management and advanced planning. *Springer*, 4.
- STEINHARDT, D., MANLEY, K., BILDSTEN, L., & WIDEN, K. 2020. Construction Management and Economics. *The structure of emergent prefabricated housing industries: A comparative case study of Australia and Sweden*, 38, 483–501. Available: <https://doi.org/10.1080/01446193.2019.1588464>
- STROEBELE, B. S. & KIESSLING, A. J. 2017. Impact Analysis of Complexity Drivers in the Supply Chain of Prefabricated Houses. *Journal of Management and Strategy*, 8.
- SUTRISNA, P. M. 2020. *Solving capacity and capability problems*. Available: https://www.massey.ac.nz/massey/about-massey/news/article.cfm?mnarticle_uuid=208F23BC-80E8-4166-B35B-3EEC6136DF3F.
- TAM, V. W. Y., TAM, C. M., ZENG, S. X. & NG, W. C. Y. 2007. Towards adoption of prefabrication in construction. *Building and Environment*, 42, 3642–3654. Available: 10.1016/j.buildenv.2006.10.003
- TAN, K. C. J. E. J. O. P., & MANAGEMENT, S. 2001. A framework of supply chain management literature. 7, 39-48.
- TOOMATH, W. 1996. Built in New Zealand: the houses we live in. *Harper Collins, Auckland, New Zealand*.
- V. TRAN, J. E. T., AND J. ROBERTI, 2012. Shaving BIM: Establishing a framework for future BIM research in New Zealand. *International Journal of Construction Supply Chain Management*, 2, 66-79.
- VRIJHOEF, R., & KOSKELA, L. 1999. Roles of supply chain management in construction. . *Paper presented at the Proceedings IGLC*.
- VRIJHOEF, R., AND L. KOSKELA. 2000. The Four Roles of Supply Chain Management in Construction. *European Journal of Purchasing & Supply Management* 6 (3):, 169–1.
- VRIJHOEF, R., KOSKELA, L., & HOWELL, G. . Understanding construction supply chains: an alternative interpretation. Paper presented at the Proceedings of 9th International Group for Lean Construction Conference, 2001.
- WANG, H., ZHU, H. & YU, C. 2018. Development of the Hunan's Provincial Key Lab for prefabricated buildings for energy conservation at the University of South China. *Indoor Built Environ.* 2018, 27, 1017–1021., 27, 1017–1021.
- Y. FEI, T. J., AND R. JOHANNES 2014. Addressing effective construction logistics through the lens of vehicle movements. *Engineering, Construction and Architectural Management*, 21, 261-275.
- YING, J. F., J. TOOKEY, AND J. ROBERTI. 2015. SCM competencies in construction: Issues and challenges in New Zealand. *J. Eng. Des. Technol.* 13 (4):, 522–538. . Available: <https://doi.org/10.1108/JEDT-01-2013-0002>
- ZHAI, X., REED, R., & MILLS, A. 2013. Factors impeding the offsite production of housing construction in China: an investigation of current practice., *Construction Management and Economics*, , 32(1-2), 40-52. Available: <https://doi.org/10.1080/01446193.2013.787491>

BIM and LCA Applications for Green Buildings in New Zealand

Fatma Abdelaal*, Brian H.W. Guo, Larry Bellamy

Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, Canterbury, New Zealand

**Corresponding author: fatma.abdelaal@pg.canterbury.ac.nz*

Abstract

There is growing concern about the environmental impacts of buildings on climate change. In this regard, the concept of adopting advanced building technology and building environmental assessment methods, namely Building Information Modelling (BIM) and Life Cycle Assessment (LCA), has arisen as innovative approaches to improve building design and environmental assessment at the early design stages. Recent studies made attempts to develop theoretical frameworks for integrating BIM and LCA into the building industry practices, focusing on the technical aspects. However, noted in the green building literature, stakeholders' perspectives on this adoption have been left overlooked. Therefore, this study contributes to the existing knowledge on the future implementation and integration of BIM and LCA for green building design and assessment. To this end, this study investigates (1) the perspectives of stakeholders on current BIM and LCA applications in New Zealand and (2) the level of stakeholders' awareness and agreement on the significance of BIM and LCA for green building design and environmental assessment. A survey was conducted among various stakeholders in the New Zealand building sector on the national level. The results indicated that BIM and LCA applications for green buildings in New Zealand are still immature. BIM is still perceived as a 3D modelling tool while LCA is not fully utilized for calculating the total emissions of a building lifecycle. Moreover, results revealed that the stakeholders' level of agreement on the significance of BIM and LCA tools is not associated with the practice levels. Although the stakeholders had a positive view of the significance of BIM and LCA for green buildings design and environmental assessment, collaborative efforts are still required to increase BIM and LCA uptake in the New Zealand building industry.

Keywords

BIM, Green Buildings, LCA, New Zealand, Stakeholders

Introduction

Buildings are responsible for approximately 35% of global energy consumption and 38% of total direct and indirect energy-related CO₂ emissions (UNEP, 2020). The building sector, therefore, has attempted to enhance sustainability in its practices through using various technologies and environmental assessment methods such as BIM and LCA to reduce potential environmental impacts of buildings.

Building Information Modelling (BIM) is considered a revolutionary technology that brings significant opportunities to the building sector (Lu et al., 2017). In the past few years, "Green BIM" has become a technical term for the integration of BIM with green building assessment systems such as LEED and BREEAM (Jalaei and Jade, 2015; Wong and Kuan, 2014). It has been demonstrated that BIM affords the great potential for optimizing building environmental assessment (Carvalho et al., 2019).

Within building environmental assessment, Life Cycle Assessment (LCA) is internationally acknowledged as a holistic method for evaluating the potential environmental impacts of a building throughout its lifecycle (Nwodo and Anumba, 2019). Previous studies on LCA demonstrated the importance of integrating it into the building environmental assessment process (Alshamrani *et al.*, 2014; Dekkiche and Taileb, 2016).

Apart from the technical aspects, the implementation of BIM and LCA for green buildings is significantly affected and shaped by stakeholders' (i.e. architects, engineers, clients, contractors, developers, etc.) perspectives (Linderoth, 2010). Worldwide, there has been increasing recognition of the importance of stakeholders' role in the green building sector (Abdelaal and Guo, 2021; Wong and Abe, 2014) since every construction project is a combination of social interaction between various stakeholders (Chinowsky *et al.*, 2008). Therefore, a deep understanding of collaboration among stakeholders is essential for the successful adoption of BIM and LCA in the building industry (Wang *et al.*, 2020). Previous research has been conducted to investigate stakeholders' perspectives on using BIM in the building sector (Lewis *et al.*, 2019; Solla *et al.*, 2019; Wong *et al.*, 2013). However, very few studies have identified the stakeholders' views on LCA applications (Jusselme *et al.*, 2020; Schlanbusch *et al.*, 2016). To our knowledge, no study has yet been conducted to explore stakeholders' perspectives on the adoption of BIM and LCA for the design and assessment of green buildings. This research explores current BIM and LCA applications in green building design and environmental assessment and investigates stakeholders' levels of awareness and agreement of the significance of BIM and LCA. The research provides unique user-centred knowledge of BIM and LCA applications for green buildings and the potentials for future integration.

Literature Review

Building Information Modelling (BIM)

BIM has been proposed as an innovative technology that can lead to a technological and procedural shift in the building sector (Panuwatwanich and Peansupap, 2013) as it is a "methodology to manage the essential building design and project data in digital format throughout the building's life-cycle" (Succar, 2009). In regards to green buildings, Azhar *et al.* (2011) confirmed that BIM tools can assist in achieving more than 35% of the LEED total points. Ilhan & Yaman (2016) claimed that automatic sustainability assessment can be achieved when BIM is integrated with the BREEAM rating system. Twenty-six (26) credits of the Hong Kong 'BEAM Plus' sustainable building rating system can be achieved using BIM technology (Wong and Kuan, 2014). Gandhi & Jupp (2014) stated that nearly 90% of Green Star Australia credits can be assisted through BIM. Abdelaal *et al.* (2019) demonstrated that 76 points of a total of 120 points of the New Zealand Homestar green building rating system can be achieved with BIM software.

Another critical benefit of BIM technology is that it facilitates effective collaboration among stakeholders due to a shared vision of the project (Wang *et al.*, 2020) since it has the capability to address issues related to stakeholders collaboration (Mihindu and Arayici, 2008). To exploit this capability, researchers have sought to better understand stakeholders' collaboration process. Wong *et al.* (2013) compared the roles of major stakeholders in public and private sectors in the Scandinavian countries for BIM implementations in the building sector. Wang *et al.* (2020) analysed the relationships among various stakeholders and their dynamic changes throughout a BIM project delivery stages. Becerik-Gerber & Rice (2010) presented the perceived value of BIM in the U.S. building sector, as seen by various stakeholders. Lewis *et al.* (2019) investigated the perceptions of green design stakeholders about the value of BIM-

based energy simulation. The current changes in the building sector practices consider holistic BIM-based approaches (Gantner *et al.*, 2018). Therefore, there is a pressing need to understand the stakeholders' perspective on Green BIM in order to enhance its implementation in green building projects.

Life Cycle Assessment (LCA)

LCA is often called cradle to grave assessment as it assesses the environmental performance and potential impacts of a building over its whole life service (Zuo *et al.*, 2017). Many studies focus on utilizing LCA in the analysis of buildings at different levels, those levels include product selection, process evaluation, and whole-building evaluation (Al-Ghamdi and Bilec, 2017). The integration of LCA in green building rating systems has been an extensively studied research area over the past decade. Zabalza Bribián *et al.* (2009) developed a simplified LCA framework as a complement for the energy certification process in the European countries. Alshamrani *et al.* (2014) presented an integrated LCA-LEED model for the structure and envelope systems of Canadian school buildings. Zhang *et al.* (2006) developed a building environmental performance analysis system (BEPAS) based on the LCA framework. However, the implementation of LCA in green building assessment has remained a challenge (Jusselme *et al.*, 2018), and LCA is still considered a complicated environmental assessment method (Hollberg *et al.*, 2021).

Although the increased number of LCA research, very limited studies have investigated the stakeholders' perspective on LCA value and applications for green buildings. Schlanbusch *et al.* (2016) conducted 57 semi-structured interviews with different stakeholders in the Nordic building industry with varying knowledge levels of LCA. The results emphasized the need for a better understanding of the LCA process. Sibiude *et al.* (2014) conducted a national survey with building stakeholders in Spain to understand their needs regarding performing LCA. Balouktsi *et al.* (2020) investigated the designers' level of awareness and acceptance of environmental performance assessment and LCA of buildings.

Research Methodology

The questionnaire survey was designed to investigate the current BIM and LCA applications for green buildings in New Zealand from the stakeholders' view. The questionnaire consists of 16 questions and was divided into three sections. The first section of the questionnaire is general background questions that cover the demographic characteristics of the participants and their experience in green building projects. The other two sections aim to explore BIM and LCA applications and tools. Moreover, to investigate the stakeholders' levels of agreement on BIM and LCA value for optimizing green building design and environmental assessment process using a 5-point Likert scale.

Potential participants were selected using random sampling to minimize error and bias in the sampling process (Fellows and Liu, 2015). The questionnaire was administered using an online survey software tool, Qualtrics survey software, and an anonymous link to the online survey was sent via email to a number of experts in the green building industry to conduct pilot surveys. Five pilot surveys were performed to check the understanding and the length of the questionnaire, assure face validity, and improve the clarity of the instruction. (Goh and Chua, 2016; Toh *et al.*, 2017). After integrating the feedback of these first participants, the questionnaire was distributed using online platforms such as LinkedIn, relevant associations, organizations, and architecture and engineering companies.

A total of 268 attempted responses were received with 80% completion rate, 53 out of 268 questionnaires were unusable due to missing and incomplete responses. Due to the relatively small size of the New Zealand green building industry, the sample size is considered

representative. 215 valid questionnaires were analysed using SPSS software for descriptive analysis to explore the current BIM and LCA applications for green buildings. The participants were invited to indicate the relative importance or significance of BIM and LCA tools for green building design and environmental assessment process based on a 5-point Likert scale with weighing from 1 to 5 ranging from “strongly disagree”-1 and “neutral”-3 to “strongly agree”-5. Normality tests were performed before conducting the statistical analysis and the results showed that the significance value p is less than .05, then the data does not follow a normal distribution. Therefore, Spearman’s Rho correlation which is a nonparametric statistic approach that can be used with Likert data has been chosen for the study (Murray, 2013) to measure the strength between the stakeholders’ levels of agreement on the significance of BIM and LCA for green building.

The survey covered a diverse range of stakeholders in the New Zealand green building industry, including architects (16.7%), engineers (19.5%), developers (5.1%), sustainability consultants (14.8%), contractors (6.9%), material suppliers (16.2%) and the “others” group (13.7%) comprising project managers, government officials, researchers, etc. The majority of the participants (48.3%) had over 15 years of experience in the building industry. Almost 14% of the participants have never been involved in green building projects, and 65% have participated in less than 10 green building projects throughout their career life

Results

Stakeholders’ perspective on BIM applications for green buildings

As shown in Figure 1. regardless of BIM being a data-rich and intelligent building modelling tool (Ansah et al., 2019), 27.4% of the participants often use it for 3D modelling and visualization purposes. 20% of participants used BIM for clash detection, while 13% used it for energy modelling to comply with the requirements of green building certifications. Further evidence that the potential of BIM is not fully utilized by the New Zealand green building industry is that only 11.5% of the stakeholders used BIM-based quantity take-off functions, 6% for cost estimation. Only 6% of participants used BIM software as a project management tool. One participant stated that *“There is not enough uptake of BIM through the entire supply chain, it often stops at the developed design stage”*.

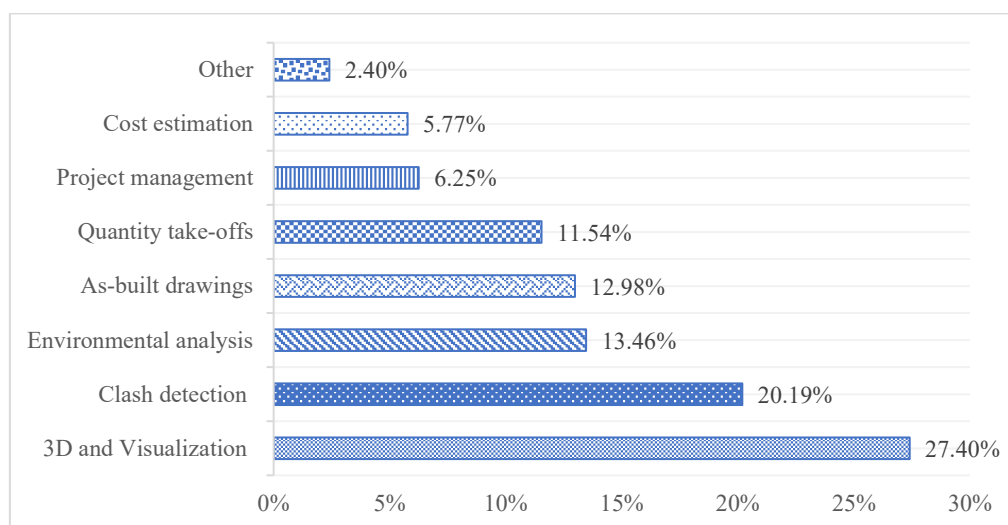


Figure 1. BIM applications in green building projects

Regarding BIM software, Autodesk Revit is the most used BIM application in the New Zealand building industry with 66%, followed by ArchiCAD with 26%. 14% of the participants used Navisworks for coordination and clash detection, and only 4% of the participants used building sustainability analysis applications such as Integrated Environmental Solutions (IES).

Stakeholders' perspective on LCA applications for green buildings

Participants were asked which LCA stages has the largest impact on the building environmental performance. The majority of the participants (58.6%) believed that the construction stage (A4-A5) has the largest impact on the building performance followed by the operational stage (B1-B7). Less than 1% of the stakeholders agreed that the end-of-life stage (C1-C4) affect the building environmental performance as shown in Figure. 2.

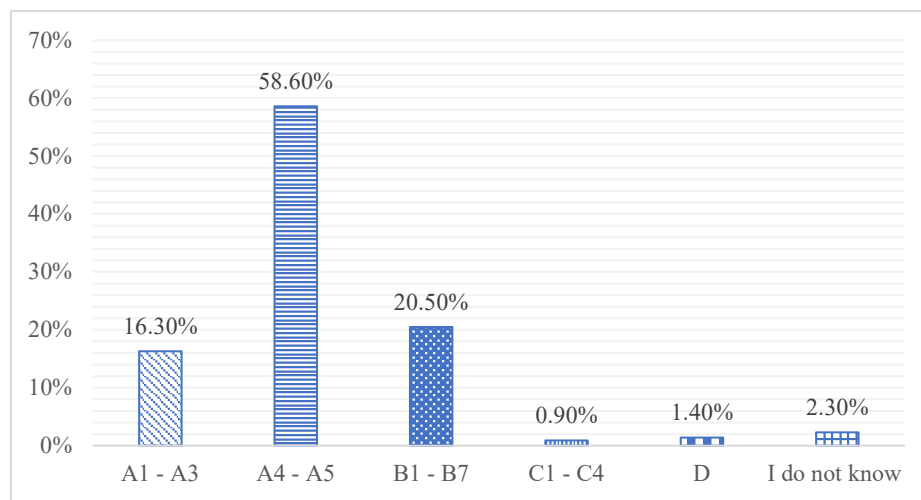


Figure 2. Stakeholders' perspectives on building environmental impacts for each LCA stage
Product stage A1 – A3; Construction stage A4 – A5; Use stage B1 – B7; End of life stage C1 – C4;
Benefits and loads beyond the system boundary stage D

30% of the participants conducted LCA to evaluate materials impact as illustrated in Figure. 3. 21% used LCA to evaluate the whole-building whole-of-life performance. 23% of the respondents claimed to conduct LCA for calculating the operational emissions while 15% of the respondents used LCA tools to calculate the embodied carbon emissions of green buildings. Life Cycle Cost Assessment (LCCA) is the least used LCA application in the New Zealand building industry.

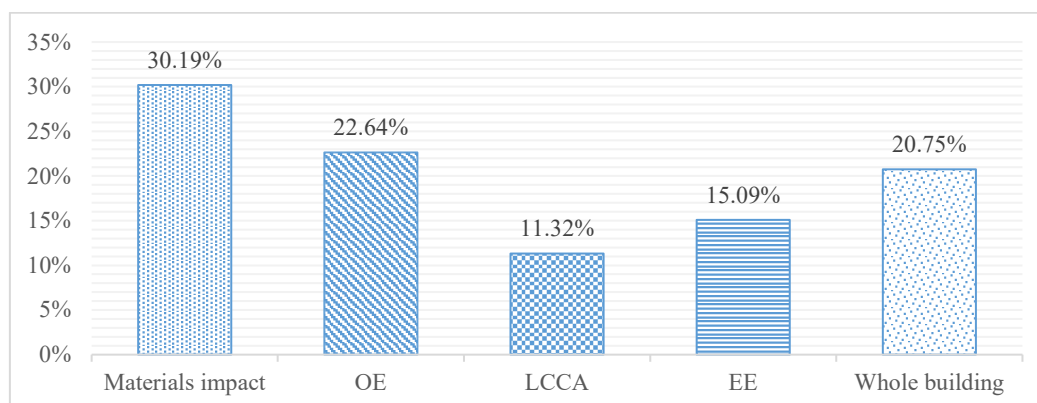


Figure 3. LCA applications in green building projects

Most of the participants (45%) used the LCAQuick tool to perform LCA for New Zealand green building projects, LCAQuick is a New Zealand tool that was developed by Building Research Association New Zealand (BRANZ). 16% of the participants used eTool, which is a web-based LCA tool developed in Australia. GaBi is used by 10% of the participants. Other tools were mentioned such as SimaPro, and some participants stated that in-house tools were developed and used to perform LCA.

Stakeholders' levels of agreement on the significance of BIM and LCA for green buildings

The results demonstrated, among all participants, the majority have a positive view of BIM and LCA as useful tools for green building design and assessment process. As presented in Table. 1, around 72% of the stakeholders who participated in the study agreed that LCA can improve the building environmental assessment process compared to the existing green building rating systems as a participant argued that *“most of the rating tools give boxes to tick without good tools for calculating the embodied carbon of buildings. Proper LCA should be used”*. 61% of respondents agreed that BIM technology can facilitate green building design and assessment process compared to the traditional methods. 33% and 26% of the participants had a neutral opinion regarding BIM and LCA tools, respectively. Around 6% of the total responses doubted BIM potentials for improving the green building design while less than 1% disagreed that LCA can improve building environmental assessment.

Table 1. Stakeholders' agreement on BIM and LCA significance

	BIM		LCA	
	f	%	f	%
Strongly agree	38	17.7	52	24.2
Agree	94	43.7	102	47.4
Neutral	71	33.0	55	25.6
Disagree	8	3.7	1	0.5
Strongly disagree	4	1.9	1	0.5

As presented in Table 2, 52.5% of the participants have not used BIM or LCA for green building projects in the New Zealand building industry while 12% have used both, BIM and LCA, for green building design and environmental assessment. It was observed that BIM is commonly implemented in New Zealand compared to LCA with 24% and 12%, respectively.

Table 2. Stakeholders implementation of BIM and LCA

		BIM	
		Yes	No
	LCA	Yes 12%	No 11.6%
	No	23.7%	52.5%

Figure. 4 shows the relationship between the frequency of participating in green building projects and the stakeholders' levels of agreement on the value of BIM. It was observed that participants who always use BIM technology for green building projects are the largest percentage strongly agreed with the significance of BIM for green building design and environmental analysis. On the other hand, participants who occasionally use LCA tools for green building projects were the majority who strongly agreed on its significance for building environmental assessment (Figure. 5).

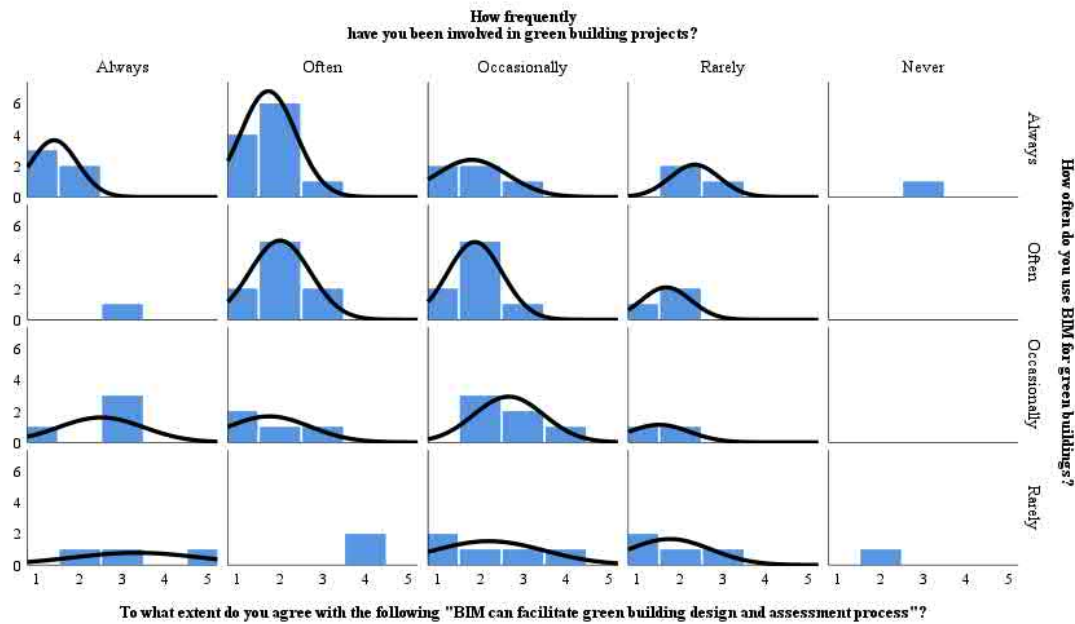


Figure 4. Stakeholders' perception of BIM importance for green buildings
1= strongly agree, 2= agree, 3= neutral, 4=disagree, 5=strongly disagree

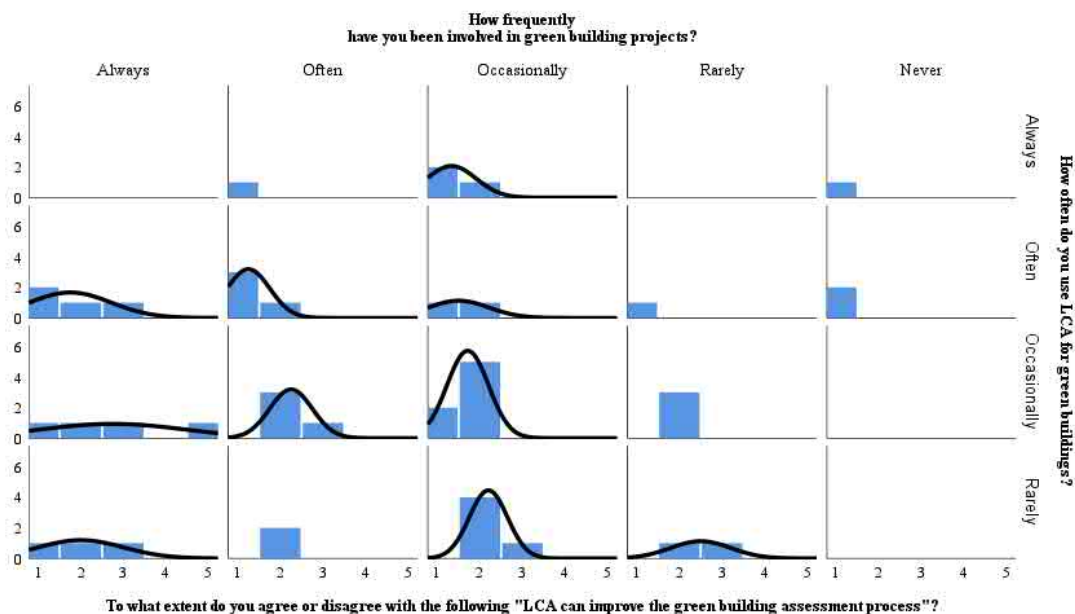


Figure 5. Stakeholders' perception of LCA importance for green buildings
1= strongly agree, 2= agree, 3= neutral, 4=disagree, 5=strongly disagree

Discussion

The results show that the adoption of BIM and LCA tools for green buildings in New Zealand is still immature as over 50% of the participants neither have experience with BIM nor LCA. The stakeholders' levels of agreement on BIM and LCA importance was examined using a 5-point Likert. The results revealed that the stakeholders' levels of agreement and awareness are not associated with the low uptake of BIM and LCA. Stakeholders who occasionally conduct LCA for building environmental assessment are the most agreed on the value of

LCA to improve the green building environmental assessment process. For BIM significance, participants who often use BIM for green buildings agreed on its potentials to facilitate green building design and environmental analysis compared to the stakeholders who always use BIM for green building projects. The results revealed that BIM is still perceived as a visualization tool. BIM's potential as an environmental analysis tool is poorly exploited in New Zealand since only 13% of the participants take advantage of BIM potentials for environmental assessment.

Although the majority of the participants considered that the embodied emissions associated with the construction stage have the most significant environmental impacts throughout the building lifecycle, only 15% of the participants conducted LCA to calculate building embodied emissions. Thus, there appears to be an inconsistency between the stakeholders' perspectives and the current applications of LCA for building environmental assessment in New Zealand. LCA is commonly performed to calculate the impacts associated with the operational phase, energy and water use, and to calculate construction materials impacts for the purpose of Environmental Product Declarations (EPDs). LCA is not fully utilized for evaluating the whole-building whole-of-life potential environmental impacts.

The statistical analysis revealed that, overall, the stakeholders' have a high perception of the value associated with using BIM and LCA for green buildings, separately. Therefore, a potential BIM-LCA integration framework for green building design and environmental assessment in New Zealand would receive limited support from the New Zealand building industry, at this point.

Conclusion

This study was carried out to explore the current practices of BIM and LCA for green buildings in the New Zealand building industry from the stakeholders' perspectives. The study also investigated the stakeholders' levels of agreement on the value of BIM-LCA for green building design and environmental assessment process, and its association with the practice levels. The results of this study provide a holistic picture of the BIM and LCA current practices in the green building industry in New Zealand. The results show that, regardless of the low level of practice, the stakeholders' have a positive perception towards LCA for building environmental assessment. Moreover, the stakeholders recognize the significance of the embodied emissions associated with the pre-operation stages of buildings. BIM potential as an environmental analysis tool is still overlooked in the New Zealand building industry. The study highlights the value of stakeholders' perspective research prior to introducing and adopting new technologies and tools to the industry in order to ensure its applicability and suitability. Although the results reveal that the stakeholders perceive a positive value of the BIM and LCA applications, a real implementation remains a challenge since only 12% of the stakeholders have the capability to use both tools. Thus, the New Zealand building industry is not yet ready to implement an integrated BIM-based LCA framework for green building design and environmental assessment. In order to increase BIM and LCA uptake in New Zealand, collaborative efforts are required from various stakeholders, the government and educational institutions.

Acknowledgement

The authors would like to thank the survey respondents for providing valuable inputs for this study.

References

- Abdelaal, F. et al., 2019. Integrating Bim Into Green Residential Building Assessment : a. Proc. 4th Int. Conf. Civ. Build. Eng. Informatics, 2019.
- Abdelaal, F., Guo, B.H.W., 2021. Knowledge, attitude and practice of green building design and assessment: New Zealand case. *Build. Environ.* 201, 107960. <https://doi.org/10.1016/j.buildenv.2021.107960>
- Al-Ghamdi, S.G., Bilec, M.M., 2017. Green Building Rating Systems and Whole-Building Life Cycle Assessment: Comparative Study of the Existing Assessment Tools. *J. Archit. Eng.* 23, 04016015. [https://doi.org/10.1061/\(ASCE\)AE.1943-5568.0000222](https://doi.org/10.1061/(ASCE)AE.1943-5568.0000222)
- Alshamrani, O.S. et al., 2014. Integrated LCA-LEED sustainability assessment model for structure and envelope systems of school buildings. *Build. Environ.* 80, 61–70. <https://doi.org/10.1016/j.buildenv.2014.05.021>
- Ansah, M.K. et al., 2019. A review and outlook for integrated BIM application in green building assessment. *Sustain. Cities Soc.* 48, 101576. <https://doi.org/10.1016/j.scs.2019.101576>
- Azhar, S. et al., 2011. Building information modeling for sustainable design and LEED ® rating analysis. *Autom. Constr.* 20, 217–224. <https://doi.org/10.1016/j.autcon.2010.09.019>
- Balouktsi, M. et al., 2020. Survey results on acceptance and use of Life Cycle Assessment among designers in world regions: IEA EBC Annex 72. *IOP Conf. Ser. Earth Environ. Sci.* 588. <https://doi.org/10.1088/1755-1315/588/3/032023>
- Becerik-Gerber, B., Rice, S., 2010. The perceived value of building information modeling in the U.S. building industry. *Electron. J. Inf. Technol. Constr.* 15, 185–201.
- Carvalho, J.P. et al., 2019. Optimising building sustainability assessment using BIM. *Autom. Constr.* 102, 170–182. <https://doi.org/10.1016/j.autcon.2019.02.021>
- Chinowsky, P. et al., 2008. Social Network Model of Construction. *J. Constr. Eng. Manag.* 134, 804–812. [https://doi.org/10.1061/\(asce\)0733-9364\(2008\)134:10\(804\)](https://doi.org/10.1061/(asce)0733-9364(2008)134:10(804))
- Dekkiche, H., Taileb, A., 2016. The Importance of Integrating LCA into the LEED Rating System. *Procedia Eng.* 145, 844–851. <https://doi.org/10.1016/j.proeng.2016.04.110>
- Fellows, R., Liu, A., 2015. *Research Methods for CONSTRUCTION* 4th Edition, Wiley Blackwell.
- Gandhi, S., Jupp, J., 2014. BIM and Australian Green Star Building Certification. *Comput. Civ. Build. Eng.* 275–282. <https://doi.org/10.1061/9780784413616.035>
- Gantner, J. et al., 2018. Ökobau.dat 3.0-Quo vadis? *Buildings* 8, 1–33. <https://doi.org/10.3390/buildings8090129>
- Goh, Y.M., Chua, S., 2016. Knowledge, attitude and practices for design for safety: A study on civil & structural engineers. *Accid. Anal. Prev.* 93, 260–266. <https://doi.org/10.1016/j.aap.2015.09.023>
- Hollberg, A. et al., 2021. Review of visualising LCA results in the design process of buildings. *Build. Environ.* 190. <https://doi.org/10.1016/j.buildenv.2020.107530>
- Ilhan, B., Yaman, H., 2016. Green building assessment tool (GBAT) for integrated BIM-based design decisions. *Autom. Constr.* 70, 26–37. <https://doi.org/10.1016/j.autcon.2016.05.001>
- Jalaei, F., Jade, A., 2015. Integrating building information modeling (BIM) and LEED system at the conceptual design stage of sustainable buildings. *Sustain. Cities Soc.* 18, 95–107. <https://doi.org/10.1016/j.scs.2015.06.007>
- Jusselme, T. et al., 2020. Surveying the environmental life-cycle performance assessments: Practice and context at early building design stages. *Sustain. Cities Soc.* 52, 101879. <https://doi.org/10.1016/j.scs.2019.101879>
- Jusselme, T. et al., 2018. An integrative approach for embodied energy: Towards an LCA-based data-driven design method. *Renew. Sustain. Energy Rev.* 88, 123–132. <https://doi.org/10.1016/j.rser.2018.02.036>
- Lewis, A.M. et al., 2019. Understanding the perceived value of using bim for energy simulation. *J. Green Build.* 14, 79–92. <https://doi.org/10.3992/1943-4618.14.1.79>
- Linderoth, H.C.J., 2010. Understanding adoption and use of BIM as the creation of actor networks. *Autom. Constr.* 19, 66–72. <https://doi.org/10.1016/j.autcon.2009.09.003>
- Lu, Y. et al., 2017. Building Information Modeling (BIM) for green buildings: A critical review and future directions. *Autom. Constr.* 83, 134–148. <https://doi.org/10.1016/j.autcon.2017.08.024>
- Mihindu, S., Arayici, Y., 2008. Digital construction through BIM systems will drive the Re-engineering of construction business practices. *Proc. - Int. Conf. Vis. VIS 2008, Vis. Built Rural Environ.* 29–34. <https://doi.org/10.1109/VIS.2008.22>
- Murray, J., 2013. Likert Data : What to Use , Parametric or Non-Parametric ? 4, 258–265.
- Nwodo, M.N., Anumba, C.J., 2019. A review of life cycle assessment of buildings using a systematic approach. *Build. Environ.* 162, 106290. <https://doi.org/10.1016/j.buildenv.2019.106290>
- Panuwatwanich, K., Peansupap, V., 2013. Factors affecting the current diffusion of BIM: a qualitative study of online professional network. *Creat. Constr. Conf. Budapest, Hungary* 575–586.
- Schlanbusch, R.D. et al., 2016. Experiences with LCA in the Nordic Building Industry - Challenges, Needs and Solutions. *Energy Procedia* 96, 82–93. <https://doi.org/10.1016/j.egypro.2016.09.106>
- Sibiude, G. et al., 2014. Survey on LCA results analysis, interpretation and reporting in the construction sector.

- World SB 14 Barcelona 23–30.
- Solla, M. et al., 2019. Measuring the feasibility of using of BIM application to facilitate GBI assessment process. *J. Build. Eng.* 25, 100821. <https://doi.org/10.1016/j.jobbe.2019.100821>
- Succar, B., 2009. Building information modelling framework: A research and delivery foundation for industry stakeholders. *Autom. Constr.* 18, 357–375. <https://doi.org/10.1016/j.autcon.2008.10.003>
- Toh, Y.Z. et al., 2017. Knowledge, Attitude, and Practice of Design for Safety: Multiple Stakeholders in the Singapore Construction Industry. *J. Constr. Eng. Manag.* 143. [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0001279](https://doi.org/10.1061/(ASCE)CO.1943-7862.0001279)
- UNEP, 2020. 2020 GLOBAL STATUS REPORT FOR BUILDINGS AND CONSTRUCTION, UN Environment Programme.
- Wang, Y. et al., 2020. Collaborative relationship discovery in BIM project delivery: A social network analysis approach. *Autom. Constr.* 114, 103147. <https://doi.org/10.1016/j.autcon.2020.103147>
- Wong, A.K.D. et al., 2013. Comparative Roles of Major Stakeholders for the Implementation of BIM in Various Countries. *J. Chem. Inf. Model.* 53, 1689–1699.
- Wong, J.K.W., Kuan, K.L., 2014. Implementing “BEAM Plus” for BIM-based sustainability analysis. *Autom. Constr.* 44, 163–175. <https://doi.org/10.1016/j.autcon.2014.04.003>
- Wong, S.C., Abe, N., 2014. Stakeholders’ perspectives of a building environmental assessment method: The case of CASBEE. *Build. Environ.* 82, 502–516. <https://doi.org/10.1016/j.buildenv.2014.09.007>
- Zabalza Bribián, I. et al., 2009. Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification. *Build. Environ.* 44, 2510–2520. <https://doi.org/10.1016/j.buildenv.2009.05.001>
- Zhang, Z. et al., 2006. BEPAS - A life cycle building environmental performance assessment model. *Build. Environ.* 41, 669–675. <https://doi.org/10.1016/j.buildenv.2005.02.028>
- Zuo, J. et al., 2017. Green building evaluation from a life-cycle perspective in Australia: A critical review. *Renew. Sustain. Energy Rev.* 70, 358–368. <https://doi.org/10.1016/j.rser.2016.11.251>

Evaluation of Structural System and Construction Material Properties of a Pre-1970 Building

Hossein Askarinejad*, Tania McGrath, Thomas Chan

Department of Engineering and Architectural Studies, Ara Institute of Canterbury Ltd, New Zealand.

**Corresponding author: hossein.askarinejad@ara.ac.nz*

Abstract

The Feb 2011 earthquake in Christchurch, highlighted the vulnerability of many buildings, in particular those designed and constructed pre-1970. In this study, the structural system and properties of a case study pre-1970 building is investigated. The building is a single storey structure which consists of a mixed structural system including steel portals, block infill walls, timber framing and concrete beams and columns. Through on-site examination, field measurements and review of the historical information, the structural elements and construction material properties of the building are discussed. Additionally, the observed earthquake damages of the building are identified and examined.

Keywords

Building structure, construction materials, earthquake damages, pre-1970 building.

Introduction

The design of buildings taking into consideration seismic design and construction was not actively instigated until the mid-1970's with the introduction of New Zealand Standard NZS 4203 1976. This standard provided guidance around structural design of buildings and was later superseded by Australia/New Zealand Standard AS/NZS 1170, 2004 which remains current today. While this standard was not compulsory at the time, it became the acceptable practice for design by engineers. With the introduction of the Building Act in 1992, AS/NZS1170:2004 became an acceptable solution for structural design of buildings. This means that buildings constructed prior to the mid-1970's cannot be considered to have seismic consideration in their original structural design and construction. It should be noted that this does not mean that they do not meet requirements, just that assessments should be conducted to ensure that they have sufficient seismic capacity to meet life risk requirements.

As a result of the Canterbury Earthquake Sequence in 2010/2011 and subsequent earthquake events in the north of the South Island, it has been identified that the earthquake prone section of the Building Act was not sufficient to allow consistency between Territorial Authorities across New Zealand. In 2017 the Earthquake-prone Building Amendment Act was introduced to amend the Building Act and provide a better level of information, consistency and requirements for New Zealand buildings. The Act created Subpart 6A in the Building Act 2004. While the Subpart clarified a number of areas and processes for territorial authorities when assessing an earthquake-prone building, it also established Section 133AV. This section establishes the requirement to set a methodology to be known as EPB methodology. This EPB methodology is the document used by the territorial authorities and engineers to identify,

assess, and make decisions on potentially earthquake-prone buildings referring to the seismic assessment of existing building guideline (MBIE 2018). It should be noted that, the assessment of existing buildings requires different considerations to that of the design for new buildings.

Referring to above guideline, this paper investigates the structural system and construction material properties of a pre-1970 case study building as a part of a preliminary seismic assessment process. A series of on-site examination and desktop studies are conducted where the historical information (drawings and material details) are examined. Additionally, the damages which occurred to the case study building due to Feb 2011 earthquake are presented and discussed.

Background and Literature Review

In June 2006, New Zealand Society for Earthquake Engineering (NZSEE) produced their recommendations (NZSEE, 2006). The document recognised that buildings designed before the publication of New Zealand Standard 4203:1976 and associated materials codes have often been designed to similar levels of strength as modern structures, they typically do not have either the level of ductility or appropriate hierarchy of failure required by current design standards. The document provides assessment procedures for a range of construction materials and introduces an assessment technique based on a displacement-based approach. While this document provided a set of guidelines that could be used by engineers, there were no legislative requirement for them to be used.

The Canterbury Earthquakes Royal Commission of inquiry (Department of Internal Affairs, 2011) was established to report on the causes of building failure as a result of the earthquakes as well as the legal and best-practice requirements for buildings in New Zealand Central Business Districts. Part Two (Volume 4) of the Final Report provided by the Royal Commission contains recommendations when assessing existing buildings which have been the subject of earthquakes. Recommendation 73 from that report states: “The Ministry of Business, Innovation and Employment should review the New Zealand Society of Earthquake Engineering Recommendations entitled Assessment and Improvement of the Structural Performance of Buildings in Earthquakes and, in conjunction with engineering practitioners, establish appropriate practice standards or methods for evaluating existing buildings. These practice standards or methods should have regulatory standing, and monitored by the Ministry of Business, Innovation and Employment (MBIE) for consistency of application.” This recommendation has now been implemented and forms the basis for the Engineering Assessment Guidelines (MBIE, 2018a-c) to which the case study building will be assessed by.

The guidelines (MBIE, 2018a-c) are separated into three components:

- Part A outlines the scope and application, and provides a general overview of the seismic assessment process;
- Part B describes the Initial Seismic Assessment (ISA) which provides a broad indication of the likely level of seismic performance of a building; and,
- Part C describes the Detailed Seismic Assessment and provides a more comprehensive assessment than the ISA.

Part A provide the assessment objectives and core principles to support Parts B and C. It outlines the underlying principles for the guidelines which is the assessment of life safety issues. Life safety issues are the basis for the earthquake score or rating. It also identifies that

the assessment of existing buildings is different to the design of a new building. It also provides details as to how the seismic process should proceed and what areas need to be covered and completed. Part C is divided into 10 sections. Each section provides information relating to a different element of the assessment process. Not all sections are applicable for every assessment and they can be utilised as required. Sections C1-C3 are common for all assessments and provides information on general issues, procedures and analysis techniques as well as earthquake loading information. C4 specifically relates to geotechnical considerations and discusses when it is required to be reviewed as part of the assessment process. Section C5-C10 relates to specific construction materials or elements that may form part of the building and they can be reviewed as applicable to the building that is being assessed. For the purpose of this project, Sections C5, C6 and C7 were relevant to the case study building.

Different case studies and methods for structural evaluation and seismic assessment of earthquake-prone buildings have been discussed by a number of researchers, such as Walsh *et al* 2013 and Vecchio *et al* 2017. Walsh *et al* 2013, describes the properties of “Art Deco buildings” which are non-residential interwar (1920 – 1940) buildings in the Hawke’s Bay region. They investigated the structural system and material properties of a case study building followed by seismic assessment using a nonlinear time history analysis.

Vecchio *et al* 2017, presents the simplified seismic assessment of a case study reinforced concrete (RC) building following the newly developed and refined NZSEE/MBIE guidelines on seismic assessment (MBIE, semi-final draft, October 2016a-c). The case study building was an 8-storey RC building built in 1974, but designed in the pre-70’s RC frames with C shaped wall and gravity columns. The report presents the structural system, material properties, reinforcement details followed by the seismic analysis.

Research Methodology

In this paper, the structural system and construction material properties of a pre-1970 case study building are investigated as a part of a seismic assessment process. For this purpose, a combination of on-site examination and desktop study are undertaken including:

- Evaluating the structural elements and construction material properties through on-site examination and review of the historical information.
- Identifying and analysing the damages occurred to the case study building due to Feb 2011 earthquake

The case study building considered for this study is a single storey made of two-bay portal structure located in the central city area in Christchurch. The building was damaged in the 2011 Christchurch earthquake. It was partially constructed prior to 1963 and was later altered in 1963. The property was a part of a commercial business and exists on a single property Certificate of Title. It is bordered on the west side by privately owned property. Located on the east side is a carpark which is considered a part of the same certificate of title.



Figure 1. A view of the case study building

Findings and Discussions

Structural System

Through on-site examination and review of the historical information, the structural system and construction material properties were identified. A review of the property file held by Christchurch City Council located three partial drawings and two specifications related to some of the alterations that were approved and completed between 1963 and 1965. The building consists of a mixed structural system including a combinations of steel portals, block infill walls, timber framing and concrete beam and columns. For the purpose of this assessment the gravity loads other than self-weight was not considered as the roof and a significant proportion of its framing structure has been removed. Figure 2 shows a model of the building created in Autodesk Revit and Figure 3 shows the elevation views. The main structural system of the building is summarised in Table 1.

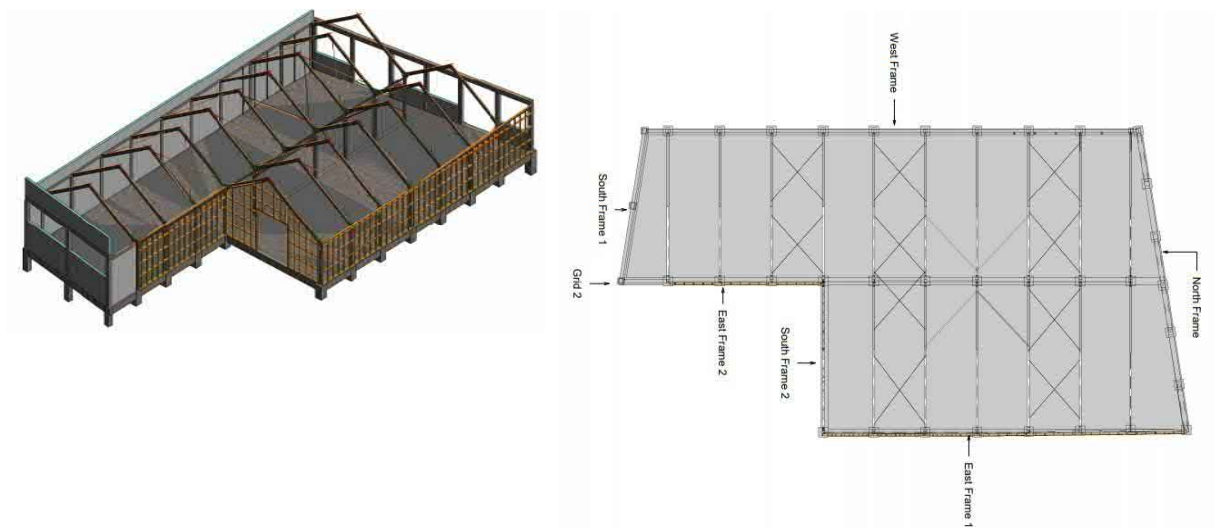


Figure 2. Revit drawing of building structure and the floor plan

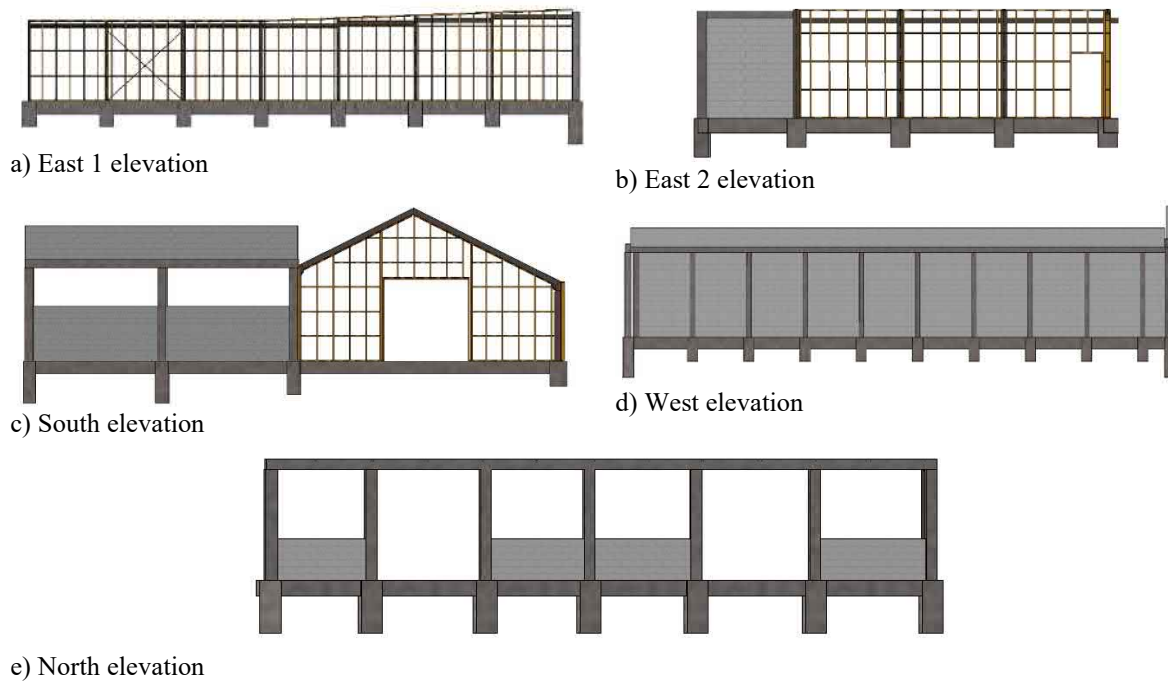


Figure 3. Elevation views of the building

Table 1. Main structural systems of the building

Location	Type	Size (mm)
West wall	Steel portal frame encased and concrete beams with filled concrete block infill	28100 L x 3200 H x 200 T
North wall	Concrete beam and column with half height filled concrete block infill	10460 L x 1200 H x 200 T
East wall 2	Part unfilled concrete block Part steel portal frame with timber infill	2770 L x 3200 H x 200 T
East wall 1	Steel portal frame with timber infill	Spacing horizontal 595mm c-c vertical 895mm c-c
South wall 1	Concrete beam and column with filled concrete block infill	9000 L x 2133 H x 200 T
South wall 2	Steel portal frame with timber infill	Spacing horizontal 595mm c-c vertical 895mm c-c

In this building, the main lateral force resisting systems are the steel portal frames. Three of the external walls are predominantly concrete beams and columns with concrete block infills to varying degrees. Figure 4 shows an example of the original drawings of the 1963 alteration on the portal frame.

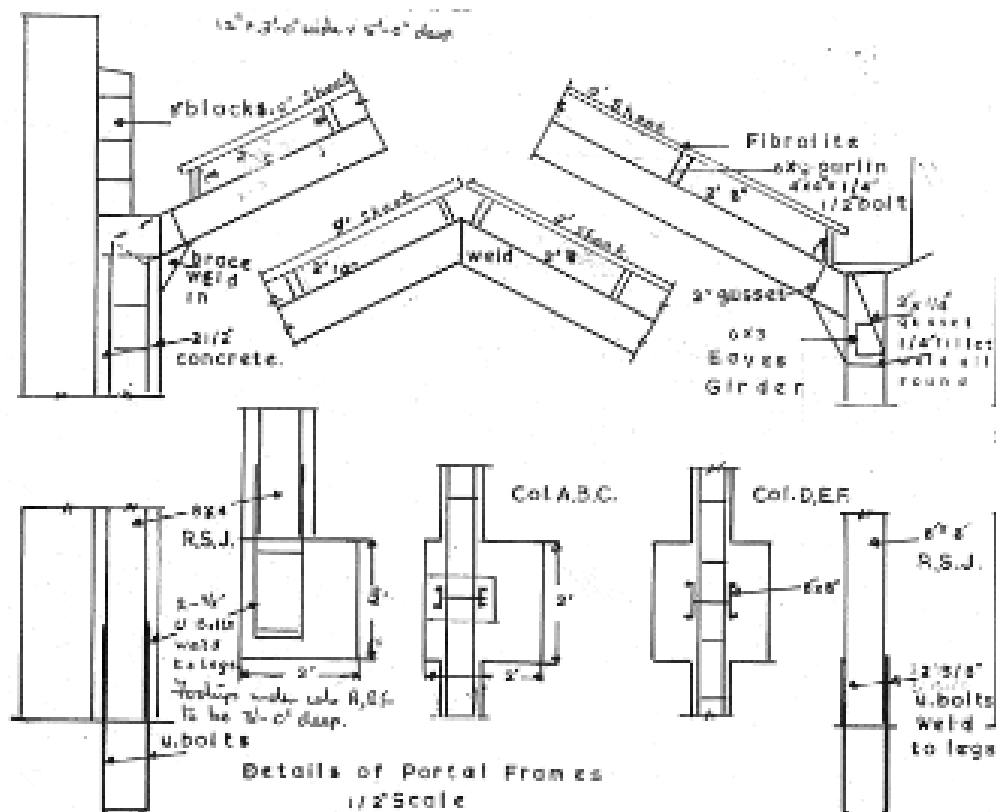


Figure 4. Example of construction details for the portal frames

Construction Material Properties and Details

One of the most significant issues when evaluating the existing buildings (in particular pre-1970), is the not only the age of the building, but also the amount of information that is available. This building has two major material types where the properties needed to be established including reinforced concrete and steel components.

The original drawings and specifications and documentation which were evaluated were in imperial units therefore needed to be converted into metric in order to be effectively assessed. For example, the concrete component had information provided in the specification dated 1963. The concrete strength was specified to be 2500 pounds to the square inch. This converts directly to 17.24 MPa. However, the MBIE guidance indicates that in the absence of specific information, the probable concrete strength of concrete ($f'c, prob$) may be taken as the nominal 28-day compression strength of the concrete specified for the original construction factored by 1.5 for strengths less than or equal to 40 MPa (MBIE, 2018c). Using this factor, the strength for the concrete was determined to be 26 MPa.

For the steel component, the guidance (MBIE, 2018c) indicates that default mechanical properties corresponding to the source and age of the steelwork can be adopted from those outlined in historical specifications. The steel material properties for this building were selected based on the tables provided in the guidance based around the time that the alterations were completed (1963-1965). Further details on the structural elements and materials properties are shown in Tables 2 and 3.

Table 2: Structural Element Details

Elements	Beam			Column			Rafter	Brace
Materials	concrete			Steel encased in Concrete	Steel			
Location	West & East 2	North & South	North & South & East	West	Centre	East 1	Roof	Roof & East
Element Size	200 x 200	305 x 305		260 x 350 200 UB 18.2	200 UC 46.2	200 UB 18.2		N/A
Bar Size	13	16	19	N/A				20
Stirrup Size mm	6.4			N/A				
Cross Section								

Table 3: Steel material properties and section details

	Steel 1956-65 rolled section (Thick<19mm)		Steel 1956-65 plate (Grade D Thick <19mm)		Connections		Steel beam 1962
Type	Structural steel	Structural steel	Steel plate	Steel stiffener	bolt	weld	Channel steel
Typical Dimension (mm x mm)	203 x 102	203 x 203	305 x 152 x 16 (Thick mm)	6 (Thick mm)	20 (Dia mm)		152 x 76
kg/m	26.8	46.1					18
Strength Modification factor	1.15	1.15	1.15	1.15	1.15	1.15	1.15
Yield strength (MPa)	236	236	236	236	240		236
Tensile strength (MPa)	432	432	432	432	400	410	432
Area (mm ²)	3419	5871			314		2277
I _{xx} (10 ⁶ mm ⁴)	23.2	45.7					6.82
I _{yy} (10 ⁶ mm ⁴)	1.49	15.4					1.3

Reinforcement has been used in all buildings constructed in New Zealand since the early 1930's after the damage that was observed as a result of the Napier earthquake in 1931. Based on this and the drawings located, it has been identified that there are no significant structural elements that does not contain reinforcement. The details of the reinforcement were specified in the drawings and specifications that were located. Figure 5 shows an example of the construction reinforcing details which were provided in the drawings for the alteration in 1963. Table 4 provides a summary of the reinforcing used as a result of the alterations completed in 1963-1965.

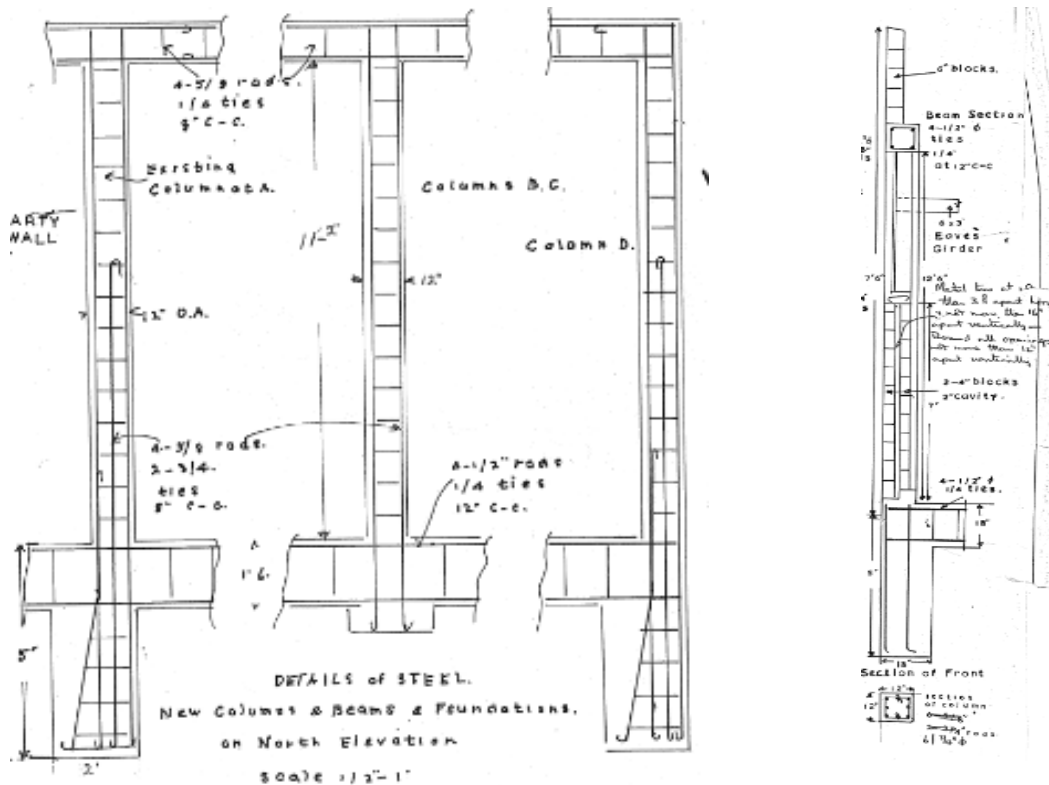


Figure 5. Example of reinforcement details (north elevation column & beams plus the south elevation column, beam and parapet)

Table 4: Concrete reinforcement details

Reinforcement	Location	Bar (No.&size)	Stirrup size (Diameter mm)	Stirrup Spacing (mm)
Column	North wall	6D19	6.4	203
Beam	North wall	4D16	6.4	203
Beam	West wall	4D13	6.4	305
Parapet	51mm above gutter	1D10 (Spacing 406mm)	none	none
Foundation	Ground	4D13	6.4	305

Earthquake Damages

The building has signs of damage which could be considered significant when conducting a seismic assessment of the building. The locations of the observed damages are indicated on Figure 6. Further details on the type of damages are shown in Table 5.

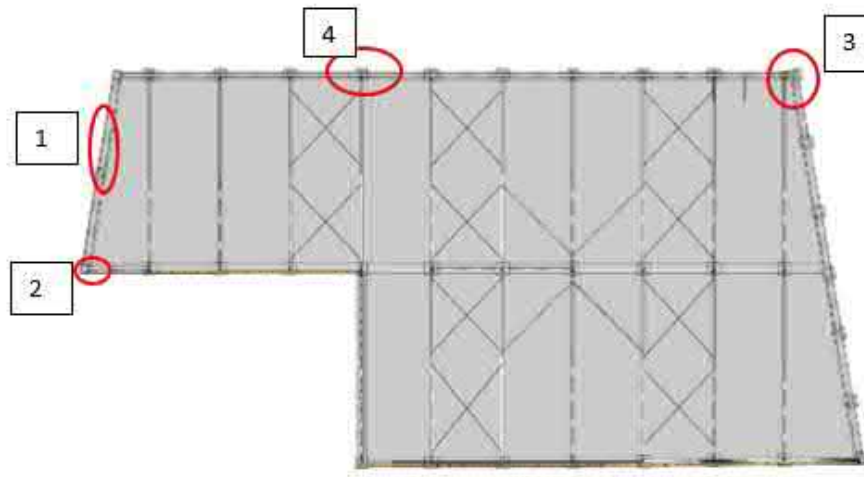


Figure 6: Location of observed earthquake damages

Table 5: Type and description of the observed damages

Number	Structural element	Damage description	Photo
1	South 1 wall	Parapet – cracking in the mortar joints	
2	East 2 wall	Junction with south column – separation between block and column resulting in exposure of reinforcing and step cracking in mortar joints	
3	North wall	West corner top – cracking at concrete beam/column/parapet junction	
4	West wall	Central – cracking in beam at the top and mortar joints of block infill	

Conclusion

The buildings constructed prior to the mid-1970's cannot be considered to have seismic consideration in their original structural design and construction. This means assessments should be conducted to evaluate their structural system, construction material properties and seismic behaviour. This paper reported the findings and the process undertaken to evaluate the structural system, material properties and reinforcement details of a pre-1970 case study building as a part of a preliminary seismic assessment process. This building was damaged in the 2011 Christchurch earthquake. In this study, a series of on-site examination along with desktop studies were conducted where the historical information (drawings and material details) were examined. The earthquake damages observed through the site inspections were also presented and discussed. It should be noted this paper only provides the preliminary evaluation of the case study building. In the future steps, detailed seismic assessment shall be conducted through structural modelling and simulation of load demands and component capacities.

References

- AS/NZS 1170.0:2002 (2002), Structural design actions, Part 0: General principles, Incorp. Amends. 1-5. Australian Standards (AS) and Standards New Zealand (NZS) Joint Technical Committee BD-006, Wellington, New Zealand.
- Department of Internal Affairs. (2011). Canterbury Earthquakes Royal Commission. Retrieved from <http://canterbury.royalcommission.govt.nz/>
- MBIE (2018a). The Seismic Assessment of Existing Buildings Technical Guidelines for Engineering Assessments. Part A: Assessment Objectives and Principles. New Zealand.
- MBIE (2018b). The Seismic Assessment of Existing Buildings Technical Guidelines for Engineering Assessments. Part B – Initial Seismic Assessment. New Zealand.
- MBIE (2018c). The Seismic Assessment of Existing Buildings Technical Guidelines for Engineering Assessments. Part C: Detailed Seismic Assessment. New Zealand.
- New Zealand Government. (2016). Building (Earthquake-prone Buildings) Amendment Act 2016. New Zealand Legislation. Wellington: New Zealand Government.
- New Zealand Parliament (2004), Building Act 2004, Date of assent: 24 August 2004. Department of Building and Housing – Te Tari Kaupapa Whare, Ministry of Economic Development, New Zealand Government, Wellington, New Zealand.
- NZS 4203 (1976). Code of practice for the general structural design and design loadings for buildings, Standards New Zealand, Wellington, New Zealand.
- NZSEE (2006). Assessment and Improvement of the Structural Performance of Buildings in Earthquakes, New Zealand.
- NZS 1170.5. 2004. Structural design actions, Part 5: earthquake actions—New Zealand - Commentary. Standards New Zealand. Vol. 5. New Zealand.
- Vecchio, C., Gentle, R., & Pampanin, S. (2016). The Simple Lateral Mechanism Analysis (SLaMA) for the Seismic Performance Assessment of a Case Study Building Damaged in the 2011 Christchurch Earthquake. University of Canterbury. Christchurch: University of Canterbury.
- Walsh, K., Liu, P., Dizhur, D., & Ingham, J. (2013). Detailed Seismic Assessment of a Hawk's Bay Art Deco Case Study Building. NZ Concrete Industry Conference. Queenstown.

4D sequencing on New Zealand's largest Infrastructure Project

Delfinado, John-Dy C* and Gathoo, Chinmay S.

Link Alliance – City Rail Link Project, Auckland, New Zealand.

**Corresponding author: john-dy.delfinado@linkalliance.co.nz*

ABSTRACT

Auckland is going through a boom in construction. Coordination, planning, and efficient execution of construction is vital for a successful project. With Building Information Modelling being so advanced, inculcating the idea of a construction methodology into the minds of Designers, Engineers, Quantity Surveyors, Contractors, and other Stakeholders is not only possible, but key to successful understanding and eventual completion of a project.

Large infrastructure, & commercial projects are currently changing the face of Auckland. Communication can be difficult due to a diverse, and sometimes geographically widespread, design and construction team. In such cases, visual representation can act as a vital lifeline in communicating the construction methodology. The technology for a proper visual representation to communicate this construction methodology may have been limited in earlier days. These communications were restricted to sketches or 2D drawings. However, with 3D Designs in play, it becomes possible that adding the dimension of time to the model is more critical than ever. 4-Dimensional sequencing comes into its own. The goal, to understand how the construction program can be visualized and understood using 4D sequencing software. Portraying the program visually to the construction professionals who are building the Environment.

The proposed method consists of a case-study using BIM & planning software for this exercise. Studying the effectiveness of a simulation, which will involve team members from a construction background to observe and critique the 4D. This research will develop the steps for 4D implementation by encompassing process definition, software and tools selection, pilot/test study and full implementation. A 4D sequence for Civil works which will potentially extend to include temporary works, Architectural fitouts & MEFH Services.

Keywords

Building information modelling; construction planning; 4D; 4D environment; BIM

Introduction

When one has a chance to look at a new building, seeing it for the first time, they may mentally critique on the form, shape, composition, context, language, design, and the structure of that built environment. Little may they know about the methodology of how the structure may have been built. However, if they started thinking in that direction one might be fascinated to know the way this Environment was built.

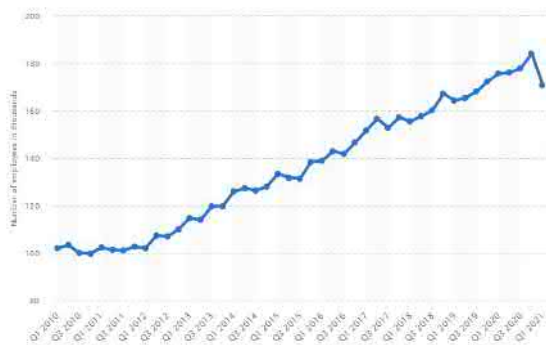
One can describe the 4D sequencing as 3D models integrated with the factor of time (Bowles & Gill, 2021). The 4D sequence may use specific 4D software which are surely used widely in the industry today. The software receives information related to design, site, sequence timing and phases of design with respect to time (Bowles & Gill, 2021). This could be used by construction site to visualize & plan their site activity, it could also be used to understand

different complicated interfaces between 2 or more different team. Health and safety might be equally interested to see the safety in design factor in the method of construction. methods team could be using this to form an enhanced, safer & effective method of construction methodologies.

The City Rail Link (CRL) project is located at Auckland CBD. In this project twin tunnels which are about 3.45km in length link with depths up to 42m below the city center. This will include redevelopment of 2 stations namely Britomart & Mt Eden. This project will also include introduction of 2 new stations Karangahape road & Aotea square. In the following paper one may see a few cases presented of the Karangahape road (KRD) station & Mt Eden station (MTE). A follow up procedure will also be mentioned ahead of one of the observations, of how we could observe that the sequence may have been followed in the construction phase.

Literature Review

Construction industry in Aotearoa, New Zealand is significantly contributing to the economic growth of the country. It is estimated that nearly 170,000 people are employed in the industry this is quite a significant amount if this number was compared a decade prior. Nearly 50,000 new homes are proposed by the Government to cater to the shortages of houses in Auckland. Due to the increase of population in the North Island & the earthquakes in the South Island, Christchurch post-earthquakes rebuilding (Granwal, 2021). Housing & public infrastructure goes hand in hand for the functioning of the society.



This may emphasize on complex projects being built in today's times & soon of New Zealand. Use of 4D sequence & inculcating the factor of time on the 3D model might be quite critical on different instances and parts of the CRL project. This has the potential to cross verify that everyone is on the same page in terms of visual interpretation of the sequence.

Figure 1: Image of the rise of employment (Granwal, 2021)



Figure 2 & Figure 3: Images above shows Piling at start. This is for the Mount Eden Portal where the Tunnel Boring machine (TBM) starts.



Figure 4: Image above shows the sequence of the construction for the capping beam and demolition of the existing.

The stick framing method is quite famous in housing pattern used in New Zealand. Given the challenges faced in smaller projects, one may think the challenges of medium & large-scale projects may be quite significant. Yes, they could be, however if a methodical & robust project management plan is formed that caters to the needs of different disciplines (such as Architecture, Structure, MEP) a project could be successfully completed on time, budget & safely (Anon., 2021). To understand a little further in detail in a methodical manner following will be the nested subsections of the Literature review:

- 2.1.Objectives
- 2.2.Brief introduction of Link Alliance
- 2.3.Evolution of the idea of the 4D sequencing
- 2.4.4D sequencing process
- 2.5.Faults identified and challenges faced
- 2.6.Interfaces and impact of 4D sequencing in interfaces

Objectives

The objectives of this paper are to:

- Understand and observe the impacts of 4D sequencing on site and on the planning of the construction team.
- Exploring the 4D capabilities of Fuzor software. And confirm if it is the right software, for the 4D experience.

The objective will be developed further through our project. Using the CRL platform and the support provide by Link Alliance, we will be testing the station model to see this 4D experience. We will be concluding on what lessons can be learnt by other infrastructure projects from the CRL & Link Alliance group.

Further objectives such as integration of the Civil works with systems on the sequence can be possible.

Brief introduction of Link Alliance

Link Alliance comes under the integrated project delivery category more specifically the Alliance contracting theory. It is a cooperative arrangement/agreement made by different bodies/companies/organizations driven by a common objective / end goal specific to the success of that project (Mistry & Davis, 2009). The 7 companies involved in Link Alliance are as follows:

1 Client:

- City Rail Link Ltd (CRL)

3 Design partners:

- WSP New Zealand Limited
- AECOM New Zealand Limited
- Tonkin + Taylor Limited

3 Construction partners:

- Vinci Construction Grands Projets S.A.S
- Downer NZ Ltd
- Soletanche Bachy International NZ Limited

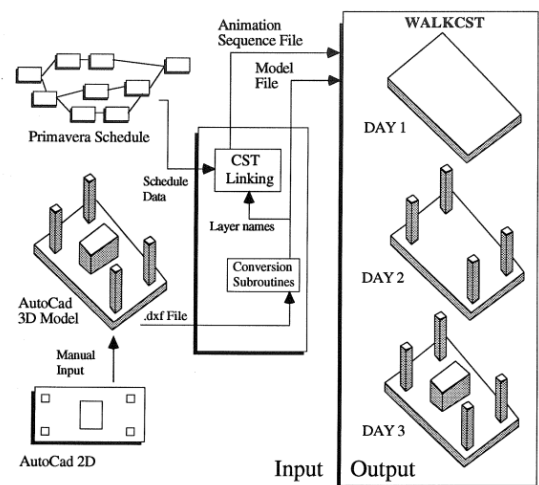


Figure 5: 4D CAD model process (Collier & Fischer, 1995)

Evolution of the idea of the 4D sequencing

If you have a time lapse camera set on site, an actual construction process can be documented. Computer aided software & animation have the capability to achieve this documentation of methodology even before the construction begins on site (Collier & Fischer, 1995). This process could be self-explanatory for the Construction team as step-by-step methodologies are set in their minds for construction. At complicated interfaces of design methodologies & sequence can be altered after viewing the 4D sequence.

Collier & Fischer (1995) have mentioned that the concept of 4D sequence was present even before BIM. They had conducted a parallel research of using CAD softwares for 4D sequencing.

This results into formation of a 4D CAD model. In the research conducted by Collier & Fischer that a video produced from the 4D model can be self-explanatory to any layman looking at the project for the first time. They also indicated that as the technology develops there would be a higher demand for the need of these 4D sequenced models.

The concept established in the process to create a 4D CAD model & a 4D sequenced BIM model in both our concepts could be similar. Both follow the following points in sequence:

- a) Using a 3D model
- b) Linking the program into the 3D model
- c) Animating the 3D model

Research conducted did show that the highest scoring card in the industry of today is making of a 4D model instead of a traditional planning system, in terms of visualization (Russell, et al., 2009). In this research Russel et al (2009), focuses in saying that the 4D model can be effective in identifying construction strategy for shortening the project timeline.

Changes and amendments can be made on the Program and a new export with updated set of dates can be feed to the 3D model if there needs to be an update in timeline.

4D sequencing process:

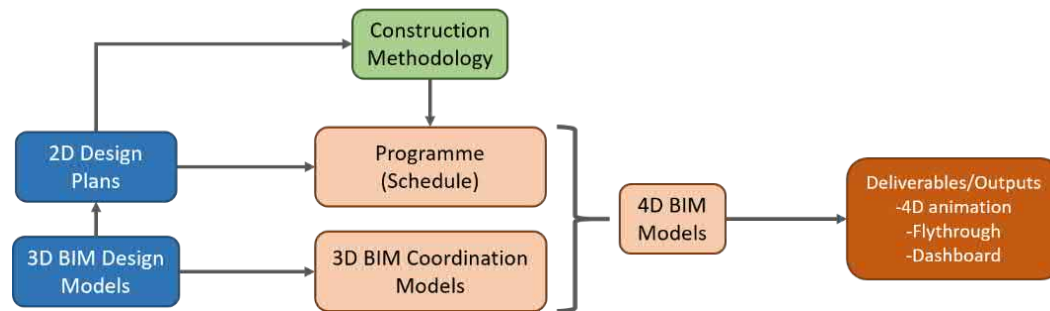


Figure 6: Image of 4D sequencing process

To best describe the process, the Design team, model the 3D elements (eg: slabs, beams, foundations, equipment, etc). The modeling could be done on Revit or Civil 3D. The construction BIM team could then divide these elements in phases based on the construction sequence, after consulting the Project Managers, Site Engineers, Quantity Surveyors & Planners. Certain construction data such as ‘Construction Activities’ can be added to the Revit file, Navisworks file or the Civil 3D file.

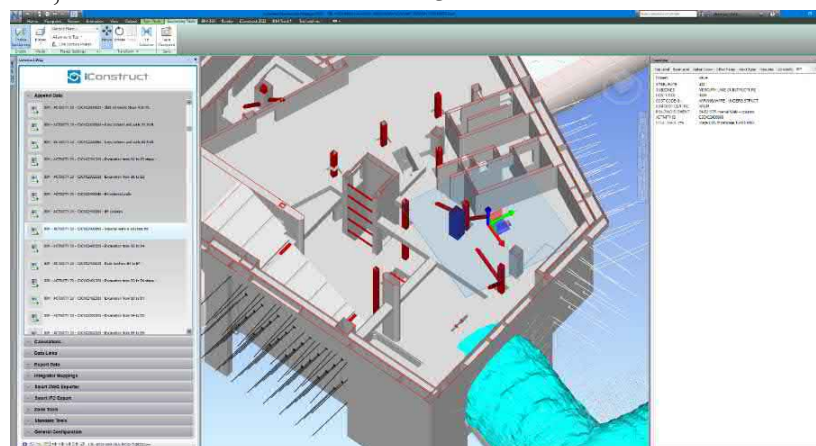


Figure 7: Construction activity data on the ‘BIM’ tab of the Navisworks file

Another preferred method which is used within the team inhouse is ‘Appending’ the construction activities on the Navisworks files. This is a more preferred without disturbing the Design team on their models. The preferred plug in used here is iConstruct’s Append Data. Once all the information is appended, information can be updated on a regular basis if there is change instructed by Program team, based on the input from the Construction team. This is then pushed onto Fuzor for 4D sequencing. The models retain the same information as the once on Revit/Navisworks/Civil 3D.

Based on the export of the program from the P6, every ‘Activity id’ can have a timeline with a ‘Start’ & ‘Finish’ date as seen below:

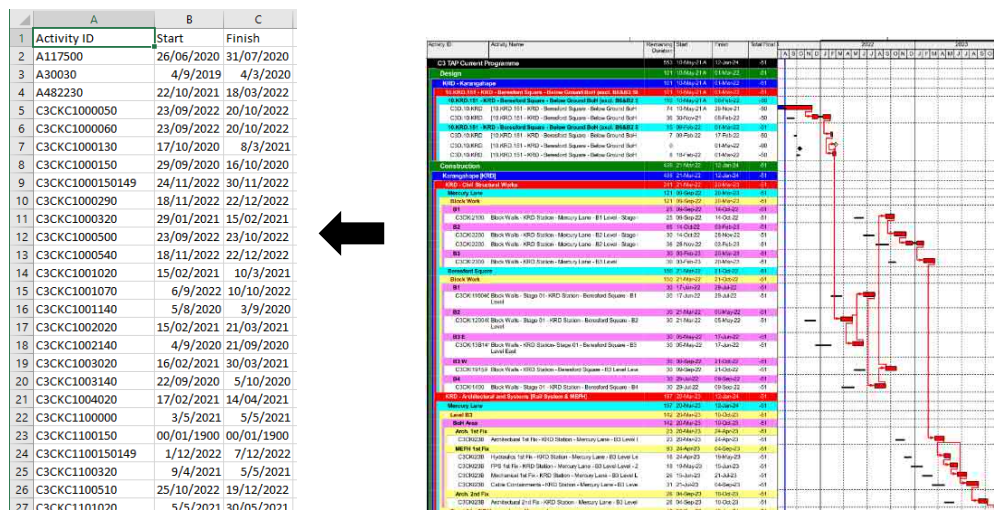


Figure 8: Screenshot from the Primavera (P6) program exporting Activity id & dates

Eventually with a collaborative effort a common goal can be achieved to produce a 4D sequenced model, on any project.

Faults and challenges faced

Faults identified in Design Phase

Coordination & joint efforts can help achieve quite amazing goals as a team. But for a coordination to work smoothly a certain amount of time needs to be spent to review the process and gain confidence in the process with respect to its outcome. Weekly clash detections and issues are raised on a share platform, which helps capture information & helps different discipline to understand the problem and come up with a joint solution. Eventually this leads to formation of a coordinated model.

Achieving a well-coordinated model can help reduce the problems in the construction/testing phase quite significantly (Hu, et al., 2019). This may not just help achieve a proper 4D model but even the construction/performance teams in future.

Faults in Activity Id

Just as mentioned in the earlier point a smooth coordination could lead to achieving a seamless 4D model. In the construction BIM team we do tend to split the model in parts as per the different construction phases of the project. Creating parts not only preserves the geometry but also helps preserve the non-graphical data of the Design model.



Figure 9: Image showing the Parts icon in the Modify tab under Create

After splitting up the model in different phases, sometimes the Activity Id on the program do not correlate with the Activity Id in the model. At such times the Programmer needs to be consulted. The dates for the missing Activity id need to be clubbed with another activity id which has been given the dates or new dates need to be determined by the programmer of the missing ids.

Also, worth mentioning if the 4D shows a specific activity out of sequence this may show the error on the program. This needs to be shown to the programmer as well.

• 2.6 Interfaces and impact of 4D sequencing in interfaces

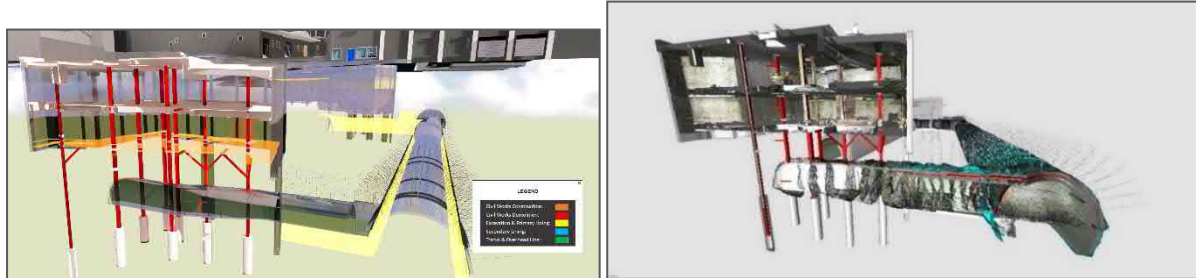


Figure 10 & Figure 11: Image above shows 4D sequenced model from the Link Alliance BIM team, focuses on the interface region between Structures & Mined tunnels. Image on right shows Point cloud scans overlayed on the BIM model, this focuses on the same interface as the image above from AS BUILT point of view

One of the major key problems during construction are the interfaces between each discipline. Those are not easily identifiable using 2D drawings because of its limitation in conveying about the clarity of information. On the City Rail Link project, as Link Alliance do have wide range of disciplines involved. Some of them being Structures, Architecture, Urban, Utilities, Geotechnical, Tunnels, Temporary works, Mechanical, Electrical, Firefighting, Comms, Systems, Hydraulic, Rail systems, Track Alignment, Tunnel Ventilation, Sub soil drainage, Survey, Subcontractors, Supply chain, etc.

Some of the complicated interfaces were faced on both these stations of KRD and MTE. Managing an interface between different teams leads to a successful management of the project with each team knowing what it needs to do (Lin, 2021). As seen in the images above an example can be stated of the Mercury shaft structure, Adit 2 (mined tunnel) & Pilot tunnel interface.

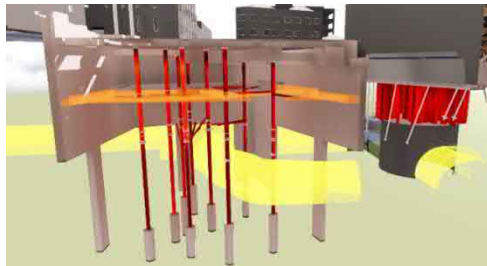


Figure 12: Pilot tunnel construction + Mercury Basement 1.

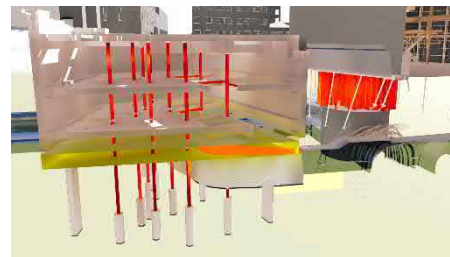


Figure 13: Mercury Basement 2 complete, excavation into Pilot



Figure 14: Pilot tunnel & back fill below demolished. Shotcrete & rock



Figure 15: Basement 7 slab being built

This plan was drafted by Designers with closely involving the Construction Managers involved. After a clear demonstration of the 4D sequence of this specific region, we think the

layman may have had a good enough idea on the steps which need to be taken for this interface to work. Indeed, separate interface coordination meetings were run on a weekly basis, these were specifically to deal with the challenges of the interface. It would have been quite critical to get updated survey excavation point cloud from the Mercury box structural surveyor & the tunnel surveyor as one can see in Figure 11. We think lessons may have been learnt from this exercise on interface for other parts of the project to learn from. Currently Mercury box structure team have finished its excavation towards the Basement Level 7 slab, as of 25^h of Jan 2022. This is reflected in Figure 15. The Mined tunnels and Mercury box are now connected. Following are some images from site of Mercury box & Mined tunnel:



Figure 16: Image of Pilot tunnel, this relates to Fig



Figure 17: Backfilling of the Pilot tunnel on sketch, this relates to Figure 13.



Figure 18: Mercury station box structure team excavating into the pilot tunnel, this relates to Figure 14.



Figure 19: Shotcrete & rock bolt installed, this relates to Figure 14.

Research methodology

Together the team had to work closely with the Programmers of their respective counter parts. As mentioned in the 4D sequence process in the Literature Review the Programmer provides Activity Id with the start & end date. This is then fed into the models for the functioning of the process.

Working closely with the survey team and receiving updated Point Clouds from each subdivision could be the key to observe the functioning of 4D sequenced program. We believe the topic ‘Interfaces & impact of 4D sequencing’ under Literature Review does prove that the research methodology of using a 4D sequenced BIM model does have an impact in a smoother understanding of teams.

File sharing system

An executable file (EXE file) can be published and shared on a common platform. It is simpler for the computer systems to identify this format and run this model without the trouble to install a new software. This can help different experts to view the model.

When an individual tries to open the exe file of the 4D model, a Fuzor viewer opens. This interface may appear like the Native file interface, but it's not as it is just a viewing tool. The native file format of Fuzor file is '.CHE'.

Participation in the construction review meetings

Our research methodology was attending construction site meetings pertaining to the interfaces, which paved way in finding that this 4D methodology is then followed by the construction teams on site. Due to circumstances on site and impact on timeline due to the Covid pandemic there could be differences seen in dates, however the sequence did remain the same. The purpose of the review with construction team works to resolve clashes of time, thus it may be making sure that the sequence works. It is also to communicate if the sequence of works. Like the topic "*File sharing system*" on 'File sharing system', producing the sequence images (.jpg) or videos (.mp4) to explain the team of how the construction works is also possible.

With the help of these meetings the process & sequence was taken to greater level of details. It was clear by looking at the Methods drawing produced of what each team should be doing. Following are images from the drawings done by construction methods teams, the image on the left showing the Structure team of the station excavating to a certain extent. The image on the right shows the mined tunnel teams excavating from the mined tunnel region into the station box. Challenges and methods to encounter were discussed in the meeting.

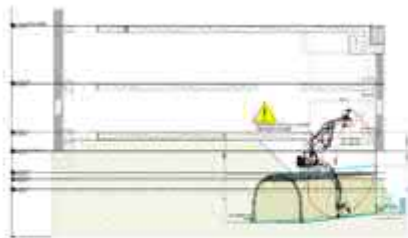


Figure 20: Method drawing of the station excavating

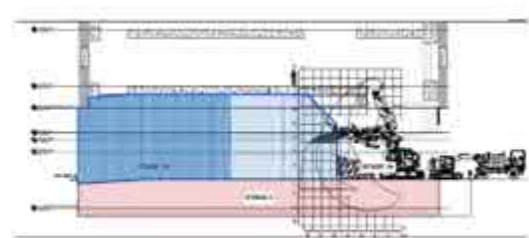


Figure 21: Method drawing of the mined tunnel team excavating into the box

It could be worth noting that the Design team were involved in these discussions at times of need. A separate point cloud model of the excavation was also used heavily in these meetings to track the progress & encounter difficulties.

Overall, the process of being involved in the construction meetings & observing the point cloud did suggest that sequence was followed. This research methodology of producing the 4D sequence did show its effect. Attending the relevant meetings did prove that the sequence was followed.

Finding and Discussion

Use and need of 4D Sequencing

The requirement of the 4D sequence may differ from project to project. The sequence may not be required for simpler projects such as the stick framing methods where limited number of teams maybe involved and each knowing their specific tasks to perform. Return on investment in terms of time and costs need to be considered in such a scenario. It could be quite vital to carry out this assessment before one initiate the process 4D sequencing. Complicated interfaces and projects involving multiple teams and disciplines may need a 4D sequencing. As mentioned above in Literature Review, the classic example of the mined tunnel & structure station box helped quite a few people in the project to understand the sequence at that point. Teams involved and workers may be clearer in what each once needs to do thanks to the Method drawings produced.

Resource loading

To add on after the model is split into construction phases using parts, as discussed in topic “*Faults in Activity Id*” a Quantity take off, of the concrete volumes & steel tonnage can help a Programmer & the Quantity survey team in updating their estimations. In general, resource loading on the BIM model could be imperative. Resource loading can be best described as the process used tag on time, workflows, and material. This can be helpful to know what is needed to be done when, where and for how long a period (Ritter, 2009). The writer of the article also mentions that the higher investments in resource loading & critical path method the lesser number of slips and better chances for the project to be a success. As mentioned before using iConstruct & parts one can load the resource loading into the BIM model thus eventually integrating the Quantity survey, planning & BIM as the core of the project.



Figure 21: Team members using VR head set to view his 4D Fuzor model

Why Fuzor?

4D sequencing can be done before, in between or after a project is complete. It depends on the requirement & need. The factors such as development of the BIM model as per Level of Detail (LOD) & development of the program may be involved directly in achieving a more advance 4D sequence. Once the Activity ids are set between the Program & the BIM model dates can be changed easily on the entire 4D sequenced model. If required by the Project manager, the dates can we changed in a 4D model to visualize and see the most ideal scenario best suited for completing a project on time and safely. Defining phases such as New Construction or Demolition of an activity can easily be selected in this software. 4D software like Fuzor make it easy to manually change the date of an activity in the software to test such scenario as Fuzor is a next generation Virtual Design and Construction (VDC) software developed by Kalloc Studio. It is one of the software which helps in creating 4D sequenced animation, supporting Augmented reality, supports Virtual reality (VR) and importing Pointcloud scans (Anon.,

2021). Achieving enhanced live review capability is another achievement that could be possible with the help of Fuzor.

The next stage: Systems and Fit outs integration on 4D sequence

The team has achieved integrating the structure and mined tunnels on the 4D sequence. This has been a major milestone on our Key Performance Indicator. The next stage is to integrate Architecture and MEP systems onto the 4D sequenced model. This will allow the systems and fit out team a possible glimpse into installation sequence of their respective scope of works. Comments from teams can be given back to the programmer after visualizing the 4D sequence. This could be quite critical for the project as this project can be Systems driven.

Conclusion

As a conclusion we do feel a 4D sequence does give a holistic overview of the entire project to any viewer. Having this overall view of the project can be helpful for several teams in knowing the different phases of Construction of the project. Being closely involved with Construction site teams does give model coordinator an idea, of the exact construction sequence followed on site. This may lead to him finding if the Sequence that was created is being followed on site or not. Fuzor can be the right software for this experience. However, the idea of the sequence may convey a story for viewers and future construction specialist of tomorrow.

Acknowledgement

We would first like to thank Link Alliance for giving us this opportunity. A few names worth mentioning who did play a key role in this research Brice Gaudin, Darrell Edwards, Sara Benlyas and Quentin Villamaux, this research may not have been possible without them. We would also like to thank Saurabh Chauhan, Mostafa Elrefaey & Rieko Zimmermann. Lastly, we would also like to thank rest of the BIM, Survey, Methods, Design and Construction team & program teams for their support.

References

- Anon., 2015. *Construction Methods: What are your options?*. [Online] Available at: <https://bonestructure.ca/en/articles/construction-methods-what-are-your-options/> [Accessed 28 October 2021].
- Anon., 2019. *LINK ALLIANCE*. [Online] Available at: <https://www.cityraillink.co.nz/crl-the-link-alliance> [Accessed 28 October 2021].
- Anon., 2021. *The Ultimate Guide to Construction Project Management*. [Online] Available at: <https://www.projectmanager.com/construction-project-management> [Accessed 28 October 2021].
- Bowles, J. & Gill, H., 2021. *4D BIM: What does it mean and how can I get involved?*. [Online] Available at: <https://www.pbctoday.co.uk/news/bim-news/4d-bim/99932/> [Accessed 20 October 2021].
- Collier, E. & Fischer, M., 1995. *Center for integrated facility Engineering*. [Online] Available at: <https://stacks.stanford.edu/file/druid:zd669fn2067/TR101.pdf> [Accessed 3 November 2021].
- Granwal, L., 2021. *Construction industry in New Zealand - statistics & facts*. [Online] Available at: <https://www.statista.com/statistics/1026508/new-zealand-construction-industry-gross-domestic-product/> [Accessed 28 October 2021].
- Hu, Y., Castro-Lacouture, D. & Eastman, C. M., 2019. Holistic clash detection improvement using a component dependent network in BIM projects. *Automation in Construction*, September, p. Volume 105.
- Lin, Y.-C., 2021. Use of BIM approach to enhance construction interface management: a case study. *Journal of Civil Engineering and Management*, 12 May, pp. 201-217.

- Mistry, D. & Davis, P. R., 2009. *A client's perspective of critical success factors in project*. Nottingham, UK, Association of Researchers in Construction.
- Ritter, T., 2009. *CPM AND RESOURCE LOADING*. [Online]
Available at: <http://ritterpm.com/resources/cpm-and-resource-loading/>
[Accessed 15 November 2021].
- Russell, A., Staub-French, S., Tran, N. & Wong, W., 2009. Visualizing high-rise building construction strategies using linear scheduling and 4D CAD. *Automation in Construction*, 1 August, pp. 219-236.
- Squarespace, 2021. *Works*. [Online]
Available at: <https://www.dcmurban.com/work>
[Accessed 28 October 2021].

Understanding the Factors Affecting Accuracy of New Zealand Public Housing Project Tender Price

Jie Chen*, Niluka Domingo, James Olabode Bamidele Rotimi

School of Built Environment, Massey University, Auckland

*Corresponding author achenl@massey.ac.nz

Abstract

To make the house price affordable to first home buyer only with low-to-medium income, all Kāinga Ora's public housing projects are with the cost cap. The accepted tender price forms the major portion of the Kāinga Ora's final project construction cost, and the level of the accuracy of the project tender price determines the possibility of achieving the cost cap. Hence, explore and develop effective tender price forecasting tools are something worth to research. To achieve this goal, literature suggests an understanding of the factors affecting the accuracy of public housing tender price is crucial important.

There is little to none research of the factors affecting the accuracy of public housing tender price in the context of Auckland, New Zealand. This research aims at filling the gap of the study of the accuracy of the public housing project in Auckland. The research aimed to identify the factors and their level of the importance to public housing project tender price in the context of Auckland, New Zealand. The questionnaire survey was processed to investigate the factors affecting the tender practice accuracy in the Auckland public housing sector. The samples were limited to the experts from with at least 5-year public housing tendering experience in New Zealand context. The frequency method and Mean Value Analysis (MAV) method were adopted to proceed data analysis.

All survey participants agreed material cost, labour cost and plant cost were the top 3 factors significantly affect the accuracy of the tender price. Moreover, some participants indentified labour supply, material supply, and market conditions should be carefully assessed too. The research identifies the loophole of the current public housing project tender practice in the context of Auckland public housing sector. It provides the direction of future research.

Keywords

Accuracy of cost estimate, Public housing tender, Tender price predition

Introduction

All construction industry participants always have a great concern of the pre-construction stage cost estimate. It is the first thoughtful efforts to estimate the cost of a project and it is crucial during the initial decision-making process for the construction of projects. The accuracy of the pre-construction cost estimate significantly affects the destiny of many projects and critically contributes to the successful project delivery. The contribution starts from the initial determination of project viability and client feasibility, by setting up the cost limit, the cost budget, and the cost target, then moves to the cost check and the remedial action (Smith, Jaggar & Love, 2016).

The participants of the public housing projects are aware of the issue. In New Zealand context, to ease the housing affordability crisis in Auckland, the public houses in Auckland area are with the cost cap (Kāinga Ora, 2021). Since cost overrun is not allowed, the cost cap raises the high requirement of accurate project tender price prediction. The inaccurate cost forecast is one of the crucial reasons of project cost overrun (Akintoye, 2000; Ashworth, Hogg and Higgs, 2013).

Because of the importance of the accuracy of the tender price, explore and develop effective forecasting tools is something worth the research. To process the research, the first step is understanding the factors affecting the accuracy of public housing tender price. This research aims to add the missing parts to the puzzle. Along these lines, the objectives of this research is identifying factors and their extent of impact on the accuracy of cost estimate in public housing project.

Literature Review

Tender Price Forecast Methods

The tender price forecast could be achieved via either rate methods or price index methods.

Rate Methods

Dysert (2003) stated the tender price was formed from the trade package items, which identified from a construction project scope statement, was quantified and priced by the application of the unit prices.

Ashworth and Perera (2015) further pointed that the rate methods highly depended on the availability of cost data developed during different design stages. The detailed level of cost estimate developed throughout the whole design stage, from the single rate method to multiple rate method as illustrated in the Figure 1 below.

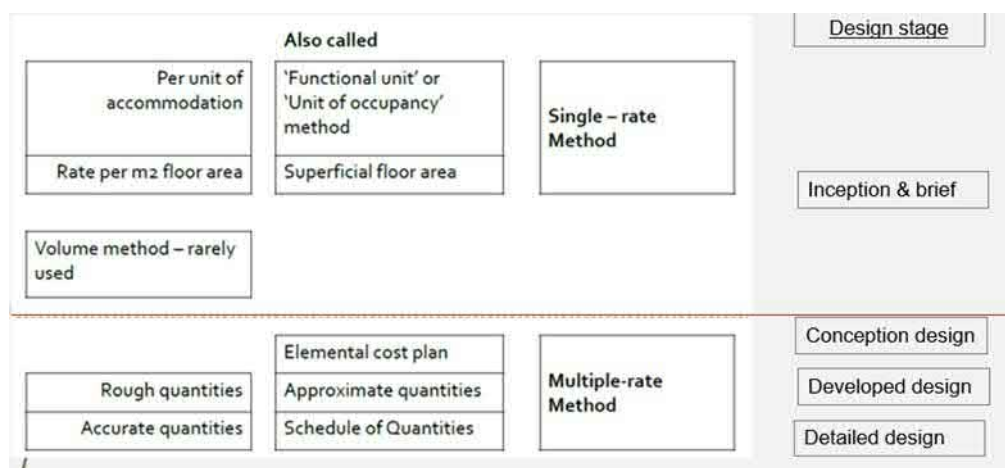


Figure 1: Summary of Rate Methods

Each construction project is unique. When building up the rate, the accuracy and completeness of design information, building functions, expected quality standards, quantities of the elements, site conditions, and contingency are the items to be considered (Smith, Jaggar & Love, 2016).

Price Index Methods

Price index methods heavily rely on the cost information and trend of cost movement over a period of time., since building costs, market conditions and inflation etc will change during this period of time. The collected data therefore, must be converted to a current date or appropriate future timescale. Under the price index method, the conversion process is achieved by means of index numbers. which measures the change that has occurred from one period to other period.

Ashworth and Perera (2015) mentioned the tender index included weighted items (factors affected tender price) in the order of their importance within the index based upon ‘the basket of goods’ principle.

Figure 2 below indicates the most prominent indices available in global context.

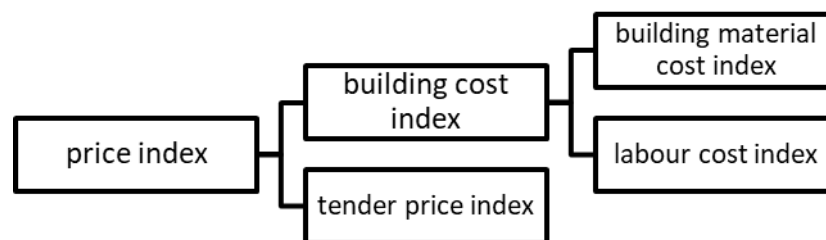


Figure 2: Summary of Price Index Methods

The building cost index measures the change in contractor's costs. It is built up on a combination of labour costs, material costs, plant/equipment and overhead expenses (Smith, Jaggar & Love, 2016). Some countries may not have building cost index, only material cost index and labour cost index are available. Comparing with building cost index, material cost index and labour cost index can only measure the trend of material cost or labour cost, they can't provide the pattern of overall changes in contractor's cost.

The tender price index is based on what the client prepares to pay for the building. It therefore besides all the items covered by building cost index, it also considers the allowance of market conditions and profit margin, and the reflection of cost fluctuations. From client's perspective, the tender price index focuses on the tendering market, hence much more useful in updating the prices in a design budget (Flemming & Tysoe, 2007).

Factors Affecting Tender Price Accuracy

Many researchers have studied the factors influencing tender price and tried to categorize and rank them. The discussion below covers the main groups of factors that could affect the tender price.

Factors Related To Project Characteristics

It is widely accepted that this group of the factors has strong impact on the accuracy of the tender price. The factors in this category could include but not limit to buildability, scale of project, construction techniques, location, programme, access, and structural type as well (Ji et al, 2014). Most of the researchers have identified project scale & scope, location and buildability are the top three factors affecting the accuracy of tender price (Akintome, 2000; Dysert, 2006; Elhag et al, 2005). The project scale and scope determine the project size, complexity, duration, and construction methodology and inevitably affects the project cost (Ashworth & Perera, 2015), in addition, the more complicated and larger the project is, the

long project duration would be, which levels up the risk of over budget of onsite and offsite expenses (Akintoye, 2000). Location has tight link with the delivery cost (Ji et al, 2014). However, the proposed research only studies Auckland market, hence the location within Auckland Region does not have too much difference.

Factors Related To Client Characteristics

Client is the core of a construction project. The client determines each element of the project delivery. The research of the impact of the client characteristics points out every client is unique, hence, the clients could be categorized to different groups as shown from Figure 3. Depends on the category that the client belongs to, the client has different attitude towards the project (Masterman, 2001).

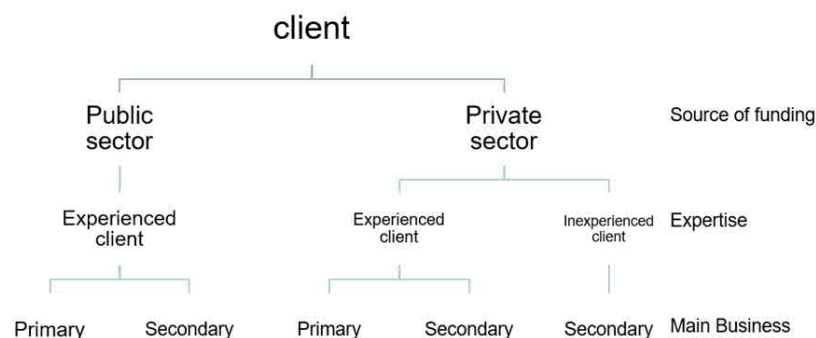


Figure 3: Client Categories

Besides the client category as discussed above, the client's experience and expertise, the budget that the client is afford to, the functionality requirement, the quality expectation, the time allowance of the construction project are the factors need to be considered carefully (Akintome, 2000; Ashworh & Perera, 2015; Dysert,2006; Elhag et al, 2005; Masterman, 2001).

In particular, the proposed research focuses on the client from public sector. The public sector clients whose primary business was construction were always experienced. They have detailed knowledge and understanding of construction project delivery process, they have sufficient expertise in managing and controlling construction projects, very highly likely there are in-house construction managers, and/or designers. As the result, they are with ability to “produce a comprehensive initial brief incorporating prioritized objective for the project's time, cost, quality and functionality” (Masterman, 2001).

Factors Related to Design Parameters

The factors in this category include but not limit to completeness and comprehensiveness of the design information, accuracy of the design information, designer's experience and expertise, availability of historical data, procedure of updating information, and the time allowance of preparing the design (Dysert,2006; Elhag et al, 2005). The completeness, comprehensiveness and accuracy of the design information are the crucial factors in this category (Ashworth and Perera, 2015). Poor design or insufficient design information could significantly affect the accuracy of the tendering price, as the estimate of tender price must be based upon the available information, vague or incorrect design parameter means the estimator is unable to get the accurate data retrieved from the design documents (Akintoye, 2000). Poor design would lead to more project variations, since there's higher potential of design change at the construction stage (Ji et al, 2014).

External Factors and Market Conditions

This group of the factors include the cost, availability and supply of the material, labour and equipment, stability of the market conditions, the labour productivity, the government policy, level of competition (Akintoye, 2000; Dysert, 2006; Odusami and Onukwube, 2008). The researchers strongly accept that the first three factors are the key factors in this group. The market competition will induce low tender price.

Knowledge Gap in Existing Literature

Although there are studies of the factors affecting the tender price accuracy in overseas context, studies about public housing projects in New Zealand remain little to none. Therefore, this study intends to fill the gap by exploring the factors affecting public housing project tender price in Auckland, New Zealand.

Research Methodology

This research was conducted to establish the perceptions towards the factors and bias affect the accuracy of public housing tender price in Auckland, New Zealand. A 3-step approach was applied.

Firstly, the researcher reviewed literature resources, identified the key factors that could affect tender price accuracy, as shown in Table 1. Secondly, a 5-point Likert scale questionnaire survey was conducted. The researcher collected the data from the experts with public housing project tender experience. Their opinions of the importance of the identified factors were gathered in this step. Lastly, the researcher used percentage method to analyse the participant's profiles, whilst the mean value analysis (MVA) method was conducted to rank and identify the importance of the factors.

The method for establishing the perceptions of a targeted group is the questionnaire survey. This is especially applicable to this research topic as the data collected is expected to reflect the industrial insights and opinions of the clients of the public housing projects. The questionnaire generates standardised answer from the pre-written questions, it allows the participants to choose and rank what are the factors affect tender price accuracy.

The questionnaire survey includes three parts. The first part focuses on the participants' profiles. The second part collects information of the participants' public housing project tender practice. The last part concentrates on the data of the participants' opinions of the factors affecting the accuracy of the public housing tender price.

Two participants were invited to test the questionnaire before it was published. Based upon their responses, some questions were modified to help the other participants' better understanding of the questions. The questionnaire was administered through Massey University's Qualtrics Survey platform from October 2021 to December 2021.

Non-random purposive sampling was used to select the sample to ensure the appropriate number of the candidates were interviewed (Denscombe, 2007). The questionnaire participants defined in the research question are the quantity surveyors with public housing project tendering experience in New Zealand. Moreover, the convenience sampling approach was adopted to collect responses. The researcher invited the colleagues and the clients with at least five years public housing project tender experience to be the questionnaire participants. With consideration of the experience of the participants in public housing project, the researcher expected that they had connections with other potential respondents, therefore some of the them were asked to distribute the survey as well.

Table 1: List of Factors Affecting Tender Price Accuracy From Literature

Group	Factor
Client Characteristic	Client's experience & expertise Client's budget Client's quality expectation Client's building function requirement
Design Parameter	Comprehensiveness of design information Accuracy of design information Completeness of design information Timely information update time allowance of preparing the design designer's experience and expertise
External factors and market conditions	Material cost labour cost plant cost material supply labour supply Market stability Inflation rate Exchange rate government policy
Project Charaterristic	Project scope Project scale Complexity of project construction methodology Project location Project timeframe Building structure

Sources: (Akindome, 2000; Ashworth & Perera, 2015; Dysert,2006; Elhag et al, 2005; Ji et al, 2014; Odusami & Onukwube,2008)

All 41 respondents are quantity surveyors with at least 5 years public housing project tendering experience. As shown from Figure 4 below, 20% of the respondents have 5 years research required experience, 48% of them have 6-10 years relevant experience, 26% of the respondents have 11-15 years public housing experience, whilst 3% have 21-25 years experience and 3% have 25+ years needed experience. The respondents are well balanced. The participants' quantity surveyor roles and public housing tendering experience would ensure rich and comprehensive data collection.

Although a total of 41 responses were received through Qualtrics Survey, 10 respondents didn't answer all questions. To keep from the bias of the result, these 10 responses were excluded from the data analysis.

The participants characteristics data and the general tender information data were analysed by using percentage method. The researcher calculated the percentage of respondents' answer to recognize the demographics information and the general practice of the public housing projects.

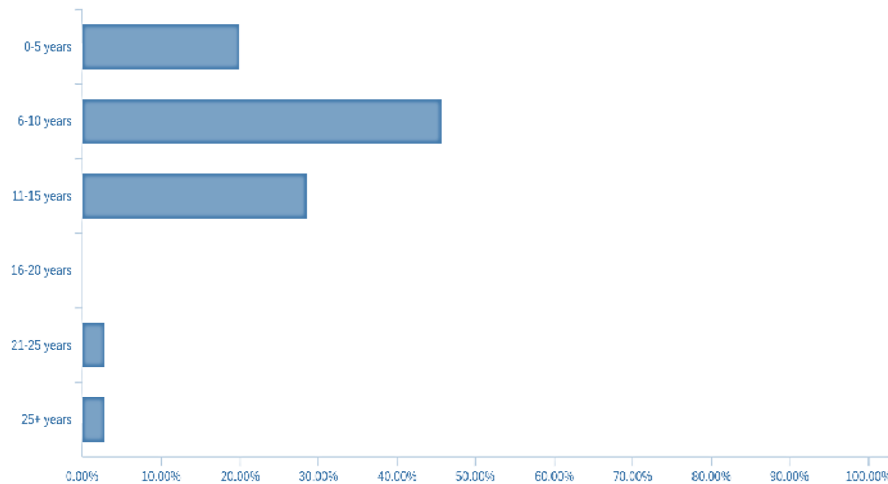


Figure 4: Years of public housing project tendering experience

The data affecting accuracy of the tender price was analysed by using mean value analysis (MVA) method, as it is considered an reliable and acceptable method for ranking factors (Jain, 2008).the researcher started from calculating the mean value of each factor identified by the respondents, In accordance with the calculated mean value, the researcher ranked factors affecting accuracy of the public housing project tender price.

Findings and Discussion

Public Housing Project Tendering Characteristics

The questionnaire asks respondents to indicate the frequency of various tendering method they used and the bias between the tender price and the actual project cost. Their overall responses are identified in Table 2 below.

Table 2: Tendering Methods And Tendering Cost Data Resources Used in Public Housing Projects

[1=never, 2= rarely, 3=sometimes, 4= frequently, 5=always]	1	2	3	4	5
Tendering Methods Used in Public Housing Projects					
Negotiate Tender Method	10%	43.33%	43.33%	3.34%	0%
Single-Stage Tender Method	0%	0%	80.65%	19.35%	0%
Two-Stage Tender Method	53.33%	43.33%	3.34%	0%	0%
Tendering Cost DataResources					
Client's Own Historical Database	0%	0%	0%	19.35%	80.65%
Quote From Sub-Contractors And Suppliers	0%	0%	6.45%	32.26%	61.29%
QV Costbuild Database	41.94%	48.39%	9.68%	0%	0%
Statistics NZ Labour Cost Index	100%	0%	0%	0%	0%
Statistics NZ Material Cost Index	100%	0%	0%	0%	0%
Statistics NZ Consumer Price Index	100%	0%	0%	0%	0%

The single-stage tender method is the most often used tender method. 80.65% of the respondents use this method frequently, and rest of the 19.35% participants use this tender method only. Besides, the respondents'organisations pick up negotiated tender methods sometimes. The two-stage tender method is used least often, over half of the respondents never adopt two-stage tender method, and 43.33% of them pick up rarely option. With consideration

of the features of the negotiated tender method and single-stage tender method, the tender price excludes client's project development cost and design cost (Morledge & Smith, 2013).

Clients' own historical cost database and the quotes from sub-contractors and suppliers are the main cost data resources used for the public housing projects. QV Costbuilder data might be referred occasionally, but no respondents adopted any cost index published by Statistics New Zealand. The clients' own cost data and the quotes from subcontractor and supplier are sufficient when using rate methods to form tender price (Ashworth and Perera, 2015; Dysert, 2003), however for the tender cost estimate by using index methods, they are not able to provide the required information to catch the trend of cost movement (Ashworth Perera, 2015; Department for Business Innovation & Skills (UK), 2020). Hence, in accordance with the responses, rate methods are the very dominant cost estimate methods of the public housing projects in Auckland.

The questionnaire asks respondents to indicate the level of deviation of the actual project cost from the tender price also. As identified in Table 3 below, the bias of most of the projects falls to the range 6-10%. This range covers over 70% of the standalone houses and detached houses cost deviation, 58.06% of the townhouse, and 45.16% of the apartment unit as well.

Table 3: Bias of Tender Price

[1=0-5%, 2= 6-10%, 3=11-20%, 4= 21-30%, 5=31-50%]	1	2	3	4	5
Standalone House	12.90%	70.97%	9.68%	6.45%	0%
Detached House	12.90%	74.19%	6.45%	6.45%	0%
Townhouse	3.23%	58.06%	32.26%	6.45%	0%
Apartment Unit	3.23%	45.16%	48.39%	3.23%	0%

Moreover, in accordance with the responses, there is higher chance that the townhouse and apartment unit exceed higher percentage of the budget based upon the tender price. 32.26% of the townhouse and 48.39% of the apartment unit could have 11-20% cost overrun. Whilst only 9.68% of the standalone house and 6.45% of the detached house are within this range.

Ranking of Factors Affecting Accuracy Of The Public Housing Project Tender Price

Mean value analysis is adopted to rank factors by the descending ranking order. The order of the mean value reflects the importance of the factors. As shown in Table 4, external factors & market conditions, design parameter are the top two categories of factors that would affect the accuracy of the tender price. The findings are similar to the studies of tender accuracy of other types of the construction projects (Ashworth and Perera, 2015).

Although a total of 41 responses were received through Qualtrics Survey, 10 respondents didn't answer all questions. To keep from the bias of the result, these 10 responses were excluded from the data analysis.

The participants characteristics data and the general tender information data were analysed by using percentage method. The researcher calculated the percentage of respondents' answer to recognize the demographics information and the general practice of the public housing projects.

Material cost, labour cost and plant cost form the first tier of the factor importance. They are all with mean value 5.00. The finding is the same as the result of a lot of researchers' work so far. The researchers all agree these three factors are the fundamental and essential elements of the cost buildup for any type of the construction project, and a major portion of the project cost price is from them (Akintoye, 2000; Dysert, 2006; Elhag et al, 2005; Liu and Zhu, 2007).



Table 4: Rank of Factors Affecting The Accuracy of The Public Housing Project Tender Price

Group	Factor	Rank	Mean Value
External Factors And Market Conditions	Material Cost	1	5.00
External Factors And Market Conditions	Labour Cost	2	5.00
External Factors And Market Conditions	Plant Cost	3	5.00
Design Parameter	Comprehensiveness Of Design Information	4	4.90
Design Parameter	Accuracy Of Design Information	5	4.74
Design Parameter	Completeness Of Design Information	6	4.65
Design Parameter	Timely Information Update	7	4.48
External Factors And Market Conditions	Material Supply	8	4.10
External Factors And Market Conditions	Labour Supply	9	4.10
Project Charaterristic	Project Scope	10	3.71
Design Parameter	Time Allowance Of Preparing The Design	11	3.71
Design Parameter	Designer's Experience And Expertise	12	3.61
External Factors And Market Conditions	Market Stability	13	3.59
Project Charaterristic	Project Scale	14	3.26
Client Characteristic	Client's Experience & Expertise	15	2.87
External Factors And Market Conditions	Inflation Rate	16	2.77
Client Characteristic	Client's Budget	17	2.62
Project Charaterristic	Complexity Of Project	18	2.58
External Factors And Market Conditions	Exchange Rate	19	2.55
Client Characteristic	Client's Quality Expectation	20	2.45
Project Charaterristic	Construction Methodology	21	2.42
Client Characteristic	Client's Building Function Requirement	22	2.39
Project Charaterristic	Project Location	23	2.29
Project Charaterristic	Project Timeframe	24	2.29
Project Charaterristic	Building Structure	25	2.19
External Factors And Market Conditions	Government Policy	26	2.03

The second tier of the factors include comprehensiveness of design information (mean value 4.90), accuracy of design information (mean value 4.74), and completeness of design information (mean value 4.65) as well. They are all from design paprameter category. The completeness. comprehensiveness and accuracy of the design information are the crucial factors in this category. Poor design or insufficient design information could significantly affect the accuracy of the tendering price, as the estimate of tender price is based upon the available information, vague or incorrect design parameter means the estimator is unable to get the accurate data retrieved from the design documents (Akintoye, 2000; Ashworth and Perera (2015)). Mbachu (2014) pointed out that poor design would lead to more variation, since there's higher potential of design change at the construction stage.

Amongst the factors listed in Table 4, although a lot of researchers have identified location is one of the factors affecting the accuracy of tender price greatly (Akintome, 2000; Dysert,2006;

Elhag et al, 2005), as location has tight link with the delivery cost (Ji et al, 2014), this research only studies Auckland market, hence the locations within Auckland Region does not have much difference.

Conclusion

Although construction project's cost estimate can't be 100% accurate (Flanagan & Norman, 1983), a reasonably accurate tender price provides significant value to the quantity surveyor in providing a reasonably realistic construction project price prediction to help the client to check the public housing project feasibility and ensure the project cost is under the budget.

Hence, identifying the factors that could affect the accuracy of the public housing projects is the first step. This study has found that the accuracy of tender price could be affected by project characteristics, design parameters, external factors and market conditions, and client characteristics. The material cost, labour cost and plant cost from external factors and market condition category contribute significant portion of the accuracy of the project tender price. Besides, the quality of the design documents could have deep impact too.

The researcher has found a gap of the current public housing tendering practice also. The current public housing project tendering price relies on the actual cost data retrieved from design documents and historical database, plus the way cost estimators use tender pricing resources, the current tender practice is adoption of the rate methods only. Rate methods are effective but time consuming, hence, they are not efficient. Price index methods are more efficient than the rate methods (Flemming and Tysoe, 2007). There is no existing tender price index (TPI) in New Zealand context so far. The future research could focus on developing a TPI system to achieve the target of efficiency.

The data collected from questionnaire is subjective, participants could measure the factors importance on their own subjective opinion. There's no guarantee that the data collected so far fully reflect the opinion and sound of the whole public housing sector in the context of Auckland, New Zealand. To overcome the limitation, the researcher would invite more eligible experts to complete the questionnaire. The more sampling the researcher collects, the less bias of the result would occur.

References

- Akintoye, A. (2000). Analysis of factors influencing project cost estimating practice. *Construction Management & Economics*, 18(1), 77–89. doi: 10.1080/014461900370979
- Ashworth, A., Hogg, K and Higgs, C. (2013). *Willis's Practice and Procedure for the Quantity Surveyor (13th Ed)*. Chichester, UK: John Wiley & Sons Inc.
- Ashworth, A & Perera, S (2015). *Cost studies of buildings (6th ed)*. New York, US: Routledge
- Department for Business Innovation & Skills (UK). (2020). Construction Tender Price Indices (TPIs) notes and definitions. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/36851/tender-price-indices-methodology-and-revision-policy.pdf
- Dysert, L. R. (2003). Sharpen Your Cost Estimating Skills. *Cost Engineering* 45(6), 108.
- Dysert, L. R. (2006). Is "Estimate Accuracy" an Oxymoron? 2006 *AACE International Transactions*, 1–5
- Elhag, T. M. S., Boussabaine, A. H., & Ballal, T. M. A. (2005). Critical determinants of construction tendering costs: Quantity surveyors' standpoint. *International Journal of Project Management*, 23(7), 538–545. doi: 10.1016/j.ijproman.2005.04.002.
- Flanagan, R., & Norman, G. (1983). The accuracy and monitoring of quantity surveyors' price forecasting for building work. *Construction Management & Economics*, 1(2)
- Fleming, M.C. & Tysoe, B.A. (2007). *Spon's construction price and cost index handbook*. New York, US: Taylor & Francis Group

- Jain, R. (2008) Mean value analysis and related techniques. Retrieved from https://www.cs.wustl.edu/~jain/cse567-08/ftp/k_34mva.pdf
- Ji, C., Mbachu, J., & Domingo, N. (2014). Factors influencing the accuracy of pre-contract stage estimation of final contract price in New Zealand. *International Journal of Construction Supply Chain Management*, 4(2), 51-64. DOI: 10.14424/ijcscm402014-51-6
- Kāinga Ora (2021). Large-scale projects. Retrieved from <https://kaingaora.govt.nz/developments-and-programmes/what-were-building/large-scale-projects/>
- Liu, L., & Zhu, K. (2007). Improving Cost Estimates of Construction Projects Using Phased Cost Factors. *Journal of Construction Engineering & Management*, 133(1), 91–95. doi: 10.1061/(asce)0733-9364(2007)133:1(91)
- Masterman, J (2001). *Introduction to Building Procurement Systems*. Taylor & Francis, 2001. ProQuest Ebook Central, <http://ebookcentral.proquest.com/lib/unitec/detail.action?docID=180520>
- Morledge, R., & Smith, A. (2013). *Building Procurement (2nd Ed)*. Chichester, West Sussex, UK: Wiley-Blackwell
- Odusami, K. T., & Onukwube, H. N. (2008). Factors Affecting the Accuracy of a Pre-Tender Cost Estimate in Nigeria. *Cost Engineering*, 50(9), 32–35
- Smith, J., Jaggard, D., and Love, P (2016). *Building Cost Planning for the Design Team (3rd Ed)*. London, UK: Routledge

Health and Safety Outlook of Offsite Construction (OSC)

Mohit Pahuja and Wajiha Mohsin Shahzad*

School of Built Environment, Massey University, Auckland, New Zealand.

*Corresponding author: mohit.pahuja18@hotmail.com

Abstract

The construction industry is labour intensive, regarded as one of the riskiest industries to work in. The need to improve health and safety conditions for construction workers has prompted construction industry leaders across the globe to adopt many safe practices, including the shift to partial or complete offsite manufacturing of building components or offsite construction. The offsite construction (OSC) approach is deemed to have all positives regarding the health and safety of construction workers, and many researchers have investigated the health and safety benefits of offsite construction. However, hardly any study has looked into the health and safety pros and cons of the offsite construction approach. This study aims to provide an in-depth analysis of health and safety issues in offsite construction. It discusses both positive and negative aspects of this construction approach. The study uses a qualitative research approach and in depth literature review has been carried out to achieve research objectives. The study identifies many benefits of offsite construction in the context of some specific activities. It also reveals that despite various nations promoting offsite construction strategies for their health and safety benefits, there are still several health and safety hazards associated with this approach. This study has identified the types of injuries, causes of accidents, and activities and equipment involved in accidents in all the stages of offsite construction. The study also presents mitigation steps to minimise further the health and safety hazards for construction workers using offsite construction. The findings of this study will provide a better understanding of the health and safety hazards associated with offsite construction.

Keywords

Construction, Construction workers, Health & Safety, Offsite Construction, Prefabrication.

Introduction

The construction industry is considered one of the riskiest industries worldwide. This industry is a paradox but at the same time, it is a very crucial industry that contributes significantly to the economic well-being of any nation (Laubier *et al.* 2019). In Construction processes, when workers feel unsafe on sites, it becomes a part of emotional debates. Risks and hazards are poorly managed and not looked after properly, across the construction sector, thereby, resulting in negative health and safety outcomes. The life of construction workers can become worse if appropriate health and safety measures are not put in place or if health and safety measures are ignored (Emuze and Smallwood 2017). Unsafe working conditions are one of the main reasons that a large number of people willing are not willing to work in the construction industry. There is an overarching need for the improvement of health and safety culture in the construction industry (McKay 2010).

The two main approaches used for building works are (i) onsite or traditional construction approach, and (ii) offsite construction. In the traditional style of onsite construction, all the construction processes are carried out on the site, whereas in offsite construction (OSC), the manufacturing takes place in a controlled environment like a factory setting with the help of specialized machinery and skilled labour (Darlow *et al.* 2021, Shahzad and Mbachu 2013 and Cunningham 2011). OSC involves three key stages: (i) Manufacturing, (ii) Transportation, and (iii) Assembly (Behera 2020). The offsite approach of construction is sometimes referred to as offsite manufacturing (OSM), industrialised buildings systems (IBS), and prefabrication (Franks, 2018). Research suggest that there are health and safety issues and greater chances of accidents and fatalities in the onsite method of construction. On the other hand, in offsite approach, the construction processes are carried out in a controlled environment that reduces the health and safety risks to a great extent by monitoring the health and safety compliance requirements (Shahzad and Rasheed 2019). The construction industry is expanding exponentially and the level of development worldwide has made the significance of health and safety in the industry more prominent than before (Ahmad and Ahmad 2019). There have been several studies in the past discussing the impact of offsite construction on the health and safety in construction. There have been discussions regarding the use of the offsite construction method to address the health and safety issues in the construction industry but this is anecdotal without any evidence. Most of the studies claimed to have offsite construction being safer due to several reasons like manufacturing at one location, no effects of extreme weather conditions, and easy to control the procedures that are unsafe (Darlow *et al.* 2021). Even though there are benefits of offsite construction, there are a few risks and hazards associated with this method as well that pose danger to health and safety of the workers. There is a need to prioritize health and safety and be cautious about the changes in risks and hazards in offsite construction methods as well (McKay 2010).

This paper will discuss the positive impact of the offsite method on health and safety in the construction industry and the prevailing health and safety issues in the offsite method that should be addressed by the industry. It also highlights the research objectives, methodology, and in-depth literature review of previous studies. The specific objectives of this research include (i) identification of the potential health and safety issues associated with offsite construction, (ii) investigating the factors that can lead to health and safety issues in offsite construction, and (iii) recommending the solutions to further improve the health and safety in the offsite construction method.

Overview of Health and Safety in Construction Industry

The economy of any country is largely impacted by the construction industry as it provides employment to a large number of people. But at the same time, it is the riskiest industry worldwide with a maximum number of incidents and fatalities occurring each day. According to one of the surveys carried out by Construction Health and Safety New Zealand (CHASNZ), in the construction industry neither workers nor employers feel safe when carrying out their jobs (CHASNZ 2020). Fatality rates are recorded to be highest in the construction industries of Australia, New Zealand, Turkey, the United Kingdom, and the United States of America compared to other industries in these countries. Australia reported 417 deaths in the construction industry between the year 2002-03 to 2013-14 which accounted for 12% of the total deaths in a workplace and was the highest for any single industry (Kamardeen 2019). Similarly, in New Zealand, 71 deaths were reported in the construction sector between the year 2012 to 2019 which was the highest fatality rate for anyone industry (Pennington 2020).

The major cause of increasing risks in construction jobs is falling objects. There is huge scope for improving the health and safety in construction with help of available data from previous research and by the creation of tools and strategies (Kamardeen 2019). The ever-increasing jobs in the construction industry have made the health and safety of workers even more important than before. Health and safety are adversely affected due to the environment leading to poor performance which in turn leads to injuries, accidents, and fatalities (Bikitsha 2010).

Health and Safety in Offsite Construction (OSC)

The foundation for the explanation of offsite construction being safer is that there are fewer activities that are performed on the project site under unsafe working conditions, thereby, reducing the chances of accidents on site. As a result of this, alternative activities are performed in a controlled environment where previous hazards are completely eliminated or replaced by safer practices (Franks 2018). For instance, replacing the work at heights to ground and moving processes from on-site to manufacturing units. Offsite construction also enforces discipline which further enhances health and safety (McKay 2010).

According to Gibb (2003), “The factory environment enables responsible manufacturers to make appropriate provision for the health and safety of their workforce. The onus on-site construction employers are just as great, but their task is more demanding because under site conditions it is far harder to eliminate the hazards or control risks”.

The project manager and his team with the help of offsite technology can mould and organize the project accordingly, so as to reduce the risks and hazards, thereby increasing efficiency (Richard 2017). OSC must be treated from a holistic perspective rather than on an element-by-element basis. There are several benefits of offsite construction in regards to health and safety including but not limited to: less time is spent by workers on the project site, productivity is enhanced due to controlled environment in a factory setting, there is less waste and noise produced in factory environment, cutting and welding processes are safer as all such activities are carried out in designated work stations (McKay 2010 and Bikitsha 2010).

There is a reduction in hazards in offsite construction as compared to onsite construction for example, in the case of concrete mixing, workers are actively involved in handling of materials which includes heavy lifting, frequent bending, and twisting, thereby increasing chances of muscular injuries. Moreover, concrete mixing and pouring on the project site requires vibrating the concrete by workers which can lead to vibration syndrome. This syndrome can cause damage to the nerves, muscles, and blood vessels leading to disabilities. All these exposures are eliminated in offsite construction (McKay *et al.* 2005).

The offsite construction means better safety conditions in the construction industry and ease of safety management in construction projects. McGraw Hill conducted a survey among construction companies of different sizes and found that 63% of big companies were more optimistic about the positive impact of offsite construction on safety whereas only 37% of small-scale companies thought safety is positively affected by the adoption of offsite construction.

Health and safety risk identification can boost the productivity of organisation by bringing down the number of accidents. It is observed that offsite construction improves safety on the site and workers feel much safer working in offsite construction manufacturing facilities. Bikitsha and Haupt (2011) documented that people involved in construction activities like site managers, agents, and foremen felt that they are more exposed during onsite construction activities as compared to offsite construction. Their findings confirmed that reduction in health and safety hazards in offsite construction manufacturing is attributed to the like hazards related to ergonomics, material handling, and environment. Steel reinforcement hazards are greatly

reduced in factory-controlled conditions. This approach also eliminates the use of scaffolding which reduces the danger of falling from heights.

Research Methodology

The objectives of this research are achieved by conducting an in-depth literature review and meta-analysis. A lot of research is conducted every year with multiple finding dimensions. The knowledge of an author is represented by literature review in a particular field which in turn helps in providing the right information to future researchers to carry out research.

A detailed and systematic review of the literature aims to address the issues by adopting the method of identification, evaluation, and integration. The basic idea behind this approach is to provide a vast overview to readers at large (Jin *et al.* 2018 and Aboagye-Nimo 2018 and Bhatia 2018). The literature review followed the following stages to achieve research objectives:

- (i) Scoping stage: During this stage, the required questions were prepared to attain the desired research results.
- (ii) Planning stage: The research questions were broken down at this stage to determine which article is relevant to the topic and which one is not. Research keywords were confirmed at this stage.
- (iii) Identification: In this stage, the databases were searched using the keywords and inspection of the outcomes of the search was also carried out.
- (iv) Screening: During the screening stage, all the research results were collated in one place.
- (iv) Eligibility: The texts were filtered at this stage and the relevant information related to the research was extracted from the texts.

In order to shortlist the articles, papers, and books for the review, it was necessary to consider the quality of the literature, evidences, and findings in the study. The quality of the outcomes of the research was also required to be considered for the in-depth literature review (Jin *et al.* 2018). Many keywords were used for the search of the previous research articles like health, safety, risks, hazards, offsite construction, prefabrication, precast concrete, offsite manufacturing, transportation, erection, assembly, installation, construction, industry, benefits, advantages, issues, and problems. The search strategy that was used for selecting articles in this research has been explained in Table 1.

Table 1: Article Selection Process

	Step 1: Words related to text were defined
	Step 2: Synonyms of those words were identified
	Step 3: Truncations were used
	Step 4: Relevant databases were identified
	Step 5: Search test was conducted
	Step 6: Search as per keywords carried out
	Step 7: Terms or words were logically collated
	Step 8: Search was repeated
	Step 9: Words were re-arranged for each database

Before initiating the search, exclusion, and inclusion criteria were set for the selection of research articles (Mengist et al. 2020). This criterion is presented in Table 2. This strategy for the search helped in identifying databases for collating the articles and books relevant for the research paper (Fernández *et al.* 2018).

Table 2: Inclusion and Exclusion Criteria

Criteria	Decision
Keyword present in title	Included
Articles or papers before 2008	Excluded
Articles or papers between 2008 to 2020	Included
Articles in English language	Included
Articles that were not accessible	Excluded
Papers or articles that were not original research	Included
Articles or Papers that highlighted health and safety in OSC	Included

The two things that helped in shortlisting the database and the number of databases required were: (i) type of topic and (ii) nature of the topic. The keywords that were used for search purposes are “Offsite Construction”, “Prefabrication”, “Health and Safety”, “Benefits”, and “Issues”. These keywords were searched in three databases; Scopus, Sage, and Science Direct.

Findings and Discussion

Health and Safety Issues in Offsite Construction

Even though offsite construction reduces risks that are ergonomic in nature, it might result in various hazards that can arise from work requiring repetition, contact stress, heavy lifting, and static postures (EC&M 2007). There are very few studies that discuss the dangers posed by this technology. The literature that already exist have discussed or studied fewer accidents and cases that addressed health and safety problems in offsite construction method. A survey was conducted through interviews and questionnaires by Becker in 2003 to identify the hazards posed by offsite construction to the workers. The most severe hazards are posed in roof works especially the fall of objects during installation and getting trapped in tilt-up roof (Becker *et al.* 2003 and Fard *et al.* 2017). Hazards intrinsic to offsite construction are not easily recognized. These hazards are mitigated, if not completely prevented, and can be imagined in an instinctive way with the help of offsite products and methods. But it is hard to isolate the hazards (Roughton and Crutchfield 2016 and Franks 2018).

The known pitfalls of the OSC approach are twofold. The first snag is linked to the heaviness of the elements. Proper training along with sequencing and coordination is required for handling the big and oversized parts on the site. It includes hoisting as well as rigging. The second snag is linked to processes not performed as planned and improper communication. The major problem arises when the installation procedure and its sequence are unclear and unrealistic. It is hard for workers to understand the whole program of installation due to its complexity. There is a high probability of occurrence of accidents especially the collision of elements among themselves and occasional chances of hitting the worker (Li *et al.* 2011 and Franks 2018).

In offsite construction, there are various risks exposed to workers involved in the transportation of prefabricated components (that required machinery for lifting) and their assembly on site. There are hazards that are posed by the suspension of loads at heights at the time of installation. People working under those loads are most at risk (Shahzad and Rasheed 2019).

In addition to this, lean tools are used to improve the productivity in the OSC method but at the same time, its implementation has negative effects on the health and safety of workers (Pasquire and Connolly 2002). For instance, the use of lean construction in offsite stage leads to an intensification of physical work and its pace, thereby, resulting in musculoskeletal injuries (Joel *et al.* 2014 and James *et al.* 2012).

Occurance of Accidents During OSC

The three main stages of offsite construction are manufacturing in factory, transportation of the components (transit), and assembly or installation on project site. Accidents in offsite construction can occur in all three stages. Franks (2018) reported that most accidents or fatalities during OSC occur during the installation process that takes place on site. The number of accidents taking place inside the factory during the manufacturing process is very few compared to onsite accidents and resulting fatalities. The least number of accidents are reported during the transit of manufactured components from factories to the site.

Fard *et al.* (2017) investigated the frequencies of various types of injuries happening during the manufacturing stage and onsite assembly. It was observed that ‘amputations’ and ‘fractures’ were the most common types of injuries taking place in the manufacturing stage, the highest reported injury on-site during the assembly process in ‘fractures’ and the number of ‘amputations’ is very less during the assembly process.

Cause of Accidents or Injuries in OSC

The literature suggests that causes of accidents of injuries can be categorized into direct causes and indirect causes. Knowing these causes helps in understanding the major risks that are involved in offsite construction which in turn helps in developing and following a program that is preventive in nature. According to (Fard *et al.* 2017), ‘falls’ are one of the major causes of injuries and accidents in offsite construction. Similar observations are made by CHASNZ (CHASNZ 2012). Another major cause of injuries is being stuck by an object or equipment. Some other causes of injuries include; heatstroke, electrocution, hit by construction equipment, but these factors account for very few accidents.

The study (Fard *et al.* 2017) reported that during onsite assembly falls caused almost half of all the reported accidents followed by being struck by objects or equipment. The trend was similar to the offsite construction considered as a whole.

Franks (2018) conducted a survey and the results were very similar to the ones discussed above. In this study, various factors were identified that can lead to fatalities or injuries in offsite construction including fall, electrocution, crushed-by heavy materials or equipment, caught between the equipment, and being struck by something. The main cause however is ‘fall from height’ which accounts for 38% of the total injuries or deaths in offsite construction closely followed by getting crushed by machinery or heavy components and accounts for 37% of the injuries. But in the manufacturing unit, getting crushed is the major cause of accidents and accounts for nearly half of the cases. The next major cause is being struck by and 20% of the accidents recorded are caused by this factor.

It is important to consider the activity being performed at the time of the accident in offsite construction. It helps to understand the pattern, so as to take the appropriate actions in order to boost the health and safety in offsite construction. Franks (2018) also did a survey on this crucial part of health and safety. As per findings, work related to connections was more prone to accidents. 27% of the accidents occurred at the time when connection work was being done by the worker. Moving or lowering work was performed 19% of the time at the time of

accidents. Activities being performed at the time of the accident are also reported and it is noted that within the manufacturing unit, most accidents occurred at the time of loading closely followed by hoisting. On the other hand, on a construction site where assembly and installation are carried out, it is found that there is a link between fall and connection work. It is important to understand that the activity performed is not the actual cause of accidents but it plays a role in the identification of risks.

Components Involved in Accidents during OSC

There are various components associated with accidents in offsite construction. The main component which is mostly involved is precast walls accounting for the majority of health and safety-related accidents. This is closely followed by other precast structures and the third major component is precast structural steel which is involved in fatalities or accidents. The contribution of precast concrete structures is more than half of the total accidents occurring in offsite construction methods (Frank 2018).

Accidents based on type of OSC buildings and Equipment used

Some studies reveal that commercial buildings score more in terms of safety standards while being constructed in a traditional manner but this is not the case in terms of offsite construction methods (Grant and Hinze, 2014). Usually, heavy prefabricated elements or components are involved in commercial buildings as compared to residential houses and small-sized and single or double-level buildings (Fard et al. 2017). Similarly, accidents in offsite construction can also be differentiated on the basis of the equipment involved. According to Fard et al. (2017) out of all the accidents that occurred in the offsite method of construction, involvement of equipment accounted for 27% and involvement of forklift in the accidents was the most with the frequency of 23.5% followed by saws accounting for 20.6%. Crane accounted for 8.8% of the accidents.

Factors leading to causes of accidents

There are several factors that could ultimately cause accidents, thereby leading to injuries and fatalities in different stages of offsite construction.

Factors in Manufacturing

The main factor that can cause accidents in the factory are the breaking of the components at the time of manufacturing. This can result from errors in designing or manufacturing. For example, precast concrete components can break at the time of manufacturing. This can happen due to design errors, transport and rotating stresses not being handled adequately and anchors being used for lifting and steel reinforcement are not installed properly.

Another factor that can lead to fatalities is musculoskeletal injuries that can occur at the time of handling heavy elements in the factory (McKay 2010). This can result from improper techniques being used for handling purposes. Moreover, prolonged exposure to harmful substances at dangerous levels can also lead to fatalities. This can be the result of not using measures for minimizing exposure to such substances (Worksafe 2018).

Factors in Handling and Transporting

The most important factor that can cause accidents in this stage is the fall or collapse of the elements leading to injuries by crushing. This can happen if elements are not stored appropriately (frames for carrying the elements are not maintained). In addition to this, overloaded and unsecured frames can also lead to the fall of elements. In the case of concrete,

there is a risk of vehicles used for transportation getting toppled due to the center of gravity of concrete being very high. Narrow access to the site, unfavorable ground conditions, and uneven surface can misbalance the vehicle making it unstable (Worksafe 2018).

In this stage too, it is highly likely that workers suffer from musculoskeletal injuries and exposure to harmful substances at alarming levels. Injuries occur due to bad techniques being used for handling of the components and exposure occurs at the handling sub-stage when components are contaminated with harmful substances. For instance, exposure occurs when precast concrete is handled while it is still in contact with chemicals being used for curing. Another factor is the fall. Workers are at risk of falling from height. This happens when proper and adequate equipment is not put for use and inspected to reduce the risks and hazards of falls from height (Kamardeen 2019).

Factors in Assembly or Installation

In this stage, fall and collapse cause major accidents and injuries related to crushing. This happens when elements collapse and it is out of control to handle the situation or when a worker gets stuck between elements and equipment or between two elements. This situation arises when there is a collapse of the structure or when temporary works like scaffolding or formwork collapse. It is also a result of extreme or bad weather and damaged elements. Another factor is associated with rigging. For example, in the case of precast concrete, panels fail as a result of rigging failure and this situation is a result of poor design for rigging with inadequate capacity, improper assembly of rigging and not using recommended ways for lifting (Frank 2018).

The most common factor in the installation stage is the overhead and underground services like water gas and overhead cables. Injuries occur as a result of damage to cables laid underground, sewerage pipes, and other pipelines. Most risks arise when overhead cables are hit while moving the prefabricated elements like concrete panels or timber walls. There are chances of accidents occurring if outdated marking for services is referred (Li et al. 2011). It is evident that accidents and injuries occur due to exposure to harmful substances for a long time and workers fall from a height like in the previous two stages. In addition to this, in the installation stage, risks also arise from vehicles on site. This is a result of improper signage on-site, nonavailability of designated loading or unloading area, and use of damaged vehicles (Worksafe 2018).

Mitigation Steps for Health and Safety Risks in Different Stages of OSC

It is observed that during the manufacturing stage of OSC in a factory setting, health and safety-related issues can be avoided by educating the factory workers about the health and safety practices with an emphasis on why these practices are important (Smith and Quale 2017). It is critical to ensure that all the equipment used in the manufacturing process is laid out properly and is maintained regularly to avoid any accidents and that the machine operators are trained to ensure safe practices (McKay 2010 and Worksafe 2018). During the handling and transition of manufactured components precautions must be taken to only employ trained workers and operators to operate lifting machinery like cranes (Bikitsha 2010). The transportation of components should meet the safety legislations of other road users. For this, the transportation process needs to be planned appropriately and appropriate transportation permits must be obtained. For assembly or installation of the manufactured component on site, appropriate equipment must be used and trained operators must carry out the lifting and assembling tasks. A Contingency plan for bad weather conditions should be prepared in advance.

Conclusion

The study concludes that although OSC has been proved to be a safer approach to construction compared to traditional construction methods, and uptake of OSC can significantly reduce the number of accidents but OSC is not a fully safe approach to construction. There are various factors that lead to health and safety hazards during the offsite method. If proper health and safety framework is not put in place of OSC, accidents can occur at any stage of offsite construction. It is however clear that the trend of accidents and injuries in offsite construction is different from the ones that occur in traditional construction projects.

It has been concluded in this paper that the different stages of offsite construction have a different trend of injuries, accidents, equipment involved, and activities are undertaken at the time of accidents. The trend in each stage is also dependent on the type of building being constructed.

As discussed, there is very less research carried out in this area, and the ones which have been done do not cover all the issues. It is recommended that all stages of offsite construction are empirically evaluated to identify the risks and hazards, specific to each stage of OSC. It will be beneficial if more strategies are developed to minimize the risks and hazards to avoid accidents and injuries. It is necessary to develop a detailed risk mitigation plan for an offsite method to encourage more uptake of OSC in the construction industry.

In brief, further empirical studies are needed in this area to make the offsite construction method a better strategy for adoption in the construction industry. It will further suppress the number of fatalities in the industry and make a better industry to work in.

References

- Ahmad, G. and Ahmad, S., 2019. An Investigation of the Attitudes of Health & Safety Personnel towards Safety in Construction Projects. *Archives of Occupational Health* (1), 291.
- Becker, P., Fullen, M., and Takacs, B., 2003. Safety Hazards to Workers in Modular Home Construction.
- Behera, P., 2020. Prefabricated Structures & Prefabrication – Concept, Components & Advantages. Retrieved 10/04/2020 from <https://civildigital.com/prefabricated-structuresprefabrication-concept-components-advantages-ppt/>
- Bhatia, M., 2018. Your Guide to Qualitative and Quantitative Data Analysis Methods. <https://humansofdata.atlan.com/2018/09/qualitative-quantitative-data-analysis-methods/>
- Bikitsha, L., 2010. The impact of prefabrication and pre-assembly on construction health and safety in South Africa. Cape Peninsula University of Technology, South Africa.
- Bikitsha, L., and Haupt, T., 2011. Impact of prefabrication on construction site health and safety: Perceptions of designers and contractors.
- CHASNZ., 2020. New Zealand' first Construction Data Lake: Project Whakatipu. Retrieved 13/04/2020 from <https://www.chasnz.org/project-whakatipu>
- Cunningham, P., 2011. Demystifying prefabrication. (build 124: NZS 3604:2011). Retrieved from build website: <https://www.buildmagazine.org.nz/index.php/articles/show/demystifying-prefabrication>
- Darlow, G., Rotimi, J.O. and Shahzad, W.M., 2021. Automation in New Zealand's offsite construction (OSC): a status update. Built Environment Project and Asset Management.
- Emuze, F., and Smallwood, J., 2017. Valuing People in Construction (First edition ed.): Taylor and Francis.
- Fard, M. M., Terouhid, S. A., Kibert, C. J., and Hakim, H., 2017. Safety concerns related to modular/prefabricated building construction. *International journal of injury control and safety promotion*, 24(1), 10-23. 10.1080/17457300.2015.1047865
- Fernández del Amo, I., Erkoyuncu, J. A., Roy, R., Palmarini, R., and Onoufriou, D., 2018. A systematic review of Augmented Reality content-related techniques for knowledge transfer in maintenance applications. *Computers in Industry*, 103, 47-71. 10.1016/j.compind.2018.08.007

- Franks, E., 2018. Safety and Health in Prefabricated Construction: A New Framework for Analysis. (Master of Science in Construction Management), University of Washington, Retrieved from <http://hdl.handle.net/1773/42883>
- Gibb, Frank Isack., 2003. Re-engineering through pre-assembly: client expectations and drivers. Building Research & Information 31:2, pages 146-160.
- Grant, A., and Hinze, J., 2014. Construction worker fatalities related to trusses: An analysis of the OSHA fatality and catastrophic incident database. Safety Science, 65, 54-62. 10.1016/j.ssci.2013.12.016
- James, J., Ikuma, L. H., Nahmens, I., and Aghazadeh, F., 2012. Influence of lean on safety risk exposure in modular homebuilding. 62nd IIE Annual Conference and Expo 2012, 2300-2306.
- James, J., Ikuma, L. H., Nahmens, I., and Aghazadeh, F., 2014. The impact of Kaizen on safety in modular home manufacturing. The International Journal of Advanced Manufacturing Technology, 70(1-4), 725. 10.1007/s00170-013-5315-028
- Jin, R., Gao, S., Cheshmehzangi, A., and Aboagye-Nimo, E., 2018. A holistic review of off-site construction literature published between 2008 and 2018. Journal of Cleaner Production, 202, 1202-1219. 10.1016/j.jclepro.2018.08.195
- Kamardeen, I., 2019. Preventing workplace accidents in construction : data mining and analytics strategies: Routledge.
- Laubier, R. d., Burfeind, A., Arnold, S., Witthöft, S., and Wunder, M., 2019. The Offsite Revolution in Construction [Press release]. Retrieved from <https://www.bcg.com/publications/2019/offsiterevolution-construction>
- Li, H., Guo, H. L., Skitmore, M., Huang, T., Chan, K. Y. N., and Chan, G., 2011. Rethinking prefabricated construction management using the VP-based IKEA model in Hong Kong. Construction Management & Economics, 29(3), 233-245. 10.1080/01446193.2010.545994
- McGraw Hill Construction., 2013. Safety Management in the Construction Industry.
- McKay, L., 2010. The effect of offsite construction on occupational health and safety.
- Mengist, W., Soromessa, T., and Legese, G., 2020. Method for conducting systematic literature review and meta-analysis for environmental science research. MethodsX, 7 10.1016/j.mex.2019.100777
- Pasquire, C., and Connolly, G. E., 2002. Leaner construction through off-site manufacturing. 263-266.
- Pennington, P., 2020. Number of work-related deaths reported goes up. Retrieved 17/04/2020 from <https://www.rnz.co.nz/news/national/408058/number-of-work-related-deathsreported-goes-up>
- Proverbs, D. G., Holt, G. D., and Love, P. E. D., 1999. Logistics of materials handling methods in high rise in‐situ construction. International Journal of Physical Distribution & Logistics Management, 29(10), 659-675. 10.1108/09600039910300037
- Richard, R.-B., 2017. Industrialized building categorization. In (pp. 3-20). 10.4324/9781315743332-1
- Roughton, J. E., and Crutchfield, N. (2016). Job hazard analysis : a guide for voluntary compliance and beyond (Second edition ed.): Butterworth-Heinemann.
- Shahzad, W., and Rasheed, E., 2019. The H&S case for prefab. Building Research Association of New Zealand.
- Smith, R. E., and Quale, J. D., 2017. Offsite architecture : constructing the future: Routledge, Taylor & Francis Group.
- Worksafe., 2018. Safe work with precast concrete : handling, transportation and erection of precast concrete elements: WorkSafe New Zealand.

Computable Planning Rules for Automating Urban Land Development

Johannes Dimyadi^{1*} and Robert Amor²

¹CAS Limited, New Zealand.

²University of Auckland, New Zealand.

*Corresponding author: jdimyadi@cas.net.nz

Abstract

Land redevelopment is not a trivial process and involves manually and painstakingly working with planning rules to develop various compliant options. The process is costly, inefficient, and lends itself to automation as long as we have the right computable data.

Existing tools have either hard-coded rules that are not responsive to changes in the operative version of planning rules, or depend heavily on user interpretation and inputs for most of the parameters needed for the calculations.

The current research combines officially published digital land information, a computable representation of planning rules, and an industry-standard financial model to provide viable compliant subdivision scenarios.

Rules from the Auckland Unitary Plan and Waikato District Plans have been translated into the open legal knowledge interchange standard known as LegalRuleML, using a semi-automated method that also incorporates a robust quality assurance process.

The findings suggest that the outcome of the automated process provides a close match with the result of the manual calculations. More importantly, however, the calculations can be performed very efficiently and accurately.

Computable planning rules can support an automated land development evaluation process and enable a cost effective feasibility assessment for various compliant subdivision options.

To test the viability of the approach, a financial model for land subdivision calculations constrained by planning rules has been incorporated into the ACALand Solution of the ACABIM commercial software platform. Several sites from various parts of Auckland and Waikato regions in New Zealand have been selected to validate the calculations. A comparison between the output of the automated calculations and those produced manually by a land development professional for a real project has been undertaken as part of the validation.

Keywords

Compliance Checking, Land Development, Land Subdivision, LegalRuleML, Planning Rules

Introduction

The primary legislation governing the allocation and management of natural and physical resources in New Zealand is the Resource Management Act 1991 (RMA) together with its latest amendments in the Resource Management Amendment Act 2020. The RMA provides a framework for the development and implementation of various policies, standards, planning documents such as regional and district plans, and process guidelines to enable central and local governments to administer sustainable management objectives of the Act. Regional plans are developed and administered by 11 regional councils and 5 unitary authorities, catering for requirements specific to each of 16 geographic regions of New Zealand. District plans are

developed to be compatible with regional plans and administered by territorial authorities (city and districts councils) in 13 cities and 53 districts and intended to accommodate territorial requirements of those cities and districts.

Each city or district is divided into planning zones having their own prescriptive rules to control activities in each zone around land use, subdivisions, and to manage environmental effects such as natural hazards and carbon emissions. Permitted and Controlled activities within each zone are those that can easily demonstrate full compliance with planning rules relevant to the zone, although often subject to some conditions. Discretionary activities are those that do not fully comply with the planning rules but may still be approved, subject to a resource consent, if they can demonstrate compliance with the intent of the RMA.

In the context of the work described in this paper, urban land development pertains to optimising the development of buildings or structures on the given land parcel within legal parameters provided by relevant planning rules. The process may involve subdividing the land parcel into multiple lots and evaluating the economic feasibility of different building shapes and sizes, as well as the provision of infrastructure and other features.

Ensuring and demonstrating compliance with planning rules for land development is, conventionally, a manual undertaking that is laborious and potentially error-prone. At the outset, legal properties of the land parcel must first be obtained from Land Information New Zealand (LINZ) as they form the basis for subsequent planning calculations. The process starts by looking up the appropriate zoning from the relevant district plan, extracting numerous associated planning rules, and then iteratively performing various compliant calculations. The entire process can take up to several days to complete including a final recommendation report.

Current Approaches and Motivation

There have been numerous research efforts on the optimisation of land subdivision, urban planning, and automated land development (Capozza & Li, 2002; Dahal & Chow, 2014; Habib, 2020; Koc *et al.*, 2020). Most of these work utilised either mathematical or economic models or both, but only a few have taken into account regulations and planning rules as one of the main constraints (Wickramasuriya *et al.*, 2011). Early work in this category represented regulations as a cluster of IF-THEN rules, embedded into a software tool called SiteCode, which can be used as part of the land development evaluation process (Shaw, 1991). Embedding rules into software tools has been a common approach among many rule-based applications. Apart from the obvious lack of transparency, this black-box approach creates or incorporates a duplicated copy of the regulations in the tool that is unresponsive to law changes and therefore poses maintainability challenges (Dimyadi & Amor, 2013).

There are some early works focusing on the economic aspect of land development, also with little considerations on the impact of regulatory constraints (Cannaday & Colwell, 1990; Chakrabarty, 1991). This is possibly due to the type of development and jurisdictions at the time that might be subject to much less stringent regulatory requirements. Even today, the level of stringency across different jurisdictions in New Zealand varies quite significantly, according to a survey published by New Zealand Institute of Economic Research (NZIER, 2015).

Research Motivation and Research Questions

The current housing shortage in New Zealand has led to urban zoning changes to promote higher dwelling density in many parts of New Zealand. This opens up opportunities to redevelop existing properties to accommodate multi-unit developments. Planning rules such as the maximum permissible building coverage area, minimum landscaped areas required,

provision of vehicle turning areas, setback distances from legal boundaries, height restrictions, etc., represent a set of design parameters that can be used as constraints to calculate the optimum number of building footprints that can be accommodated on a given land parcel. Additionally, a cost-benefit analysis can be used in conjunction with a financial model to optimise the size of buildings and the number of storeys within the same footprint.

The combination of economic considerations and regulatory constraints is considered an important factor to automating urban land development. One immediate benefit is to gain a quick insight into the economic feasibility of an investment, which is particularly important in today's fast changing economic climate. Furthermore, the transparency and maintainability aspects of the computable representation of regulations are important to guarantee planning rules extracted for calculations are those of the latest amendment. These have been the main motivation behind the current research.

Furthermore, this work sets out to investigate to what extent planning rules can be represented in a computable form to enable the land development process to be automated and what overall levels of accuracy can be achieved when they are used in conjunction with a financial model.

Computable Planning Rules and a Case Study

Planning rules are conveyed in natural language not intended for computer processing. So they need to be translated into a computable form that is suitable for software queries and calculations. The emerging open legal knowledge interchange standard, LegalRuleML (LRML) (Athan *et al.*, 2013), has been selected for this purpose as it is specifically designed to represent the semantics of normative requirements and fully supports deontic operators and legal reasoning. Furthermore, a LRML document can exist and be maintained independently from any software application using it. The current approach advocates that the computable representation of planning rules should be maintained by the authority alongside the paper-based source provision and be made available for on-demand access from an official central repository. This would ensure that only the latest amendment of the rules is accessible by the software tool that performs the land development calculations.

For our case study, planning rules from two districts in New Zealand, namely the Auckland Unitary Plan, and the Waikato District Plan, have been translated and encoded in LRML (Figure 2). There are nearly 1000 rules involved, but only 350 rules are commonly applicable. A semi-automated translation process has been used with a professional manually formalising and extracting rules from the paper-based planning rules into a proforma worksheet (Figure 1). A software tool is then used to encode the logical content into LRML while checking for correctness and highlighting any anomalies (Dimyadi *et al.*, 2020). In the case of planning rules, most of the regulatory requirements can be conveyed in a tabulated form.

An example of the LRML encoding from the formalised planning rules in Figure 1 is shown in Figure 2 and a more human-readable version of the same rule is shown in Figure 3.

table	1.1				
input	(1 2 3)				
output	4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 & 14 & 15 & 16 & 17 & 18 & 19 & 20 & 21 & 22				
	1	2	3	4	5
site.zone =	site.activityDescription =	site.zoneDescription =	building.height <=	roof.height =	recess
H1	Residential	Large Lot	8	1	
H2	Residential	Rural and Coastal Settlement	8	1	
H3	Residential	Single House	8	1	
H4	Residential	Mixed Housing Suburban	8	1	
H5	Residential	Mixed Housing Urban	11	1	
H6	Residential	Terrace Housing and Apartment Buildings	16	0	

Figure 1: Knowledge capture proforma worksheet

```

</ruleml:Expr>
<ruleml:Expr>
  <ruleml:Fun iri="lovo:equal"/>
  <ruleml:Atom>
    <ruleml:Rel iri="buvo:activityDescription"/>
    <ruleml:Var iri="buvo:site"/>
  </ruleml:Atom>
  <ruleml>Data xsi:type="xs:string">Residential</ruleml>Data>
</ruleml:Expr>
<ruleml:Expr>
  <ruleml:Fun iri="lovo:equal"/>
  <ruleml:Atom>
    <ruleml:Rel iri="buvo:zoneDescription"/>
    <ruleml:Var iri="buvo:site"/>
  </ruleml:Atom>
  <ruleml>Data xsi:type="xs:string">Terrace Housing and Apartment Buildings</ruleml>Data>
</ruleml:Expr>
</ruleml:Or>
</ruleml:if>
<ruleml:then>
  <ruleml:And>
    <ruleml:Expr>
      <ruleml:Fun iri="lovo:lessThanEqual"/>
      <ruleml:Atom>
        <ruleml:Rel iri="buvo:height"/>
        <ruleml:Var iri="buvo:building"/>
      </ruleml:Atom>
      <ruleml>Data xsi:type="xs:integer">16</ruleml>Data>
    </ruleml:Expr>
  </ruleml:And>
</ruleml:then>
</ruleml:if>

```

Figure 2: A planning rule represented in an LRML document

NZ_RMA-AUP-STANDARDS#1.0_t1.1.6	
IF	THEN
<pre> site.zone == string H6 site.activityDescription == string Residential site.zoneDescription == string Terrace Housing and Apartment Buildings </pre>	<pre> & building.height <= integer 16 roof.height == integer 0 recession.angle <= integer 45 recession.height <= measurement 3 m building.coverage <= decimal 0.5 frontYard.clearance >= measurement 1.5 m sideYard.clearance >= measurement 1 m rearYard.clearance >= measurement 1 m riparian.clearance >= measurement 10 m lakeside.clearance >= measurement 30 m coastal.clearance >= measurement 10 m groundLevel.outdoorLivingArea >= measurement 20 m² upperLevel.outdoorLivingArea >= measurement 5 m² frontFence.height <= measurement 1.4 m sideFence.height <= measurement 2 m rearFence.height <= measurement 2 m site.impermeableArea <= decimal 0.7 site.landscapeArea >= decimal 0.3 </pre>

Figure 3: A more human-readable version of an LRML planning rule

A land parcel subdivision algorithm incorporating these planning constraints has been developed in conjunction with a commonly accepted real-estate financial model. To test the viability of the approach, the algorithm has been implemented into a commercial software tool, ACALand, which is a modular solution of the integrated cloud-based ACABIM software system (Dimyadi & Amor, 2018) (Figure 4).

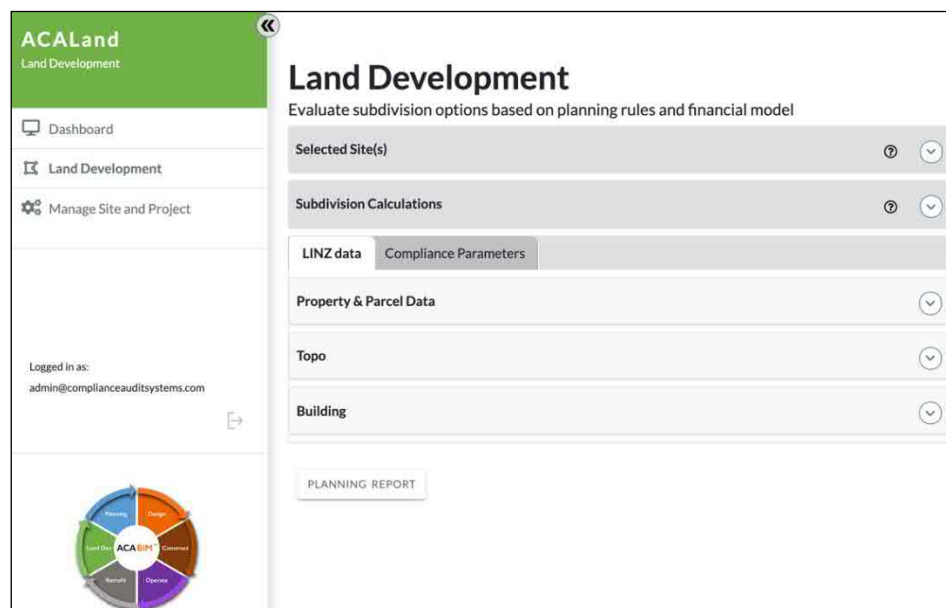


Figure 4: Screenshot of ACALand

To validate the automated calculations result, an existing real project in Auckland, New Zealand, has been selected as the case study. The project is a feasibility study of a land redevelopment as the planning zone had changed from an existing single dwelling zone to a higher-density terraced-housing zone. The project was completed by a professional planner with manual calculations and a feasibility report, which took 2 to 3 days to complete, excluding architectural design and any peer-review tasks.

Given the planning zone, rules can be extracted from the LRML document via a workflow-driven query (Figure 5) that can be developed and verified visually for transparency. The output is a set of compliance parameters for subsequent calculations (Figure 6).

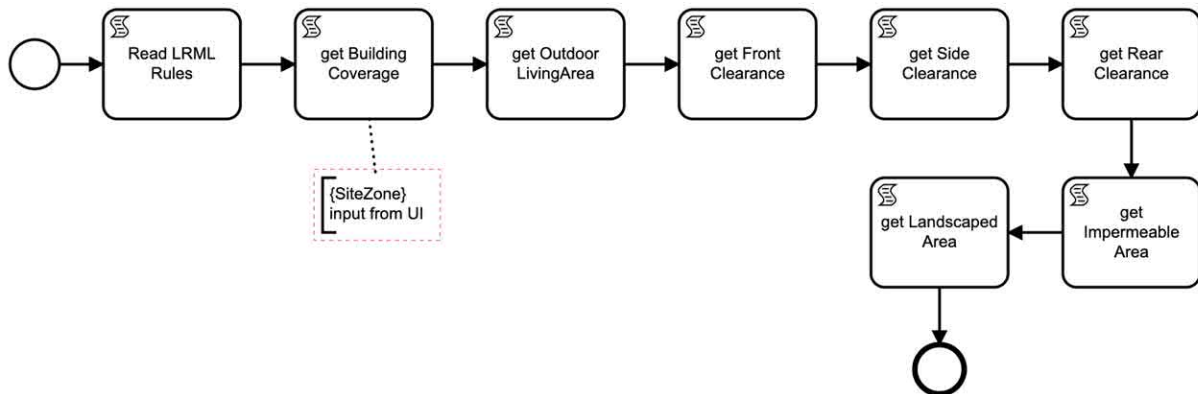


Figure 5: Workflow-driven LRML Query

LINZ data	Compliance Parameters
Parameter	Value
Zone	H6 Residential - Terrace Housing and Apartment Buildings
LandscapedArea	0.3
ImpermeableArea	0.7
RearClearance	1
SideClearance	1
FrontClearance	1.5
OutdoorLivingArea	20
BuildingCoverage	0.5
LrmlRuleId2	NZ_RMA-AUP-STANDARDS#1.0_t1.1
maxParkingRate	16.80
LrmlRuleId1	NZ_RMA-AUP#14_t6.2.1

Figure 6: Extracted planning rules from LRML

Given the site address, legal properties of the land parcel can be extracted automatically from LINZ via their APIs (Figure 7).

LINZ data

Compliance Parameters

Property & Parcel Data

^

Attribute	Value
Title No.	NA117A/374
Status	LIVE
Title Type	Freehold
Land District	North Auckland
Issue Date	Tuesday, June 9, 1998
Guarantee Status	Guarantee
Estate Description	Fee Simple, 1/1, Lot 79 Deposited Plan 186820, 682 m2
Number of Owners	1
Shared	false
Land District	North Auckland
Legal description (Survey)	Lot 79 DP 186820
Deposit Plan # (Survey)	DP 186820
Parcel intent (Survey)	DCDB
Topology (Survey)	Primary
Titles (Survey)	NA117A/374
Survey area (Survey)	682 m²

Figure 7: LINZ land properties extract

Apart from the financial input parameters, two other manual property parameter inputs required for the automated process are the average floor area per storey and the number of storeys per lot. Given these user inputs, the number of lots is calculated automatically based on the extracted planning rules from the LRML document, and land properties extracted from LINZ.

As shown in Figure 8, given a user input of 3 storeys with an average floor area of 48 sqm per storey, the optimum solution has been calculated to be 5 buildings. A change in any one user-input parameter would trigger recalculations and the optimum solution updated. Please note that manual user-input fields are indicated by dashed-line borders in Figure 8. These manual and automatically calculated input data are then used for subsequent financial calculations to determine the feasibility of the investment (Figure 9).

Property Parameters	Financial Parameters (+GST)
Average floor area per storey: 48 m ²	Property purchase price: 1565226 \$
Number of storeys per Lot: 3	Expected sale price per Lot: 1026093 \$
Number of lots: 5	Property value for 2 nd tier: 1000000 \$
Section size: 682 m ²	2 nd tier financing: 53 %
Total building floor area: 720 m ²	2 nd tier interest rate: 10 %
Max building coverage (50%): 341 m ²	Construction cost per m ² : 2863 \$
Total outdoor living area: 100 m ²	Professional fee per m ² : 196 \$
Min landscaped area (30%): 205 m ²	Commissions 3% : 125000 \$

Figure 8: Manual and automatically calculated data input

Findings and Discussion

Given the user's input parameters and the calculated number of buildings, further financial calculations can then be performed (Figure 9), the details of which are beyond the scope of this paper. However, it is worth noting, that the automated process including manual data inputs take less than 10 minutes to perform (including a PDF report), which is significantly more efficient than the manual process that would take days to compete. Each subsequent iterative calculation would then be almost instantly performed using this automated approach.

Subdivision Outcome		Analysis
Cash Only Investor		
Cash needed (ex GST)		\$4,091,427
Profit (ex GST)		\$914,038
Profit (after 33% company tax)		\$612,405
% ROI after tax		14.97 %
Annualised over 21 months		8.06 %

Figure 9: Financial calculations results

As a comparison, the output of the automated calculations in the case study is within 5% of the manual calculations result on the conservative side. This is mainly due to conservative assumptions in the application of the planning rules on the land parcel. The error is expected to be higher for land parcels with a more complex geometry. However, the level of accuracy is considered acceptable for the ability to quickly evaluate multiple compliant options and assess the viability of a project.

Conclusion

The findings of this research suggest that an open legal knowledge interchange standard such as LRML can be used to represent planning rules effectively for automated land development calculations. The automated approach is far more efficient than the manual process, and the case study results match quite closely with that of the manually performed analysis.

The automated approach described in this paper is practical and particularly useful to evaluate various compliant options quickly to determine the economic feasibility of an investment.

Acknowledgement

The authors would like to acknowledge the contribution of the original financial calculation model by Casa Ecco Limited, and the contribution of the manually prepared feasibility analysis and report for the case study by NFL Developments Ltd.

References

- Athan, T. et al. (2013) 'OASIS LegalRuleML', in The International Conference on Artificial Intelligence and Law. Rome, Italy.
- Cannaday, R. E. & Colwell, P. F. (1990) 'Optimization of subdivision development', *The Journal of Real Estate Finance and Economics*, 3(2), pp. 195–206. doi: 10.1007/BF00216592.
- Capozza, D. R. & Li, Y. (2002) 'Optimal land development decisions', *Journal of Urban Economics*, 51(1), pp. 123–142. doi: 10.1006/juec.2001.2240.
- Chakrabarty, B. K. (1991) 'Optimization in Residential Land Subdivision', *Journal of Urban Planning and Development*, 117(1), pp. 1–14. doi: 10.1061/(asce)0733-9488(1991)117:1(1).
- Dahal, K. R. & Chow, T. E. (2014) 'A GIS toolset for automated partitioning of urban lands', *Environmental Modelling and Software*. Elsevier Ltd, 55, pp. 222–234. doi: 10.1016/j.envsoft.2014.01.024.
- Dimiyadi, J., Fernando, S., Davies, K. & Amor, R. (2020) 'Computerising the New Zealand Building Code for Automated Compliance Audit', in 6th New Zealand Built Environment Research Symposium (NZBERS2020), pp. 39–46.
- Dimiyadi, J. & Amor, R. (2013) 'Automated Building Code Compliance Checking. Where is it at?', in Proceedings of the CIB World Building Congress 2013 and Architectural Management & Integrated Design and Delivery Solutions (AMIDDS). Brisbane, Australia, pp. 172–185.
- Dimiyadi, J. & Amor, R. (2018) 'BIM-based Compliance Audit Requirements for Building Consent Processing', in Proceedings of the 12th European Conference on Product and Process Modelling (ECCPM). Copenhagen, Denmark, pp. 465–471.
- Habib, M. (2020) 'Proposed Algorithm of Land Parcel Subdivision', *Journal of Surveying Engineering*, 146(3), p. 04020012. doi: 10.1061/(asce)su.1943-5428.0000322.
- Koc, I., Cay, T. & Babaoglu, I. (2020) 'Different Approaches to Automated Land Subdivision using Binary Search Algorithm in Zoning Applications', *Proceedings of the Institution of Civil Engineers - Municipal Engineer*, pp. 1–27. doi: 10.1680/jmuen.18.00066.
- NZIER (2015) 'Land use regulation in New Zealand - Improving the evidence base', Report to the New Zealand Productivity Commission, (May 2015).
- Shaw, D. T. T. (1991) 'Knowledge-based regulation processing for site development', *Computers & Structures*, 40(1), pp. 23–30. doi: 10.1016/0045-7949(91)90452-R.
- Wickramasuriya, R., Chisholm, L. A., Puotinen, M., Gill, N. & Klepeis, P. (2011) 'An automated land subdivision tool for urban and regional planning: Concepts, implementation and testing', *Environmental Modelling and Software*. Elsevier Ltd, 26(12), pp. 1675–1684. doi: 10.1016/j.envsoft.2011.06.003.

Feasibility Analysis of Cross Laminated Timber (CLT) for the Christchurch Rebuild Project in New Zealand

Shitong Tian¹ and Don Amila Sajeewan Samarasinghe^{2*}

¹College of Engineering, Construction and Living Sciences, Otago Polytechnic Auckland Campus, New Zealand.

²School of Built Environment, College of Sciences, Massey University, New Zealand.

*Corresponding author: D.Samarasinghe@massey.ac.nz

Abstract

In 2012, the Christchurch Central Recovery Plan (CCRP) was issued after a large earthquake ruined most of the Christchurch, New Zealand, city centre. CCRP aimed to rebuild Christchurch city to a high standard. However, the rebuilding process was not as fast as expected, resulting in significant project delays in most anchor projects. Cross Laminated Timber (CLT) is a building product invented in Europe in the early 1990s. CLT has positive features such as good environmental performance, high fire resistance, high shear force resistance and rapid assembly, all of which are in line with the objectives of CCRP.

There are insufficient feasibility studies about CLT materials in the New Zealand market; CLT research only began in the last decade. This research aims to identify the suitability of CLT in multi-storey buildings in New Zealand, especially for accelerating the rebuild of Christchurch. This study aims to identify CLT features suitable for the construction market in terms of earthquake resistance and fire resistance and promotes how CLT could be used in the rebuild Christchurch.

A mixed-method approach was used to achieve the research purpose. Qualitative and quantitative data were gathered using secondary data sources. The applications of CLT products in multi-stored buildings worldwide were analysed and compared with the requirements of CCRP. Desirable aspects were observed from seismic tests and fire resistance tests, which provided confidence in the ability of CLT products to perform well in a multi-storey building in Christchurch. However, further experimentation and research need to be conducted using local timber materials to prove the feasibility of widely using CLT products in multi-storey buildings in New Zealand. This research is also necessary to create an excellent local CLT product standard and regulations.

The research provides a new constructional idea for the New Zealand construction market, accelerates the construction cycle and protects the public from a natural disaster.

Keywords

Christchurch Rebuild Project, Cross Laminated Timber (CLT), Multi-storey Buildings, New Zealand

Introduction

New Zealand is an earthquake-prone country: there were 23,577 earthquakes in 365 days, and 253 of these were greater than magnitude five (GeoNet Geological hazard information for New Zealand 2021). As New Zealand is located on the junction of two tectonic plates – the Pacific Plate and the Australian Plate – it is inevitable that earthquakes frequently (GNS Science n.d.).

The public will suffer from the direct impact of the earthquake and consequent disasters such as conflagration and building collapse. The public agony may last a long time, and so may a city's rebuilding. Christchurch is still in the process of rebuilding after the devastating earthquake that struck its centre on 22 February 2011. To enhance the rebuilding process, CLT should be considered as a new light structural building material when constructing multi-storey buildings in Christchurch and other earthquake-prone regions of New Zealand.

CLT is a manufactured timber panel comprising multiple layers orthogonally placed and glued in parallel (Fortune and Quenneville 2011). As a new building structural system, CLT was included in both the 2015 International Building Code (IBC) and the 2015 National Design Specification (NDS) for lumber construction (American Wood Council 2015). The standard laminates are in odd numbers such as three, five or seven (Park et al. 2003). The dimension of a single panel can reach up to the length of 16 m, a width of up to 2.5 m and a thickness of up to 500 mm. The panels can be manipulated to suit a variety of locations and purposes due to their unique construction, such as mechanical joints and glued connections (Kuilen et al. 2011). This type of timber panel layout makes CLT much stronger than traditional timber structure systems such as plywood and plasterboard (Crampton 2017); therefore, it is an appropriate material for use in multi-storey residential and mercantile buildings (Polastri et al. 2014). For example, London's Murray Grove Building is the first urban housing project with a CLT structure, including CLT shear walls, floor slabs, and lift cores (see Figure 1). The main advantages of CLT are its high lateral resistance, eco-friendliness, fast installation and fire protection properties.

High lateral resistance: CLT is a more lightweight material than traditional materials used in construction. The density of triple-laminated CLT is approximately 427 kg/m^3 (Serrano and Enquist 2010), while reinforced concrete is approximately 2406.53 kg/m^3 . In addition, the CLT wall panel is good at resisting lateral load if it has a proper connection to the floors below. Using step joints (half-lap joint) in long run walls reduces the seismic input load by reducing wall stiffness and increasing wall deformation capabilities (Popovski and Karacabeyli 2012).

Eco-friendliness: CLT provides an eco-friendly constructional environment since its carbon emissions during production are lower than traditional materials. Its carbon emissions per ton of timber are 33 kg, while recycled steel and concrete produce 220kg and 265 kg, respectively (Crampton 2017).

Fast installation: CLT panel is a quick-erection building material since it is highly prefabricated with pre-cut openings. This means installing a structure of CLT is not difficult and does not require highly-skilled workers to erect and connect it on-site (Divekar 2016). Consequently, there may be considerable savings on on-site operation costs due to the rapid assembly of the CLT components.

Fire protection: CLT panel provides good fire protection to buildings due to its multiple layer panel structures. When fire breaks out, the surface layer of the panel chars and the subsurface dries, preventing oxygen from penetrating deeper and supporting combustion; therefore, the burning process stops. CLT panel does not need to be coated with fire-resistant materials, though it is still coated with a gypsum-fibre board (Henek, Venkrbec, and Novotny 2017). Since it is difficult for fire to go deeper into the CLT panel, the core loadbearing layer will maintain its integrity for an extended period to support the structure of the building, thus giving enough time for people to escape.

To date, in New Zealand, CLT is not a common building material. Two main issues need to be addressed before CLT can be widely used in New Zealand. One of the problems is that existing CLT research is based on the European softwood, which has a lower density than the New

Zealand local species of radiata pine and Douglas fir (Brown *et al.* 2020). Another problem is there are insufficient feasibility studies about the use of CLT materials in the New Zealand market, with CLT research starting only in the last decade (Lqbal 2018).

It is acknowledged here that the few local articles limited this study in reference to applying CLT in the New Zealand construction market. All the CLT standards and research in this report refer to European, Japanese, and American standards since no New Zealand standards apply to CLT.



Figure 1: Murray Grove building, London
Source: (Waugh Thistleton Architects n.d.)

Literature Review

Introduction to Cross Laminated Timber (CLT)

CLT is a product, and building system invented in Europe (Austria and Germany) in the early 1990s. It developed quickly to become a celebrated product that allowed for the extensive use of timber materials in construction (Muszynski, Hansen, Fernando, Schwarzmann and Rainer 2017). CLT panel is made from crosswise glued timber boards. This type of board layout has the advantage of increasing shear capacity and load-bearing capacity from two directions and reducing the swelling and shrinkage caused by humidity variation in the plane (Kuilen *et al.* 2011). CLT has excellent potential for making good use of timber resources since low-value timber from insect-damaged wood or small-diameter wood can be transferred into high-value CLT structural applications (Mallo and Espinoza 2015). This takes the best advantage of the natural resources and reduces timber waste in New Zealand. Additionally, CLT has good features such as a solid environmental performance (Mallo and Espinoza 2015), high fire resistance, high shear force resistance, and can be erected quickly—all of which are appropriate for rebuilding a city in the earthquake zone, such as Christchurch—with high environmental protection requirements.

Applications of CLT for the CCRP

It is crucial to note that Christchurch is the primary service centre in the South Island, contributing to 70% of the economic output of the Canterbury region and 12% of the national Gross Domestic Product (GDP) (Canterbury Earthquake Recovery Authority 2012). In rebuilding the city, the height of buildings in the rebuild plan is limited to:

- Central city business zone (core): 28m;
- Central city business zone (gateway): 17m;
- Central city mixed-use zone: 17m (Canterbury Earthquake Recovery Authority 2012).

From experience in other countries as a guide, it is possible to build with CLT materials at these heights. There are some existing CLT buildings of similar sizes, which are listed below:

Table 1: Examples of existing CLT buildings

Name of building	Height (m)	Location
Forte	32	Melbourne, Australia
Dalston Lane	33	London, UK

Source: (Construction Review Online 2021)

Based on community responses, the Christchurch Central Recovery Plan developed in 2012 included a Green City as one of five key elements of the draft of the Central City Plan. This means the citizens require the new city to be rebuilt and decorated as a Green City and built with green materials. Determining how to reconstruct a city that can be organically developed over a century and a half is one of the aims of the Christchurch City Council in the city rebuild (McDonald 2020). In New Zealand, controlling greenhouse gas (GHG) emissions from human activities is one of the main issues for reducing global warming. New Zealand is a small country with only five million people. Still, gross carbon dioxide was 7.7 tonnes per person, ranking it 17 out of all 32 OECD countries (Ministry for the Environment and Stats NZ, 2020), which is undesirable. New Zealand's target for GHG emissions in 2050 is 39.4 million tonnes of carbon dioxide equivalent, a 37% reduction from 2020 when it was 62.7 million tonnes of carbon dioxide equivalent (New Zealand's projected greenhouse gas emissions to 2050 2021). The construction industry currently contributes 18% of the country's GHG emissions (New Zealand's greenhouse gas emissions 2020), while the rate is 38% worldwide. Fortunately, there has been a downward trend in construction and manufacturing GHG emissions – these have decreased 9.9% from 2017. The predicted trend will transform the traditional reinforced concrete building structures into timber structures and reduce GHG emissions from the construction industry in the future. The Whole Life Cycle Cost (WLCC) of a CLT building is estimated to have a global warming potential 22% lower than similar concrete buildings when considering carbon sequestration, or 13% lower if not considering carbon sequestration in the WLCC (Durlinger *et al.* 2013). Forests are nature's carbon storage, and they are constantly absorbing carbon dioxide through photosynthesis from the air (Darby *et al.* 2014), so when a forest is harvested and made into a CLT product, it continues to store carbon dioxide for a long time, thus climate change mitigation (Hassan, Oberg and Gezelius 2019). Thus, from this perspective, timber-based construction materials are becoming mainstream due to the strict environmental protection principles currently applied in New Zealand.

Key features of CLT products

Fire is another potentially lethal hazard after an earthquake; thus, high fire resistance performance is one of the key considerations when selecting building materials for use in an

earthquake zone. Unlike reinforced concrete material, CLT products can retain good structural stability when exposed to high temperatures for 90 minutes if appropriately designed (Stora Enso 2013). When the CLT material is exposed to fire, the material's surface becomes charred, and the flame continues to spread. The charring contributes to reduced fire penetration to the core of the material by converting the panel's surface into an insulator. As the charring goes deeper, the cross-section of the structural load-bearing system decreases, and finally, the structure fails. A char rate is incorporated into experiments to quantify the charring behaviour calculate how fast the timber becomes charred when exposed to fire (Moser *et al.* 2016). After an investigation by the University of Canterbury, the char rate of CLT is measured between 0.83 ± 0.2 mm/min.

The strength of CLT panels against fire damage and shear force is significantly impacted by the behaviour of the adhesive that bonds the laminations (Frangi *et al.* 2009) and the type of priming coating on the surface. Thus, the analysis and development of CLT should focus not only on the timber but also on the appropriate adhesive used to connect each independent timber panel, the use of screws securing CLT panels to maintain structural integrity, and the performance of the primer used. The standard adhesives to assemble timber panels are polyurethane (PUR), phenol-resorcinol-formaldehyde (PRF) (Sikora *et al.* 2016), epoxy resin (EP) and emulsion polymer isocyanate (EPI) (Lu *et al.* 2018). With the protection of the priming treatment by Hydroxy Methylated Resorcinol (HMR), the bond performance and mechanical properties of CLT can be enhanced effectively (Lu *et al.* 2018).

The connections significantly impact the strength of the CLT structure in multi-storey buildings. Common connections in CLT buildings are self-tapping screws (STS), toe-screwed (TS) at 45 degrees (Fitzgerald *et al.* 2020), nails, lag screws and bolts in combination with metal ties, plates and brackets (Mohammad 2011). Proper combinations between different screws to connect CLT panels may result in higher strength. Partially-threaded STS is 15 times greater than fully-threaded STS in ultimate deformation capacity in seismic performance. Still, the yield strength of partially-threaded STS is only 48% of that of fully-threaded STS (Fitzgerald *et al.* 2020).

The construction period with CLT can be shortened due to the outstanding capacity for panel precast and modular manufacture (Chang *et al.* 2019). In the construction of Bridport House in London, the erection of an eight- and five-storey CLT building frame occurred within 10 weeks, while a similar reinforced concrete building frame would have taken 14 weeks (Darby *et al.* 2014). The 10-storey Forte Building in Melbourne, one of the tallest timber structures globally, was erected within 10 weeks, significantly shorter than similar reinforced concrete buildings, which would take about four months for erection (Lendlease Corporation 2016).

The main issue in adopting CLT products in New Zealand

The rebuild of Christchurch after the 2010 and 2011 earthquakes has been slow to gain traction due to physical and emotional turmoil (Gjerde 2017). The earthquake ruined 10,000 buildings and wiped out most of the city's infrastructure, leaving it in limbo (Parkes 2020). After the earthquake, the Christchurch City Council planned to rezone the ruined district and rebuild it, and called the reconstruction "anchor projects". The anchor projects were estimated to cost \$4.8 billion (Mathewson and Turner 2013), and the Christchurch City Council promised in its original timeline that all would be done by 2017. However, none of the 16 major Anchor Projects has been completed, except some small parts such as the justice precinct, bus interchange and retail precinct (Zaki 2021).

The main issue in adopting CLT in construction in New Zealand is building code compatibility (Mallo and Espinoza 2015) – NZS3603 does not cover the design provisions of CLT and the

relative penetrations for connections 1993 Timber Structures Standard (Brown *et al.* 2020). Meanwhile, in New Zealand, there is a lack of awareness about CLT among contractors, developers, managers, architects, and engineers is also essential, in contrast to Europe, where the CLT system is already relatively well established (Espinoza *et al.* 2016). In New Zealand, the lack of standards and codes is the first issue when applying CLT to the market. To establish the standards and codes, the first step is to fund institutes and organisations to carry out the necessary tests into the manufacturing possibilities with local timber resources, as well as loadbearing strength, seismic performance fire resistance, and so on, to ensure the CLT material is suitable for the local market. The European CLT test results provide appropriate references and comparisons for New Zealand tests (Klippel and Schmid 2018).

XLam Ltd., based in Nelson, was established in 2010 and was the first and only established CLT manufacturer in New Zealand in the past decade. As a pioneer of CLT products in New Zealand, XLam Ltd. was the leading company in the CLT industry because of the XLam Fire Design Guide. The guide is the only reference for designers to rely on in the CLT industry at that moment because there is no national industry guidance about CLT structures in New Zealand. Unfortunately, this single New Zealand CLT products plant was closed as "the existing highly manual, capacity-constrained operation in Nelson was not commercially sustainable for the future CLT manufacture. The future CLT supply will be from the new operations at Wodonga, Australia" (Perinotto 2019). This situation will be replaced with the broader use of CLT products as more manufacturers enter the industry. To avoid disorder in the market, the standard of CLT design should be regulated by the Building Code and New Zealand Standards as soon as possible.

Feasibility of adopting CLT products in New Zealand

The University of Canterbury studied and tested timber strength using local trees to produce CLT panels with local trees such as Radiata Pine, Douglas Fir, and Mountain Ash Timber (Fortune and Quenneville 2011). Furthermore, these investigations confirmed other characteristics of New Zealand CLT products, such as the flexural behaviour, stiffness values, and the heterogeneous nature of CLT, would not influence the joint strength of layers under high compression (Lqbal 2018).

In the seismic performance test, Dunbar *et al.* (2013) tested the same post-tensioned CLT stair wall using low seismic loading and high seismic loading. The investigators allowed U-shaped flexural plates to strengthen the connection between panels and the corner's steel square hollow section (SHS). The test CLT panel was connected with screws, allowing relative movement between panels to disperse energy. Finally, the seismic performance tests showed the satisfactory result that only low-damage recentring behaviour occurred to panels. In the low-seismic performance test, the best option was to use a small number of screws to connect panels, allowing them to move individually. In the high-seismic performance test, corner reinforcers were the key components against shear force. These tests proved that CLT products could be used in multi-storey buildings in Christchurch, located in the seismic zone.

Research Methodology

To achieve the purpose of the research, a mixed-method was adopted to collect data to form the report since the application of CLT in Christchurch needed to be demonstrated by numerical and non-numerical data. The mixed-method approach included secondary qualitative data gathered from past literature to identify CLT applications in building construction and quantitative secondary data collected to analyse the feasibility of CLT for the CCRP project.

The quantitative secondary data mainly included tests conducted to measure CLT performances on seismic and fire resistance. In the seismic resistance tests, high-seismicity region testing and light-seismicity region testing were collected and analysed. Three test results obtained from CLT wall and floor specimens were collected and analysed in the fire resistance tests.

The qualitative data were about the citation and analysis of other articles and reports to fulfil the research content. This was the primary data about CLT products to be collected and analysed in this report. In this process, the key findings were the features of CLT products, including the advantages and disadvantages of CLT building. Then, the study compared these features with the natural conditions and regulations in New Zealand to conclude whether CLT multi-storey building was suitable for Christchurch. When collecting the qualitative data, existing CLT multi-storey buildings were analysed using existing examples as a reference.

In the qualitative data analysis, thematic analysis was used to consider the existing research. During thematic analysis, a set of readings about the same topic was done before the investigation and identifying the data patterns in the specific topic (Braun and Clarke 2006). In this process, data was read and understood before analysis. After that, a table was created to present the initial codes for further pattern identification when rereading the data. Then the initial codes were grouped into sets by category and theme. The themes were reviewed and revised later to ensure enough data supported themes. Similar themes were merged, and themes without enough support were removed. After all the steps above, the theme was written, including the description of the data and the interpretive analysis.

Data were collected as secondary data in the research. Most of the secondary data were from overseas research articles, journal articles and conference presentations because there were few locally experimental results about feasibility studies of CLT products in New Zealand. Also, there was a lack of well-established local standards to support the systematic use of CLT so far. The small number of CLT professionals in New Zealand resulted in difficulty making contact with local CLT researchers. Another reason to allow secondary data to complete the research was that frequent Covid-19 lockdowns added difficulty to interviewing CLT product researchers. Most of the secondary data were from the articles and research in Google Scholar; only a few came from physical journals because of the Covid-19 lockdown.

To ensure the reliability and validity of the data, the general references about the features of CLT were mostly from published reports of experiments, published journals, university research, standards of other countries or proceedings of conferences. Information about Christchurch after the earthquakes refer to local or national news reports or Christchurch City Council plans. All information referenced has been selected from the current research if multiple selections about the same topic.

Findings and Discussion

As Christchurch has suffered earthquakes thus far, any building materials and components should perform well against these events. In this section, the key features of CLT are analysed in terms of seismic design and fire resistance. The seismic design and fire resistance data come from two reports of experimental testing conducted by the Structures Laboratory of the University of Canterbury and the National Research Council of Canada's Fire Research Resource Center.

Seismic design of CLT walls for multi-storey buildings

An experimental test of the performance of CLT products with different connections was conducted in the Structures Laboratory of the University of Canterbury. In this testing, two

half-scale two-storey stairwells, produced with post-tensioned CLT, were tested under a quasi-static loading regime (Dunbar *et al.* 2013). The CLT wall panels tried were five-layer boards made by XLam Ltd., New Zealand, with dimensions of 100 x 1600 x 3750 mm. A conduit along the longitudinal direction was left in the centre for post-tensioning with a steel tendon for each panel. The shape of the specimens was selected for two-storey stairwells due to the limitations of the laboratory, in which there was limited height and space for cranes and hydraulic actuators. The two specimens were tested individually for high-seismicity and low-seismicity regions. In each, the specimen was tested in the long and narrow directions, independently, then in bi-direction load testing. In both seismicity regions, the specimen was tested without stairs; then, a stair was installed to the well for further testing. The results of the tests are presented in Table 2.

High-seismicity region testing (Specimen 1)

In the high-seismicity region testing, U-shaped flexural plates (UFP) were placed to reinforce the wall panels and corner columns attached as energy dissipation devices (see Figure 3). Square hollow sections were allowed to be the corner columns. The deformation of the UFPs could dissipate the energy.

Four beams were attached to the CLT walls and connected to corner columns representing the floor slabs in long and short directions. Thus, the lateral force could be applied in orthogonal beams to simulate natural force against the building structure. The lateral load was transferred from the beams to the columns and the CLT wall panels since they were in contact. This design minimises the force transferring to the floor slabs to limit the deformation of floor slabs during an earthquake. Direct connection between the floor slabs and the wall panels could cause devastating damage to the floor slabs under a shaking wave.

The connections used in this testing were UFPs, timber rivets and bolts. UFPs are designed to be the dissipater devices connecting wall panels. UFPs were attached with steel plates and M14 bolts on each edge of the CLT panel. Other plates were pinned and secured with timber rivets to allow elastic deformation. The detailed connections for the UFPs are shown in Figure 2. Beams were screwed with M16 bolts to the SHS through threaded holes in the loading beam connection. Oversized threads should be allowed to provide some flexibility rotation to the beams and the columns when the lateral force is attached to the structure. Meanwhile, the columns were fixed to the foundation during the experiment, and loading beams remained horizontal to protect the floor slab and avoid displacement incompatibility. The detailed design of the loading beam is shown in Figure 4.

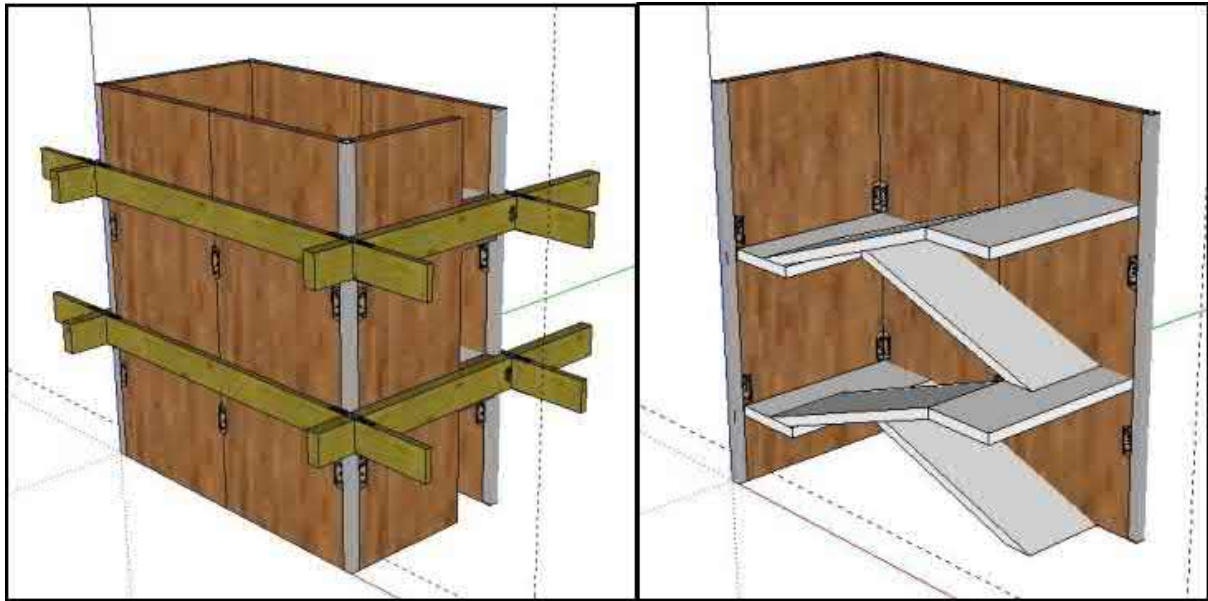


Figure 2: Layout of Specimen 1

Source: (Dunbar *et al.* 2013)

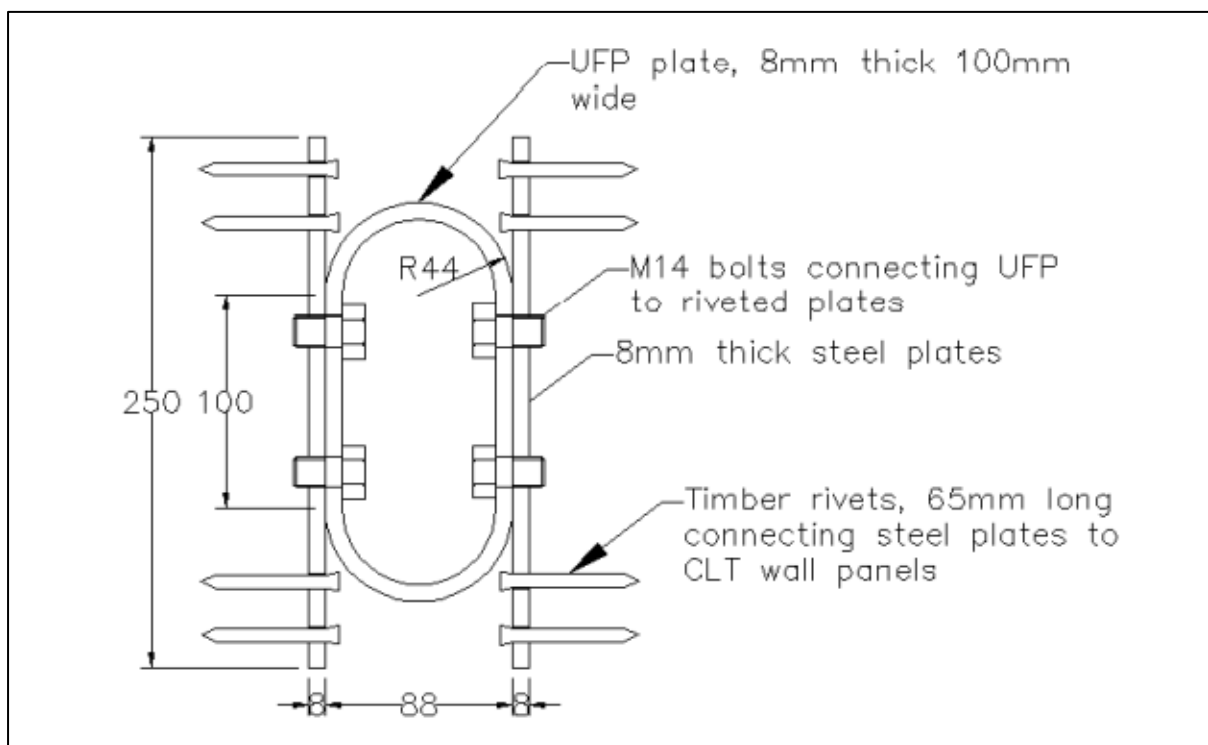


Figure 3: Connections in high-seismicity option

Source: (Dunbar *et al.* 2013)

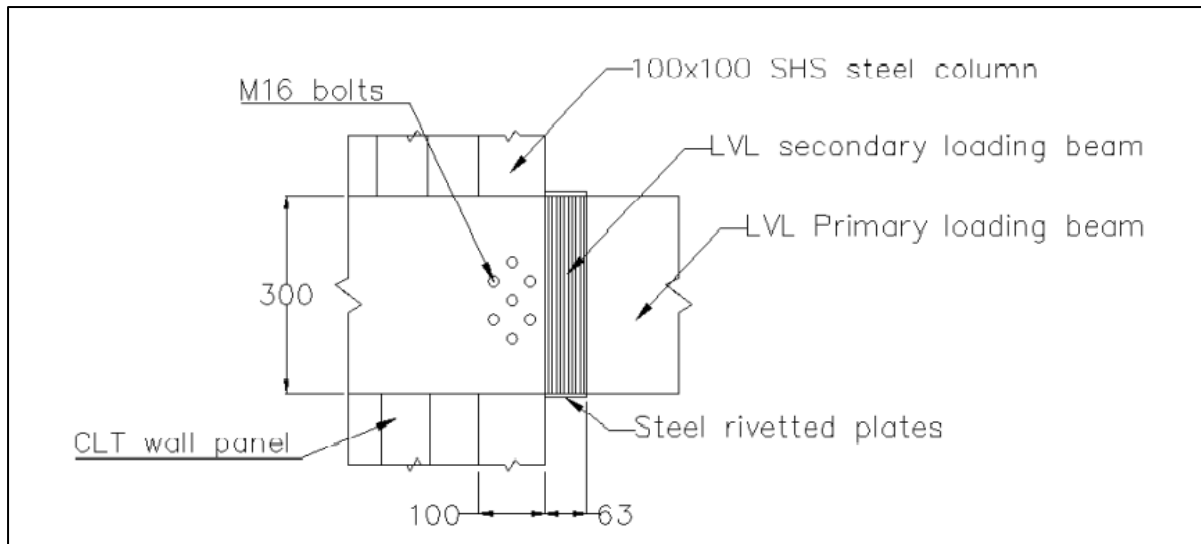


Figure 4: Loading beam connection in high-seismicity option
Source: (Dunbar *et al.* 2013)

Light-seismicity region testing (Specimen 2)

Low-seismicity testing aims to observe if the screw connection performs well in the CLT system. Thus, the same specimen layout was allowed in this testing. In Specimen 2, a smaller number of screws were used first, with the number of screws being increased in order to observe different results. The shear connection was adopted in this testing, which allowed the shear force to transfer between CLT components and connections during the movement in the specimen. The shear connections provide semi-rigid joints for the structural connection, thus allowing proper deformation to the connections to dissipate energy in an earthquake. There was no SHS corner column for the corner connection nor UFPs as dissipators in the low-seismicity testing. Instead, beams were pinned to the CLT wall directly at the wall centre (see Figure 5).

In Specimen 2, only screws and bolts were used to connect structural components. A halved joint with a 6mm diameter and 90mm long screw connection was designed to connect CLT walls in the long direction. In comparison, the orthogonal connection between panels was simply a 6mm diameter, 200mm long screw (see Figure 6). M16 bolts connected beams and CLT wall panels (see Figure 7). With the increasing number of M16 bolts in this specimen, the direct connection would result in displacement incompatibility between wall panels and beams when suffering significant drift. In this process, there is no uplifting to the wall, which may result in the bend of the loading beam, and further cause damage to the floor slab.

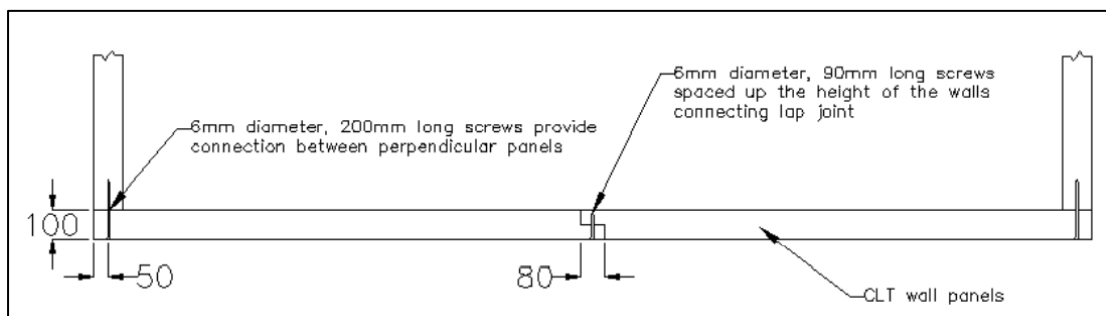


Figure 5: Layout of Specimen 2
Source: (Dunbar *et al.* 2013)

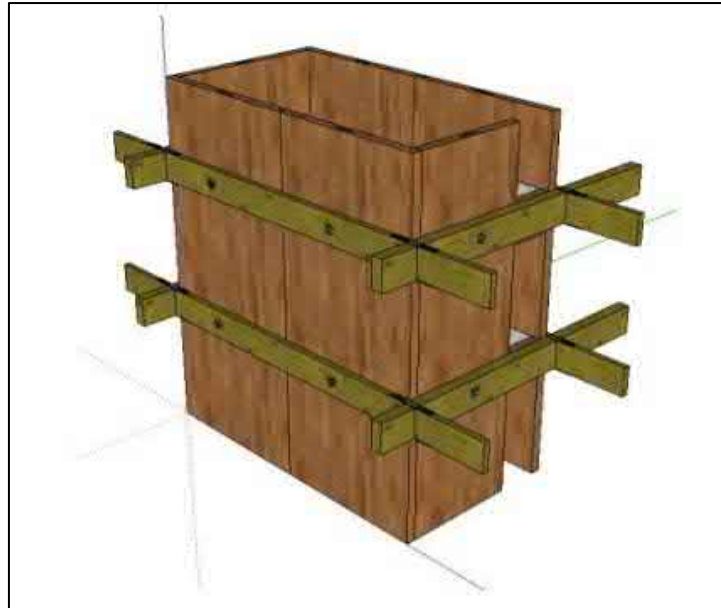


Figure 6: Connections in low-seismicity option
Source: (Dunbar *et al.* 2013)

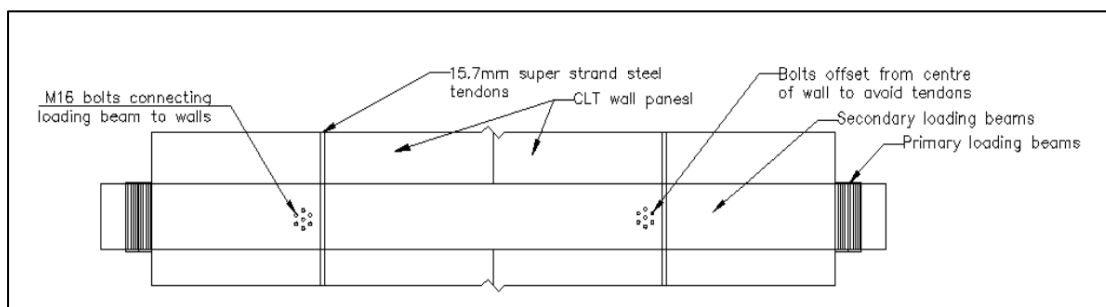


Figure 7: Connection between loading beam and wall panels
Source: (Dunbar *et al.* 2013)

Fire-exposed CLT model testing

Fire damage is another lethal injury risk to residents during and after an earthquake. Excellent fire resistance in building materials provides enough escape time by allowing strong structural stability. CLT panels have been verified to have good fire resistance when integrated with other protectors, such as gypsum board and adhesive, to prevent heat or gases flowing through the gaps between boards (Osborne *et al.* 2012).

Fire resistance testing of CLT products was undertaken by FPI innovations, Canada, who aimed to confirm the fire resistance calculation of CLT in protected and unprotected circumstances under loading conditions. To avoid specimen inequity, CLT products were adopted from two manufacturers in Canada in the experiment, and tests were taken in three series.

Series One: a three-layer floor and a wall protected with gypsum board.

Series Two: a five-layer floor and a five-layer wall that were unprotected.

Series Three: a three-layer floor, a five-layer floor which was protected; a seven-layer floor which was not protected; a five-layer wall with thinner plies.

The results of the tests are summarised in Table 2.

Table 2: Summary of fire resistance tests

Test title		Numbers of layers	Thickness (mm)	The load applied (kN/m ² to floor, kN/m to wall)	Duration of the test (minutes)	Charring rate (mm/min)	Protection
Wall	Test 2	3	114	333	106	0.55	2 x 12.7 mm Type X Gypsum board
	Test 4	5	175	333	113	0.6	Unprotected
	Test 8	5	105	72	57	0.98	Unprotected
Floor	Test 1	3	114	8.74	77	0.53-0.72	Unexpected test stoppage by lab staff
	Test 3	5	175	11.75	96	0.64	Unprotected
	Test 5	3	105	2.4	86	0.78	1 x 15.9 mm Type X Gypsum board
	Test 6	5	175	8.1	124	0.88	1 x 15.9 mm Type X Gypsum board
	Test 7	7	245	14.58	178	0.79	Unprotected

Tests of Series One

The three-layer CLT floor and wall panels were made with black spruce boards and glued with polyurethane adhesive (PUR). Panels were cut into the exact width of 763mm, while the length of floor panels and wall panels were 4786mm and 3048mm, respectively. The two outer layers were 1650Fb-1,5E machine stress rated (MSR) lumber, while the inner layer was spruce, pine and fir (SPF) No.3/stud. Outer layers of the specimen were protected with two layers of 12.7 mm fire-rated Type X gypsum board in this series.

In the testing process, the specimens were tested according to the local standards, such as the CAN ULC S101-Standard methods of fire endurance tests for building construction and materials. The furnace temperature was regulated in the standard, which required the temperature to be close to the regulated temperature curve. The tolerance of furnace temperature accuracy to the standard should be less than 10% within an hour of combustion, 7% between one to two hours, and 5% for longer than two hours. In Series One, the accuracy of the two tests was -0.6% and -0.4%, respectively, which are within the tolerance of the standard. The temperature curves of the two tests are shown in Figure 8.

Test one - three-layer floor: The load applied to the three-layer floor is 8.74 kN/m². After the CLT floor was placed and preloaded for one hour, the fire resistance test began and lasted 77 minutes. The test was stopped by laboratory staff due to concerns about furnace safety. The test process was thoroughly recorded. At 60 minutes, gypsum began to fall off; at 66 minutes, the second layer of gypsum began to fall off; at 76 minutes, the first gypsum fell off; and at 77 minutes, the test is stopped, with the second layer of gypsum remaining in several places. After the test, the rest of the gypsum board was removed to observe that all the exposed surfaces were charred, while the unexposed surfaces remained unchanged. Temperatures caught by thermocouples at different depths were from 22°C at the unexposed surface to 918°C at the exposed layer. The temperature between gypsum and CLT was seen to be 623°C. The char depth was measured at five spots on the panel, with a depth of 8.3mm to 11.3mm, and a charring rate (mm/min) from 0.53 to 0.72.

The maximum deflection of the floor was measured at the mid-span, which was 15.2 mm at the moment of the preloading. It was then zeroed before the fire resistance test. After the 77 minute test, the deflection at the same spot was 32.1mm. This was the first CLT test in this laboratory. The unexpected test stoppage provided evidence of much uncertainty as to the CLT performance since the structural failure was not observed.

Test two - three-layer wall: The specimen of the CLT panel was in the same ambient environment as the specimen in Test One. The preload applied to the CLT wall was calculated as 333kN/m. This test lasted 106 minutes until structural failure due to buckling was observed. This process was recorded thoroughly as well. Key moments were: at 15 minutes, a 1mm deflection occurred at the wall centre; at 30 minutes, water was driven off at the unexposed surface; at 74 minutes, the first layer of gypsum began to fall off; at 86 minutes, a piece of the second layer of gypsum began to fall off, and smoke at the unexposed side joint was 86°C; at 106 minutes, there was a structural failure due to buckling.

After the test, the fire was extinguished quickly, and the rest of the gypsum was removed. The whole surface on the exposed side was charred. The temperature caught by the thermocouple was from 24°C at the unexposed surface to 814°C between gypsum layers. The deepest char was measured as 25.13mm, with a charring rate (mm/min) of 0.55.

The maximum deflection at the preloading stage was 0.7mm at mid-span. Then the load was removed, and the deflection was zeroed. After the test, the average deflection was 47.5mm along the centre line, while the maximum deflection was measured as 55.3mm at the mid-height of the centre of the specimen. Two layers of gypsum postponed the charring of the CLT panel wall by approximately 60 minutes.

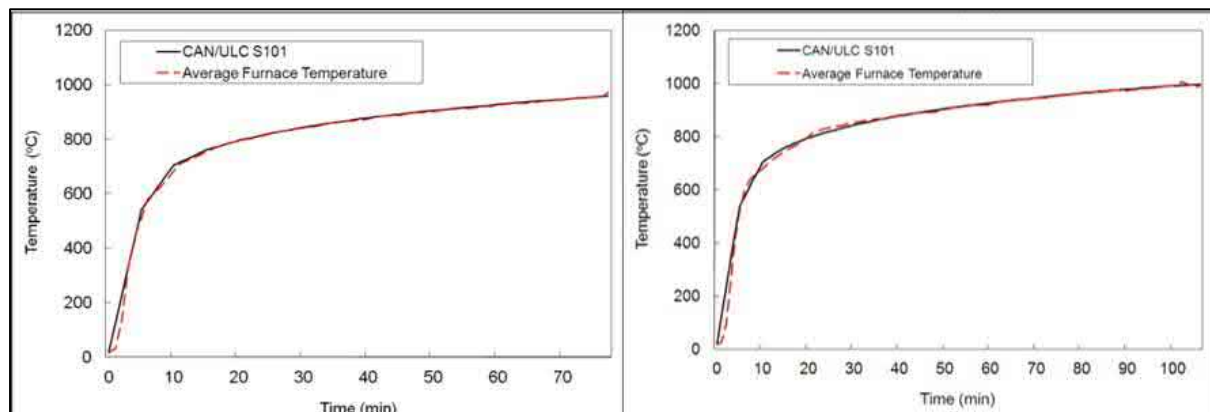


Figure 8: Temperature curve in Series One Source: (Osborne *et al.* 2012)

Tests of Series Two

Five-layer CLT unprotected panel floors (Test Three) and unprotected walls (Test Four) were tested in Series Two. The same materials were adopted in the manufacture of the CLT panels – black spruce boards – but the type of outer longitudinal layers was 1950Fb MSR. The inner transverse layer remained the same with Series One as SPF No3/stud. Both the specimen of the floors and walls were made up of three panels. Panels were fastened with halved joints and screws. The total dimension of the floor was 4846 wide x 3632 high, and the size of the wall was 3658 wide x 3048 high. Five thermocouples were evenly attached to the floor and the wall respectively to monitor the temperature in the test. The deflection was measured at nine spots for each floor and wall.

The testing process met the same Standard as Series One, and the accuracy of the furnace temperature was -0.4% for Test Three and 1.6% for Test Four (see Figure 9). At the beginning of Test Four, drastic fluctuation occurred because of the flashover caused by the burning of the unprotected surface.

Test three - five-layer unprotected floor: The applied load to the CLT floor was 20.7kN/m². The test lasted 96 minutes as flaming was observed at the joint. Before the test, a one hour preload was attached to the floor under ambient conditions, with an average deflection of 23.7mm at the mid-span. Then, the load was removed for further fire resistance testing until failure. During the testing, key observations were recorded: at two minutes, the entire exposed surface charred; at 50 minutes, a 55mm deflection was observed at the centre of the floor; at 57 minutes, a small piece of the first layer began to fall off; at 60 minutes, large fragments of the first layer fell off; at 92 minutes, smoke penetrated the joint; at 96 minutes, test failures due to flaming were observed at the joint. The average charring rate for the first layer was 0.55, and the average charring rate was 0.64.

The test ended at 96 minutes as the floor could not protect the residents in the building. Then the specimen was removed from the furnace, and the fire self-extinguished without visible flame found. The first layer of the exposed surface was almost burned out and fell off, and a low percentage of the second layer fell off. Only a slight char was observed on the surface on the unexposed side. The average temperatures caught by the thermocouple were from 20°C at the unexposed surface to 1005°C at the 17.5mm depth of the floor.

In the preloading stage, the maximum deflection was 23.7mm. Then the measurement was zeroed before the fire resistance test. When the test ended, the maximum deflection was measured as 129.4mm at the centre of the floor.

Test four - five-layer unprotected wall: In the preloading stage, the applied load to the CLT wall was 333kN/m, causing an average deflection of 1mm. In the fire resistance test, structure failure occurred at 113 minutes due to structural buckling, and flames were observed. Key observations were: at 25 minutes, the average temperature on the surface reached 300°C; at 52 minutes, the first layer began to fall off; at 105 minutes, the second layer began to fall off; at 113 minutes, the wall failed due to structural buckling, and flames were observed.

Only small pieces of the first and second layers remained in place after the test. In addition, the wall was observed to be detached from the frame, and the loading beam pivoted outwards. The charring rate in this specimen was between 0.55 to 0.94 – the average charring rate was 0.6 for the first layer and 0.71 for the second layer.

At the first 20 minutes of the test, the maximum deflection of the CLT wall in the furnace was 0.03mm, and the final average deflection was 47.5mm, with a maximum of 55.3mm.

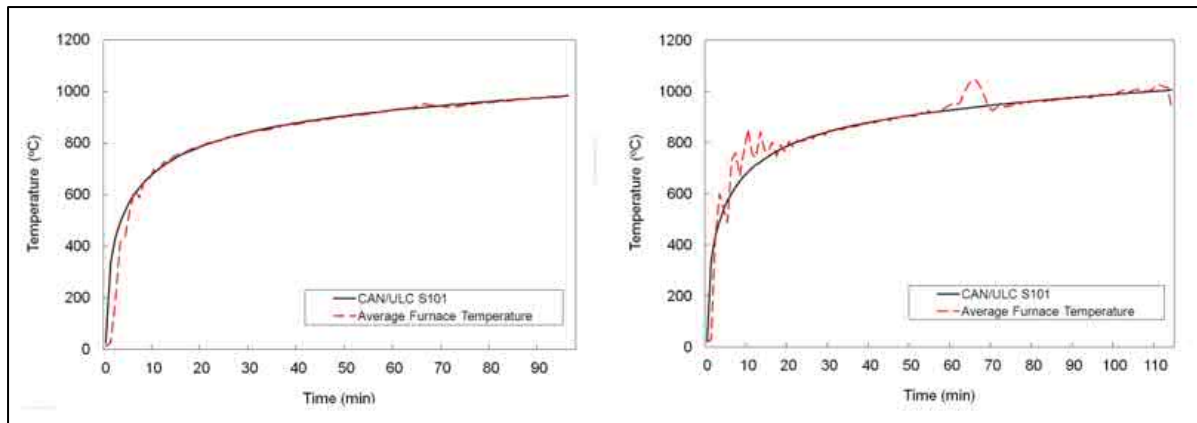


Figure 9: Temperature curve in Series Two Source: (Osborne *et al.* 2012)

Tests of series three

In this series, the floor layers were 35 x 127 board, while the wall layers were 21 x 127. Layers are bonded with Purbond polyurethane adhesive. The floor and the wall consisted of three equal-sized panels, with a total floor dimension of 4846 x 3607 and a total wall dimension of 3660 x 3048. The three-layer and five-layer floors were protected with one layer of 15.9 mm Type X gypsum board, and the seven-layer floor and five-layer wall were unprotected. Other ambient conditions remained the same as the tests above.

Test five - three-layer floor with one-layer protection: This test had just one layer of protection. Thermocouples were embedded in the floor to measure the temperature during the test. The accuracy of the temperature in the furnace was -0.5% (see Figure 10). The load applied to the panel was 2.4kPa, and 74 psi hydraulic pressure was applied to the loading frame.

The test lasted 86 minutes, ending with flame penetration at the joint and integrity failure. Key observations were recorded and listed: at 11.5 minutes, deflection at the panel centre was 7.6 mm; at 19 minutes, light flaming was observed at some joints; at 28 minutes, smoke was monitored at panel edges; at 30 minutes, there was flaming at all joints; at 50 minutes, gypsum began to fall off; at 53 minutes, the deflection was 55 mm; at 78 minutes, pieces of the first layer began to fall off; at 86 minutes, the test ended due to visible flame at the unexposed side and integrity failure.

After the test, the entire gypsum fell off, and the exposed surface was charred. Most of the first layer had fallen off, and only a small piece of the second layer had fallen off. The temperature was read to be 60°C at the unexposed surface and 949°C behind the gypsum board. Later the specimen was cut at seven places to observe the charring rate. The average depth of char was from 42 mm to 54 mm, while the charring rate was from 0.69 to 0.88, with an average rate of 0.78.

In the preloading stage, the average deflection was 22 mm at the centre line, and then it was zeroed for the fire resistance test. At 75 minutes into the test, the deflection rapidly rose but decreased at 80 minutes, which means the entire first layer fell off, and it lost its loadbearing capacity. Maximum deflection happened at the centre of the floor, with a value of 321.4 mm.

Test six - five-layer floor with one-layer protection: The five-layer floor had only one layer of protection in this test. Thermocouples were embedded in the floor to measure the temperature during the test. The accuracy of the furnace temperature in the test was -0.3% (see Figure 11). The load applied to the panel was calculated to be 8.1 kPa, and 222 psi hydraulic pressure was applied to the loading frame.

The fire resistance test ended at 123 minutes because of visible flame on the unexposed side joints. In this process, the entire gypsum board fell at 26 minutes; at 35 minutes, smoke was observed at the panel edge; at 66 minutes, pieces of the first layer began to fall off; at 108 minutes, the second layer began to fall off; at 123 minutes, the test ended due to flame penetrating the joint, and it was predicted that structural failure might occur soon.

The entire gypsum board fell at 26 minutes, much earlier than expected. Later, the entire first layer fell off, then most of the second layer fell. The highest temperature captured by the thermocouple was 971°C at a depth of 35mm, while on the unexposed surface, it was 27°C. Information about the charring was measured at six locations on the floor. The average char depth was 86mm, and the overall charring rate was 0.78 to 0.98, with an average rate of 0.88.

The preloading caused a 19 mm deflection of the floor. In the fire test, the maximum deflection was captured at 156 mm along the centre line of the floor.

Test seven - seven-layer floor without protection: The seven-layer floor remained unprotected in this test. Thermocouples were embedded in the floor to measure the temperature during the test. The accuracy of the temperature in the furnace was -0.1% (see Figure 12). The load applied to the panel was calculated to be 14.58 kPa, and the loading frame was allowed to be 398 psi by hydraulic pressure.

The test lasted for 178 minutes, ending with structural failure. During the test: at 44 minutes, small pieces began to fall off; at 100 minutes, a small part of the second layer began to fall off; at 122 minutes, the flame was observed at the edge; at 145 minutes, a crack was heard; at 155 minutes, there was heavy smoke at the joint; and, at 178 minutes, structural failure.

After the test, the exposed surface was charred, the first two layers had completely fallen off, and a large piece of the third layer had fallen off. Significant deflection had been found after the test – panel one remained deformed after the load was removed, but the other two panels returned to their original shape. The char depth was measured in five spots and showed charring from 133mm to 149mm, with a charring rate from 0.75 to 0.84 and an average rate of 0.79.

The initial deflection at the preloading stage was 15.9mm. After the fire resistance test, the maximum deflection was measured to be 170mm at the centre of the floor.

Test eight - five-layer wall without protection: The five-layer wall remained unprotected in this test. Thermocouples were embedded in the floor to measure the temperature during the test. The accuracy of the temperature in the furnace was 7.5% (see Figure 13), which was within the range of tolerance since the test lasted 77 minutes. In the preloading stage, 72 kN/m was applied to the panel.

The test lasted 57 minutes when the failure occurred due to flame penetrating a halved joint connection. Key observations in this test were: at one minute, a small amount of smoke was observed at the centre of the unexposed side; at 30 minutes, the first layer began to fall off; at 51 minutes, the second layer began to fall off, and the third layer was burning; at 57 minutes, flame penetrated through the joint, and the test stopped.

After the test, the entire first layer had fallen off, and most of the second layer had fallen off. The flame penetration was caused by a structural failure between panels two and three, where buckling of panel two unsealed the halved joint between panels two and three. The highest temperature of 903°C occurred at a depth of 10.5mm, while the lowest temperature of 30°C was at the unexposed surface. The char depth was between 53 to 60 mm measured at seven spots, and the charring rate was from 0.93 to 1.06 with an average rate of 0.98. The maximum deflection at the preloading stage was 1.3 mm and occurred at the centre of the wall. Then the

measurement was zeroed for further test. After the fire resistance test, the maximum deflection was 77 mm.

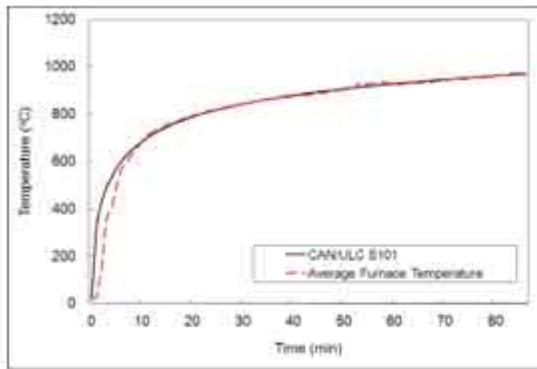


Figure 10: Temperature curve in Test five
Source: (Osborne et al. 2012)

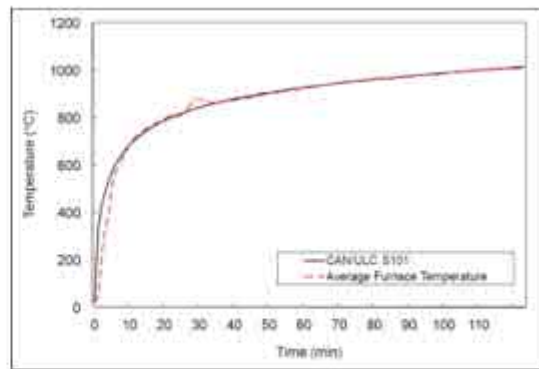


Figure 11: Temperature curve in Test Six
Source: (Osborne et al. 2012)

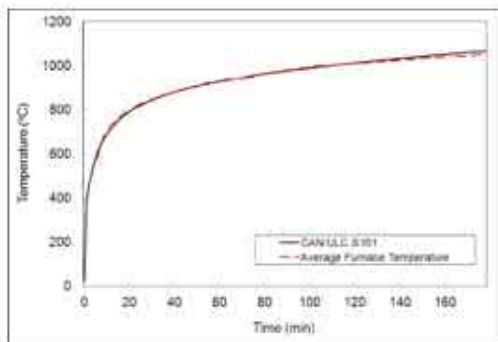


Figure 12: Temperature curve in Test Seven
Source: (Osborne et al. 2012)

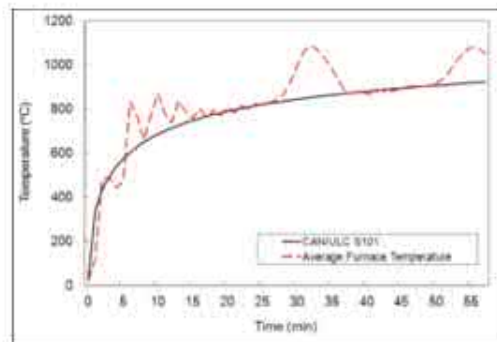


Figure 13: Temperature curve in Test Eight
Source: (Osborne et al. 2012)

A desirable aspect of post-tensioned CLT wall panels was observed in the seismic tests from the Structures Laboratory of the University of Canterbury. In Specimen 1 (high-seismicity region testing), the corner columns were the key components against shear force and took the perpendicular load. In Specimen 2 (low-seismicity region testing), a smaller number of screws in the structure showed better structural-stability performance by allowing the CLT wall panels to rock individually. This experiment provides the necessary confidence in using CLT products in multi-storey buildings in earthquake-prone Christchurch.

From the fire resistance test performance of CLT above, the essential aspect is preventing heat and toxic gases from penetrating from one fire cell to another and postponing structural failure in a fire. According to the Acceptable Solution for Buildings with Sleeping (non-institutional) (Risk Group SM), the fire resistance ratings for a multi-storey apartment should be: Life rating = 60 minutes, Property rating = 60 minutes; if the building is provided with automatic fire sprinkler system with smoke detectors and manual call points (Type 7 of fire alarm systems), the fire ratings should be: life rating = 30 minutes, and Property rating = 30 minutes. From the tables of fire resistance tests of CLT products, all the results meet the requirement under Type 7, but it is recommended that CLT products should be protected at least on one face to delay structural failure, as happened in Test 5 where the test ended in 57 minutes due to structural failure. To sum up, CLT products present very high performance against fire while protected with Type X Gypsum Board Protection, and double-faced protection is better than single-faced protection.

Conclusion

Since its development, CLT products have become a widely-used building material in single-family houses and multi-storey buildings in Europe. In New Zealand, there are already some existing buildings, such as the Tait Communications Building, with some CLT components. However, these existing buildings are only combinations of CLT and other engineered timber products or building materials such as reinforced concrete. In New Zealand, there is no building erected with only CLT products.

From the seismic and fire resistance tests undertaken by the Structures Laboratory of Canterbury and FPI innovations, CLT products have excellent performance in earthquakes and fire.

These test results show that multi-storey buildings erected with CLT product theoretically have good tolerance against earthquakes and subsequent fire hazards. They could contribute to saving lives after an earthquake. In the seismic tests, it is clear that some of the key elements contribute to the increase of the CLT products performance in an earthquake, such as installing corner columns against shear force and allowing each CLT product to rock by using a smaller number of screws in the system. In the fire resistance tests, the duration of wall tests lasted from 57 minutes to 113 minutes, and the floor tests lasted from 77 minutes to 178 minutes, depending on the number of plies, board thickness, and the protection conditions. The fire resistance performance of CLT products will be substantially improved by applying a Type X gypsum board on at least one side of the CLT board. However, more research still needs to be done using local timber materials to prove the feasibility of widely using CLT products in multi-storey buildings in Christchurch and develop regulations in accordance with sound local CLT product standards.

There is no regulation about the height of CLT multi-storey buildings, but the building height in central Christchurch is limited to 28m. From the guide of Wood Solutions in Australia, CLT

apartment and office buildings can reach 25m in height, so this could be a suitable reference for New Zealand about CLT product development.

References

- American Wood Council, 2015. *Cross Laminated Timber in the 2015 IBC and NDS (MAT242)* [Online]. Available from: <https://www.awc.org/pdf/education/mat/AWC-MAT242-CLT-2015NDS-2hr-150825.pdf>
- Braun, V. and Clarke, V., 2006. Using thematic analysis in psychology. *Qualitative Research in Psychology*, 3(2), 77-101.
- Brown, J., Li, M., Karalus, B. and Stanton, S., (2020). Withdrawal behaviour of self-tapping screws in New Zealand cross-laminated timber. *New Zealand Timber Design Journal*. 28(2).
- Canterbury Earthquake Recovery Authority, 2012. *Christchurch central recovery plan*. Christchurch: Canterbury Earthquake Recovery Authority.
- Chang, S. J., Wi, S. and Kim, S., 2019. Thermal bridging analysis of connections in cross-laminated timber buildings based on ISO 10211. *Construction and Building Materials*, 23, 709-722.
- Construction Review Online, 2021. *Top tallest timber buildings in the world* [Online]. Available at: <https://constructionreviewonline.com/biggest-projects/top-5-tallest-timber-buildings-in-the-world/>
- Crampton, A., 2017. *Cross-laminated timber: An innovative building material takes hold in Oregon*. Portland: Portland State University.
- Darby, H., Elmualim, A. and Kelly, F., 2014. A case study to investigate the life cycle carbon emissions and carbon emissions and carbon storage capacity of a cross laminated timber, multi-storey residential building. *In: Sustainable Building Conference*, 23-25 April 2013, Munich, Germany.
- Divekar, N., 2016. Introduction to new material-cross laminated timber. *International Journal of Engineering Research*, 5(3), 675-679.
- Dunbar, Pampanin, S., Palermo, A. and Buchanan, A., 2013. Seismic design of core-walls for multi-storey timber buildings. *In: New Zealand Society for Earthquake Engineering Technical Conference and AGM*, 26-28 April 2013. Wellington, New Zealand.
- Durlinger, B., Crossin, E. & Wong, J., 2013. *Life cycle assessment of a cross laminated timber building*. Melbourne: Forest and Wood Products Australia Limited.
- Espinoza, O., Trujillo, V. R., Mallo, M. F. L. and Buehlmann, U., 2016. Cross-laminated timber: Status and research needs in Europe. *BioResources*, 11(1), 281-295.
- Fitzgerald, D., Sinha, A., Miller, T. H. and Nairn, J. A., 2020. Toe-screwed cross-laminated timber connection design and nonlinear modeling. *Journal of Structural Engineering*, 146(6).
- Fortune, A. and Quenneville, P., 2011. Feasibility study of New Zealand Radiata Pine cross-laminated timber. *New Zealand Timber Design Journal*, 19(3), 3-7.
- Frangi, A., Fontana, M., Hugi, E. and Jubstl, R., 2009. Experimental analysis of cross-laminated timber panels in fire. *Fire Safety Journal*, 44(8), 1078-1087.
- GeoNet Geological hazard information for New Zealand, 2021. *Earthquake Statistics*. [Online] Available at: <https://www.geonet.org.nz/earthquake/statistics>
- Gjerde, M., 2017. Building back better: Learning from the Christchurch rebuild. *Procedia Engineering*, 198, 530-540.
- GNS Science, n.d.. *Earthquakes at a Plate Boundary*. [Online] Available at: <https://www.gns.cri.nz/Home/Learning/Science-Topics/Earthquakes/Earthquakes-at-a-Plate-Boundary>
- Hassan, O. A., Oberg, F. and Gezelius, E., 2019. Cross-laminated timber flooring and concrete slab flooring: A comparative study of structural design, economic and environmental consequences. *Journal of Building Engineering*, 26.
- Henek, V., Venkrbec, V. and Novotny, M., 2017. Fire resistance of large-scale cross-laminated timber panels. *In: World Multidisciplinary Earth Sciences Symposium (WMESS 2017)*, Prague: IOP Publishing. Checkrepublic.
- Klippel, M. and Schmid, J., 2018. Design of cross-laminated timber in fire. *Structural Engineering International*, 27 (2), 224-230.
- Kuilen, J. V. D., Ceccotti, A., Xia, Z. and He, M., 2011. Very tall wooden buildings with cross laminated timber. *Procedia Engineering*, 14, 1621-1628.
- Lendlease Corporation, 2016. *It's cheap and speedy to erect - could timber help solve the housing crisis*. [Online] Available at: <https://www.lendlease.com/better-places/20160803-cheap-and-speedy-timber-housing>
- Lqbal, A., 2018. Cross laminated timber in New Zealand: Introduction, prospects and challenges. *New Zealand Timber Design Journal*, 22, 3-8.
- Lu, Z., Zhou, H., Liao, Y. and Hu, C., 2018. Effects of surface treatment and adhesives on bond performance and mechanical properties of cross-laminated timber (CLT) made from small diameter Eucalyptus timber. *Construction and Building Materials*, 161, 9-15.

- Mallo, M. F. L. and Espinoza, O., 2015. Awareness, perceptions and willingness to adopt Cross-Laminated Timber by the architecture community in the United States. *Journal of Cleaner Production*, 94, 198-210.
- Mathewson, N. and Turner, A., 2013. *Anchor projects bill totals \$4.8 billion*. [Online] Available at: <https://www.stuff.co.nz/the-press/news/city-centre/8849251/Anchor-projects-bill-totals-4-8-billion>
- McDonald, L., 2020. *Christchurch nine years on the reshaping of a city*. [Online] Available at: <https://www.stuff.co.nz/national/119421238/christchurch-nine-years-on-the-reshaping-of-a-city>
- Ministry for the Environment and Stats NZ, 2020. *Our atmosphere and climate 2020 summary*. [Online] Available at: <https://www.stats.govt.nz/information-releases/new-zealands-environmental-reporting-series-our-atmosphere-and-climate-2020>
- Mohammad, M., 2011. Connections in CLT Assemblies. In: *Cross Laminated Timber Symposium*, 8-9 February 2011, Vancouver, Canada.
- Moser, T., Aitken, M. and Spearpoint, M., 2016. Measuring the char rate of cross laminated timber in an intermediate-scale furnace. *The New Zealand Timber Design Society Journal*, 24 (1), 3-9.
- Muszynski, L. et al., 2017. Insights into the global cross-laminated timber industry. *Bioproducts Business*, 2(8), 77-92.
- Osborne, L., Dagenais, C. and Bénichou, N., 2012. *Preliminary CLT Fire Resistance Testing Report*, Canada: Advanced Building Systems–Serviceability and Fire Group.
- Park, H.M. et al., 2003. Static bending strength performances of cross-laminated woods made with five species. *Journal of Wood Science*, 49(5), 411-417.
- Parkes, B., 2020. *Rising from the rubble: How Christchurch rebuilds*. [Online] Available at: <https://www.intheblack.com/articles/2020/04/01/how-christchurch-rebuilds>
- Perinotto, T., 2019. *XLam confirms it's closing New Zealand operations*. [Online] Available at: <https://thefifthestate.com.au/innovation/building-construction/xlam-confirms-its-closing-new-zealand-operations/>
- Polastri, A. et al., 2014. Structural characterisation of multi-storey buildings with CLT cores. In: *World Conference on Timber Engineering*, 10-14 August 2014, Quebec City, Canada, 10-14.
- Popovski, M. and Karacabeyli, E., 2012. Seismic behaviour of cross-laminated-timber structures. In: P. Quenneville, ed. *World Conference on Timber Engineering*, 16-19 July 2012, Auckland, New Zealand.
- Serrano, E. and Enquist, B., 2010. Compression strength perpendicular to grain in cross-laminated timber (CLT). In: *11th World Conference on Timber Engineering (WCTE)*, 20-24 June 2010 Trentino, Italy: Trees and Timber Institute, National Research Council.
- Sikora, K. S., McPolin, D. O. and Harte, A. M., 2016. Shear Strength and Durability Testing of Adhesive Bonds in Cross-laminated Timber. *The Journal of Adhesion*, 92(7-9), 758-777.
- Stora Enso, 2013. *CLT-Cross Laminated Timber Fire Protection* [Online]. Available from: https://www.trada.co.uk/media/5878/13_04_30_clt_documentation_on_fire_protection.pdf
- Waugh Thistleton Architects, n.d. Murray Grove: The original timber tower. [Online] Available at: <https://waughthistleton.com/murray-grove/>
- Zaki, A., 2021. *Ten years after Christchurch's devastating quake 'anchor projects' yet to be completed*. [Online] Available at: <https://www.rnz.co.nz/news/national/436883/ten-years-after-christchurch-s-devastating-quake-anchor-projects-yet-to-be-completed>

Theme 2: Building Performance

An approach to construct Bayesian networks for use in living environment field, taking Chinese CCRCs as the example

Xuechun Wang* Bo Xia Jiaxuan E and Lindy Osborne Burton

Queensland University of Technology, Australia.

*Corresponding author: xuechun.wang@hdr.qut.edu.au

Abstract

Fast population aging has been considered one of the most challenging demographic transitions globally. The influence of older adults' living environment on their well-being cannot be ignored. Although the importance of living environment factors on the well-being of people has been widely recognized, the interaction between these factors and their interactive influence on the well-being of older people have not been quantified.

This paper presents a detailed approach to develop a Bayesian network (Bns), focusing on constructing, parameterizing and quantitatively evaluating the Bns, with the ultimate purpose of revealing the impact of living environment on residents' well-being in Chinese Continuing Care Retirement Communities (CCRCs). Living environment variables that may affect well-being were first identified via comprehensive literature review. Two contextually appropriate scales were then selected to measure well-being. Based on this, we further developed the construction process of Bns for the CCRCs, including qualitative and quantitative parts.

Fifteen living environment variables were identified, comprising community daily life service, urban infrastructure accessibility, community management and operation, greening space, safety, connection with family, social engagement, community daily support facilities, social connection within the community, walkability, community social activities engagement, community barrier-free infrastructure, health services, and age-friendly indoor environment. The Ryff Scale and the Short Form-36 Scale were considered appropriate for measuring well-being. Combining these findings, the process of developing a definite whole Bns approach for the CCRCs is proposed. Experts' viewpoints and Dempster-Shafer Theory (DST) are utilized to construct Bns. Knowledge Engineering Bayesian Networks (KBEN) are adopted to combine expert and data sources to parameterize and evaluate the Bns.

This research promotes the innovative application of Bns in environmental research, involving the elements and methods of constructing the model. Researchers can refer to the guidance and use it as a feasible instrument to apply to their research, which advances future investigations in the field.

Keywords

Bayesian networks, CCRCs, China, Living environment, Well-being

Introduction

The United Nations predicts that over 30% of the Chinese population will be over 60 years old by 2050 (United Nations 2019, Zhu and Walker 2021). In the past two decades, China benefited from a strong and rigorous arrangement of family commitments, which the elderly depend on

for extensive help (Lu *et al.* 2021). However, the scaling down of family structures and other social changes have put increasing pressure on aged care, which has shaken customary locally established home-based care for the elderly (Peng 2011).

In this specific circumstance, the Continuing Care Retirement Communities (CCRCs) are an arising institutional living arrangement for the expanding number of more established Chinese (Hu *et al.* 2019), which alleviates the aging problem from the housing perspective. As a practical housing choice for more older individuals, CCRCs need to provide an age-accommodating living environment, that fulfills occupants' necessities as far as a way of life and environmental friendliness (Shinan-Altman *et al.* 2020). Therefore, the incorporation of more established adults' living environments, which are adapted for aging, cannot be overlooked. However, the living environment in CCRC is a complex system as it consists of various living environmental factors and, more importantly, these factors have an interactive and combined impact on the well-being of residents in CCRCs.

Bayesian networks (Bns) offer a practical and deductively solid way to display this sort of complex system (Liu *et al.* 2018, George and Renjith 2021, Laskey and Mahoney 2000), and they have been widely applied in environmental research (Kaikkonen *et al.* 2021). The general procedure for building a Bns is widely recognized, with its priority to obtain a set of research variables as the nodes in the structure. Subsequently, a causal graphical model is constructed, as a Directed Acyclic Graph (DAG) based on the selected variables, which is followed by the data-based and expert knowledge-based parameterization (Conditional Probability Table (CPT) determination) and quantitative evaluation (Nwadigo *et al.* 2020).

However, a concrete and practical construction procedure of developing a Bns model for the field of living environments is still lacking, with the context of CCRCs no exception. Simultaneously, it has been observed that the primary impediment in Bns calculation in environmental research is the high measure of information it requires, noting that the earlier widespread application of Bns was in the field of computers, where large amounts of data are easily accessible (Amin *et al.* 2019).

Therefore, to address this research gap this study proposed a definite whole Bns procedure, to understand the effect of comprehensive living environment factors on the well-being of residents in Chinese CCRCs, and adopting a more practical approach for small sample studies to avoid obstacles like insufficient data. In this paper, the Bns structure was built utilizing experts' viewpoints and Dempster-Shafer Theory (DST), based on the 15 living environment variables and two well-being scales that we selected. The Knowledge Engineering of Bayesian Networks (KEBN)'s method was subsequently proposed to combine expert and data sources, to parameterize and evaluate the Bns (Korb and Nicholson 2004, Sanchez *et al.* 2020).

Literature Review

The definition of CCRCs and Chinese CCRCs

CCRCs began in the United States as a special sort of senior-arranged development (Kennedy and Coates 2008). Ordinarily, CCRCs offer an assortment of housing choices to retirees, and care and clinical service to residents in the community where they reside independently, and with few health problems. The elderly in these communities maintain independent living as long as possible, supported by daily care services provided to meet their particular needs, as they continue to age (Doron and Lightman 2003). A proper care unit ought to be set up in CCRCs, to support the needs of the residents who experience physical or mental illness. The intent is that these older occupants remain in the CCRC, as their levels of care continue to increase, and until the end of their life (Zarem 2010).

In China, the development of CCRCs is in its initial stages. Hu *et al* (2018) define various perspectives and meanings of CCRCs. They explain that Chinese CCRC programs can provide either accommodation intended for older adults in their local area, or independent living retirement communities. The former program supports more independent Chinese individuals, who are assisted by family and community care services like the Xinfuhui project developed by Vanke. The later program, provides arranged institutional care services within an aged and homogeneous community, for instance, community projects created by Taikang Life (Hu *et al*. 2018).

Living environment factors in CCRCs

Hall and Richards (2000) argue that the living environment has a prominent place in CCRCs, but there is no agreement on the interrelationships between living environment factors, that impact older occupants. Several variables have been presented through different investigations, of significant living environments.

Li et al (2011), Wang (2021), Wang and Hong (2020), Jiang and Liu (2007), and Lee (2020) report that age-responsive environment factors, such as indoor barrier-free design, indoor comfort, and indoor privacy protection, are significant to the living environment. Wennberg et al (2010) explain the important role of barrier-free facilities in the community living environments. The study undertaken by Hou (2018), proposes that convenient commercial daily service facilities in the community would improve the living environment. Shippee (2012), Campbell (2015), Boeder et al (2020), Aviles et al (2020), and LeBard-Rankila (2021), outline the elements of key community activity facilities, including relaxed activities/facilities, age-appropriate physical activities/facilities, and rehabilitation equipment.

Shiran (2019) conducted a comprehensive study, reviewing the influence of green spaces on living environments, within communities. While Hwang et al (2019) and Colistra (2019) focus rather, on the influence of walkability in communities. Ayalon and Green (2013) and Ayalon (2015) emphasize that safety and security is another key factor that should be considered. Lam and Yan (2021) state that accessibility of municipal facilities, should be valued as well. Snow et al (2018), Murty (2017), and Chum et al (2020), propose that staff-resident interactions and a sense of connectedness between neighbourhood and community, are two aspects of social connection within the community that influence living environments. Yuan et al (2018) emphasize that engagement in community social activities, is also an important factor that should be considered and accommodated for.

The study led by Glass (2014) argued for the importance of a sense of connectedness with family in living environments, within community living. Bowes (2017), Koren and Ayalon (2019), and Ayalon and Yahav (2019), report that social engagement factors such as continuity of the past through the continuation of social roles, and social connection with people of different ages, are important factors to include in living environments. Furthermore, holiday benefits (Lam and Yan 2021), sanitary conditions (Parker 2020, Lee 2020), community regulation (Lam and Yan 2021), and complaint and suggestion services (Lee and Severt 2018), are four fundamental aspects to be factored into community management and operations. Lee and Severt (2018), Dorner and Friedrich (2018), Ayalon (2018), and Lu et al (2021), agree that the key factors of community daily life include: information dissemination service, food and beverage service, daily life service, and shuttle service. Lee and Severt (2018), and Jester et al (2021) stress the role of health service and emergency service within the community, to enable appealing living environments for residents.

Well-being measurement scales

As the target note of the Bns, “well-being” can be quantified by using scales, so its definition and selection of appropriate scales must be made clear. However until now, there has been little agreement on the clarity and definition of the concept and how it should be measured. Different methods to characterize and estimate “well-being” have been established, for example, the expressions “subjective well-being”, “adjustment”, “life satisfaction”, “happiness”, “quality of life”, “psychological health”, and “morale,” all allude to aspects of well-being (Stanley and Chee 2003). The utilization of so many terms to describe a similar underlying construct, has prompted a lot of discussions, but also noteworthy confusion (Shmotkin 1990).

The World Health Organization (WHO) defines “well-being” as including physical and mental health, emotional well-being, and social functioning (Baernholdt *et al.* 2012). For instance, Ryffs Scales of Psychological Well-being (RPWB) (Ryff 1995) is one of the scales widely used to assess well-being of the elderly. It has six domains: self-acceptance, positive relations, autonomy, environmental mastery, purpose in life, and personal growth; and includes all the aspects proposed by the WHO, with the exception of physical health. To validate this, it is important to include another measure to supplement the Ryff scale, to document the physical status of the inhabitants. The most significant and widely utilized evaluation on physical health is the 36-item Short Form Survey (SF-36). This survey contains 36 inquiries, and provides eight spaces including: vitality, physical functioning, bodily pain, general health perceptions, physical role functioning, emotional role functioning, social role functioning, and mental health. In addition, other combinations of scales are also feasible, as the choice of measurement standards will depend, to a large extent, on the research question being studied (Coster 2013).

Bns for environmental research

Bns is an useful tool in assessing environment under various backgrounds (Hosseini and Ivanov 2020). It is extremely valuable to forecast, for diagnosis, and as a dynamic examination tool (Anderson and Vastag 2004, Gupta and Kim 2008). Evidence suggests that Bns has been widely used in environmental fields to achieve various research purposes.

Kemperman *et al* (2019) apply Bns to analyze the loneliness of older adults, from the perspective of social networks in the elderly community. Tran *et al* (2019) analyze reforestation decisions by rural mountain communities in Vietnam, utilizing this methodology. Chen *et al* (2021) develop Bns to assess the impacts of certain variables including participation intensity, subjective norm, social identity, group norm, functional value, emotional value, social value, share, interaction, user experience, and user satisfaction on tourism community.

In another review, Kemperman and Timmermans (2014) apply this methodology to demonstrate and analyse direct living environments, and the social life of older adults. Similarly, Goodson and Jang (2008) adopt this methodology together with the nursing home care quality assessment, to assess quality of life. This methodology has also been applied to analysing a group social activity intervention, with seniors in institutions (Navarro Pardo *et al.*, 2018). Moreover, to investigate social interaction patterns in a nursing home environment, Bns is also strategically applied (Chen *et al.* 2004). Furthermore, this methodology has also been utilized for demonstrating and to analyse other similar domains, for example, the wildfires environmental risk management (Penman *et al.* 2020), urban biological risk transmission (Zhang *et al.* 2021), and water pollution accidents (Tang *et al.* 2016).

Research Methodology

First, we conducted a literature review of English-language journals, to summarise foundation information about living environment factors of CCRCs. The way we obtained this was through searching keywords like “living environment” and “CCRCs” in the Web of Science, John Wiley and JSTOR journal databases. Similarly, we searched the same keywords in the full-text data set of Chinese Academic Journals, otherwise called CNKI, to supplement the findings with Chinese perspectives. Reviewing this literature provided background information about the impact of the living environment on the well-being of CCRC residents in China, and helped with the development of a comprehensive list of living environment variables, as a basis for constructing Bns nodes.

Second, we constructed a questionnaire for data collection consisting of various living environment questions, and two well-being questionnaires that were translated into Chinese language. The first questionnaire was framed around the above variables, which directly or by implication, impacted the well-being of the CCRCs’ mature residents, and which cannot be measured directly. A six Likert scale questionnaire was subsequently designed to respond to this. The latter required us to select the most suitable existing measurement scales of well-being, for utilisation. As Coster (2013) asserts, the choice of measurement standards will depend to a large extent on the research question being studied. Therefore, for each study the source and measurement tools were summarized, and their domains were reviewed separately for comparison with the living environment factors noted above. This assisted with predicting whether the scale can measure all the factors of the living environment.

One of the strategies to determine sample size, is to utilise published tables that provide recommendations which are underpinned by agreed measures (Israel 1992) according to three standards: the degree of accuracy, the degree of confidence or risk, and the level of variability in the properties being estimated (Miaoulis and Michener 1976, Israel 1992). Table 1 shows the sample size needed for a given blend of precision, confidence level, and variability.

Third, as there is little formal guidance on how to construct Bns for CCRCs, we proposed a detailed methodology for this process, and utilized Netica as an analytics platform. We conducted the process adhering to idiomatic guideline standards of Bns.

Bns consists of both qualitative and quantitative components:

- The qualitative part is prepared from a Directed Acyclic Graph (DAG), comprised of nodes that represent variables. While directed arrows between variables address direct causal conditions, dependent on process understanding, measurable, or different sorts of affiliations (Sari *et al.* 2018, Nwadigo *et al.* 2020).

- The quantitative part is prepared from Conditional Probability Tables (CPTs), that are utilized to portray the probability of each value of the child node. These are conditioned on each possible combination of values of its parent nodes (Amin *et al.* 2019, Tang and Huang 2019).

Table 1. Test Size for $\pm 3\%$, $\pm 5\%$, $\pm 7\%$, and $\pm 10\%$ Precision Levels where Confidence Level Is 95% and $P=5$; a = Assumption of typical populace is poor (Yamane 1967).

Size of Population	Sample Size (n) for Precision (e) of:			
	$\pm 3\%$	$\pm 5\%$	$\pm 7\%$	$\pm 10\%$
3,000	811	353	191	97
4,000	870	364	194	98
5,000	909	370	196	98
...	...	...	...	...

Findings and Discussion

Living environment variables

We found 28 factors that directly or by implication, impact well-being of the CCRCs' mature residents. Then we classified these as 15 variables: community daily life service, urban infrastructure accessibility, community management and operation, greening space, safety, connection with family, social engagement, community daily support facilities, social connection within the community, walkability, community social activities engagement, community barrier-free infrastructure, health services, and age friendly indoor environment.

In addition, we referred to Hu et al. (2018)'s classification of living environments, which includes built environmental sustainability, social-friendliness, and sufficient service. Next we incorporated the 15 variables into these, thus constituting a three-level classification of the living environment factors of the CCRCs. Table 2 shows the final 28 main factors, 15 variables and three categories of living environments in the CCRCs.

The data gathering tool - questionnaire

The data collection process involved current residents of the selected CCRCs. The living environment component utilized questions such as "Indoor facilities help me to be as independent as possible, how much do you agree with this?" Answers were presented on a 6-item Richter scale with options ranging from "strongly disagree to strongly agree".

The remainder of the questionnaire was about residents' well-being. We identified and summarized 77 measurement instruments of well-being, which were developed from hundreds of publications that could be applied to the elderly. These are summarized in Table 3. As previously described, we applied the Ryffs Scales of Psychological Well-being (RPWB) (Ryff, 1995) to our study, and the 36-item Short Form Survey (SF-36) was used as a supplement to the Ryff scale, to document the physical status of the inhabitants.

Table 2: Three categories, fifteen variables and twenty-eight main variables of living environment in the CCRCs.

Categories	15 living environment variables	28 living environment factors
Built environmental	Age-friendly indoor environment	Indoor barrier-free design (Li <i>et al.</i> 2011, Wang 2021) Indoor comfort (Wang and Hong 2020) Indoor privacy protection (Jiang and Liu 2007, Lee 2020) Barrier-free facilities in the community (Wennberg <i>et al.</i> 2010).
	Community barrier-free infrastructures Community daily support facilities Community activity facilities	Convenient commercial daily service facilities in the community (Hou 2018) Relaxed activities or facilities (Shippee 2012, Campbell 2015) Age-appropriate physical activities facilities (Boeder <i>et al.</i> 2020, Aviles <i>et al.</i> 2020) Rehabilitation equipment (Wang and Wong 2018, LeBard-Rankila 2021) Greening space (Shiran 2019) Walkability (Hwang <i>et al.</i> 2019, Colistra 2019) Safety and secure (Ayalon and Green 2013, Ayalon 2014) Municipal facilities accessibility (Lam and Yan 2021)
Social environmental	Greening space Walkability Safety and secure Urban infrastructure accessibility Social connection within the community	Staff-resident interactions (Snow <i>et al.</i> 2018) Sense of connectedness between neighbourhood and community (Murty 2017, Chum <i>et al.</i> 2020) Community social activities engagement (Yuan <i>et al.</i> 2018)
	Community social activities engagement Connection with family Social engagement	Sense of connectedness with family (Glass 2014)
Services	Community management and operation Community daily life service Health service	Continuity of past with continuation of social roles (Bowes 2017, Koren and Ayalon 2019) Social connection with people of different ages (children) (Ayalon and Yahav 2019) Holiday benefits (Lam and Yan 2021) Cleanliness/sanitary conditions (Parker 2020, Lee 2020) Community regulation (Lam and Yan 2021) Complaint and suggestion service (Lee and Severt 2018) Information dissemination service (Lee and Severt 2018) Food and beverage service (Dorner and Friedrich 2018). Daily life service / butler services (Ayalon 2018) Shuttle service (Lu 2021) Health service (Lee and Severt 2018) Emergency service (Lee and Severt 2018, Jester <i>et al.</i> 2021)

Table 3: 77 Measurement scales of well-being (the complete form is in Annex 1 Table 4)

No.	Author(s), year	Name of measurement scale (abbreviation)	Domains
1	Nieboer, 2005	Social production function (SPF-IL)	Universal goals affection, behavioural confirmation, status, comfort and stimulation
2	Ryff, 1995	Ryffs Scales of Psychological Well-being-84 (RPWB)	Self-acceptance, positive relations, autonomy, environmental mastery, purpose in life, personal growth
3	Tellegen, 1996	Multidimensional Personality Questionnaire Well-being Scale (MPQ-WB)	Social potency, achievement, social closeness, stress reaction, alienation, aggression, control, harm avoidance, traditionalism, absorption
4	Mezzich, 1994	Multicultural Quality of Life Index (MQLI)	Physical SWB, psychological SWB, self-care, independent functioning, occupational functioning, interpersonal functioning, social-emotional support,

5	Neugarten 1961	Life Satisfaction Rating Scale (LSR)	community and services support, personal fulfillment, spiritual fulfillment, overall quality of life
...	...	...	Zest, resolution and fortitude, congruence between desired and achieved goals, positive self-concept, and mood tone.
77	Russell, 1982	Loneliness: The UCLA Loneliness Scale The de Jong Gierveld Loneliness Scale (UCLA)	...

Constructing Bayesian networks for CCRCs

Stage 1: construct a causal graphical model as a Directed Acyclic Graph (DAG) based on the selected variables

The Bns analysis' first stage is to fabricate the graphical model as a coordinated DAG that is causal, and it addresses interrelationships among every single designed variable (Sari *et al.* 2018).

As previously described, there is no globally accepted model to identify well-being of occupants impacted by living environment variables in CCRCs, so we had to construct our own model for this study. The living environment variables of CCRCs mentioned above can be used to construct DAG.

There are two fundamental methods upon which these can be built: utilizing structure learning algorithms, eliciting experts' viewpoints, and both (Mohammadfam *et al.* 2017). The former uses an assortment of algorithms. The primary obstruction to using calculations, is the high measure of information they require (Amin *et al.* 2019). Constructing Bns utilizing the second methodology appears more suitable in CCRCs field, wherein specialists should be approached to appoint a causal relationship for each pair of variables.

Among them, the approach of eliciting expert opinion, the Dempster-Shafer Theory (DST) is a choice suitable for the field. It is extensively used to solve complex decision problems because of its advantages in representing uncertain information. Dempster (1967) developed the Dempster-Shafer theory (DST) in 1967, and it was later expanded upon by Shafer (1976). It works on the numerical treatment of the "probabilities" of events that do not have clear defined bounds. For example, it is a valuable way to reduce inconsistencies, when data is gathered from different sources. Thus, the DST can be applied to incorporate the probabilities acquired from various specialists.

This process was carried out in two steps. The first step was to propose a preliminary conceptual Bns structure model suitable for CCRCs, based on a literature review showing the interrelationships of selected living environment variables. The second step was to use DST to re-assign the inter-relationships between the selected variables, that are considered by experts to be improved (Misuri *et al.* 2018). Specialists then assigned a probability to every three imaginable connections between each pair of variables, in the progression. Dempsters' rules of blend were utilized to coordinate the experts' perspectives, and lastly the relationship with the highest mass value was chosen to construct the Bns.

Three potential relationships were characterized between each pair of living environment variables, that were considered to need improvement. For example, between variable "greening space (A)" and variable "community social activities engagement (B)", three potential connections are as per the following: variable A directly influences variable B ($A \rightarrow B$), variable B directly influences variable A ($A \leftarrow B$), or there is no connection between variable A and variable B ($A \uparrow B$).

The justification for allocating these three connections as the main potential ones, is that they are the main three connections that can be characterized between two variables in the Bns. In this progression, specialists must be approached to indicate a likelihood for each of these three potential connections, and the sum of the three determined probabilities should be equivalent to one. Dempster's role of blend that was utilized in this study, is the following equations (1) and (2). The relationship that has the greatest mass value was appropriated, to address the connection between two variables.

$$m(A) = \frac{1}{1-K} \sum_{A_1 \cap A_2 \dots \cap A_n = A} m_1(A_1) \cdot m_2(A_2) \dots m_n(A_n) \quad (1)$$

$$K = \sum_{A_1 \cap A_2 \dots \cap A_n = \emptyset} m_1(A_1) \cdot m_2(A_2) \dots m_n(A_n) \quad (2)$$

Where in the above conditions; “ $m(A)$ ” is the mass probability developed for every relationship (for example, variable “greening space (A)” and variable “community social activities engagement (B)”, “ $m_n(A_n)$ ” is the likelihood that CCRCs specialists “ n ” indicated to a relationship. “ K ” is a measure of the amount of dispute among sources of data and “ $1-k$ ” is the normalizing factor.

Stage 2: determine Conditional Probability Tables (CPT)

After variable selection as well as Bns construction, another phase is the estimation of the parameter (Korb *et al.* 2004), involving stipulating the CPTs for each variable. The cell's number within every table, represents the outcome of multiplication of variable states' number and its parent nodes' states' number. Such CPTs may be provided from professionals, estimated from data, or comprise of both.

In environmental study, accessing only expert knowledge or data for parameterization, is difficult. On the one hand, to date many Bns established for the management of environment have become parameterized, employing purely knowledge elicitation. Such models are not only increasingly qualitative, but the effort and time engaged in an intricate Bns elicitation, may become overwhelming (Kaikkonen *et al.* 2021). Moreover, according to Cooke (1991) along with Morgan and Henrion (1990), expert knowledge is, at times, partial. Regrettably, within environmental applications data solely seem frequently limited for Bns parameterization (Uusitalo 2007). In the community environmental research, the parameter number within the study's Bns will usually exceed the available data people can collect.

Consequently, the manner in which Bns can be parameterized utilizing elicited information from CCRCs experts, as well as data (questionnaires that we developed, as previously described) from the community, appears more feasible in CCRC fields. We adopted a comprehensive approach for the procedure from Pollino *et al.* (2007), which emphasize Bns parameterization through both experts' opinions and databases, whose approach accentuates the Knowledge Engineering of Bayesian Networks (KEBN) (Woodberry *et al.* 2004). KEBN denotes a spiral or iterative method of modeling development of a prototype, founded on the process of software development (Korb and Nicholson 2004).

Figure 1 illustrates how this can be implemented in a study. Cycle pathways are shown using arrows. They follow through with distinct processes of knowledge engineering, indicated by rectangular boxes, and carried out by people (the CCRCs experts, light grey shade) or through a computer calculation (data from the questionnaire, dark grey shade). The main choice points

are indicated through hexagons, applying Woodberry et al (2004). The estimates in parameter may be generated from CCRCs professionals, in the first path. Estimates of the parameter may be further acquired from the data we collected from communities questionnaires, in the second path. The research implements an approach combining data (questionnaires) with expert knowledge (CCRCs experts) sources, which is demonstrated in the third path. The development of Bns appears to be a process that is iterative.

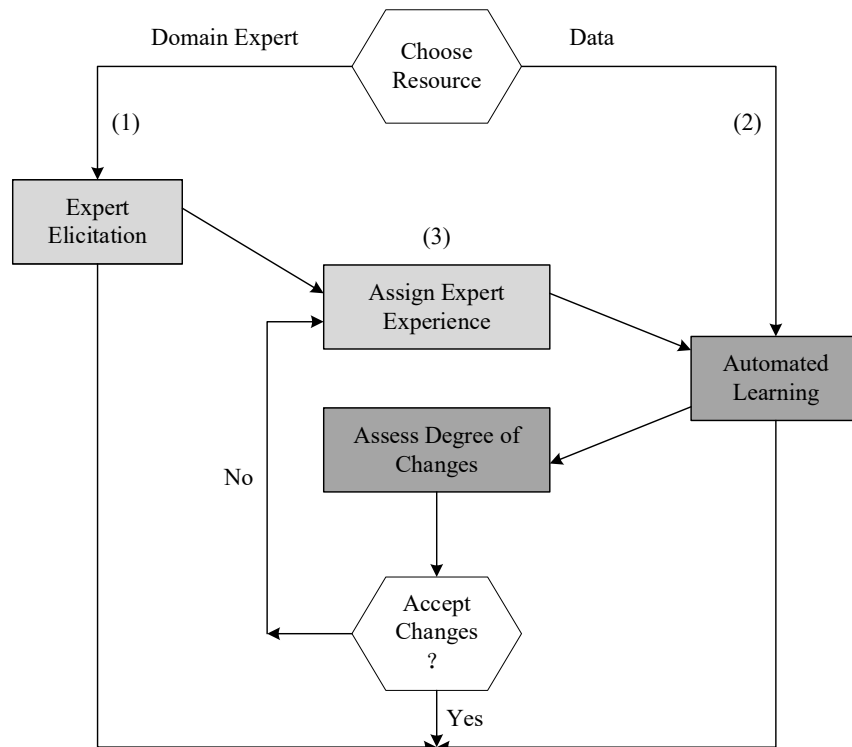


Figure 1: Knowledge Engineering of Bayesian Networks KEBN-determine CPTs (Mohammadfam et al. 2017)

Stage 3: Quantitative evaluation

After parameterisation of the Bns, there is the other KEBN major significant aspect as displayed in Figure 2, which is quantitative assessment. Evaluative criticism can be produced utilizing either CCRCs specialists or data from questionnaires, or both. These findings or outcomes can be utilized to aid Bns improvement.

Evaluation using data

The information ought to be utilized for assessment where possible (Chen and Pollino 2012). A typical method for assessment for a Bns is to measure predictive accuracy. It estimates the frequency with which, the anticipated node expresses that with the most noteworthy probability is noticed, comparative with the real worth. In the CCRCs case, the questionnaire data is likewise being utilized to parameterize CPTs. It is important to separate information into a training set and a test set. For example, if we withhold the data for the variable “greening space”, and then use the model to predict the outcome of this variable, the model error rate can be detected. Another test is to evaluate whether patterns in model expectation are stable, with past or current circumstances. For the CCRCs Bns, if trends between predictions and data are maintained, the test results are better (Li et al. 2019).

Evaluation using experts

It is similarly significant for Bns assessment using specialists. This should be possible by means of a structured review of the model. For the CCRCs Bns, a semi-formal model walkthrough (Goulding *et al.* 2012), could be directed with specialists. If the model provides a positive output, it could be viewed as a practical portrayal of reality. For example, the Bns should be routinely refreshed, which is referenced "next stage" in Figure 2. Alternatively to consider whether the CCRCs Bns should be strengthened, to fit more CCRCs from distinctive locations.

Sensitivity analysis

Belief refreshing (Mohammadfam et al. 2017) is a noteworthy component of Bns, that can be utilized for evaluating the impacts of changing certain variables, on others. Utilizing this function, we can evaluate the sensitivity of the "target note (also called inquiry node-“well-being”)”. Two kinds of sensitivity analyses can be utilized in assessing the CCRCs Bns. The first, sensitivity to findings, considers how the Bns’ posterior distributions change under various conditions, while the second, sensitivity to parameters, considers how the Bns’s posterior distributions change, when parameters (means CPTs) are modified.

Accept model prototype

After the above assessment, if the CCRCs Bns is accepted, then it can be developed further. This choice is not intended to be the end of the process, rather, the KEBN calls for proceeding with an improvement of the model (Korb and Nicholson 2004). The CCRCs Bns can receive new data into the model, and permit the model to be consistently adjusted and refined, empowering innovative reactions to novel circumstances. This interaction can be led utilizing the assessment process described earlier in this paper.

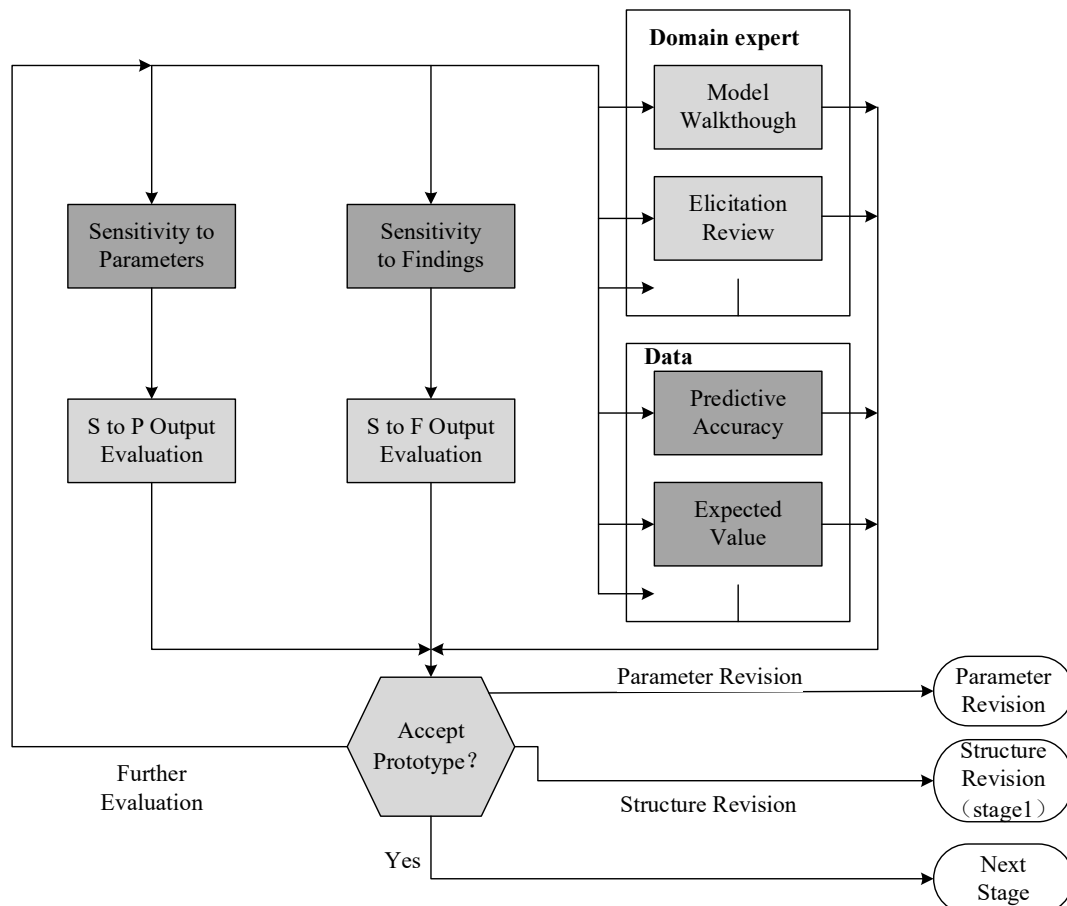


Figure 2: Knowledge Engineering of Bayesian Networks KEBN- Quantitative evaluation (Mohammadfam *et al.* 2017)

Conclusion

Despite the fact that the living environment is a significant research field, the interaction between living environment factors and their interactive influence on the well-being of the elderly, have not been quantified. Bns is a practical research approach for dealing with such a complex system, that has been largely recognized in environmental fields (Liu et al. 2018, George and Renjith 2021, Laskey and Mahoney 2000). Unfortunately, formal guidance on how to construct Bns for living environments, where the main obstacle is the high amount of information it requires, is lacking.

Therefore, in this paper, we have presented a detailed Bns approach to this process, with the ultimate purpose of revealing the impact of living environments on people's well-being, taking Chinese CCRCs as the example.

Firstly, we discovered and summarized 15 living environment variables through an extensive literature review. Subsequently, 77 measurement instruments of well-being were identified and consolidated from hundreds of publications applicable to the elderly, and two contextually appropriate scales were then chosen for the study. Following this, we illustrated how to utilize these variables in constructing the Bns, joining experts' viewpoints and DCT, for construction of DAG. Finally, we adopted expert elicitation, combined with data from the questionnaires, for parameterization of Bns, which was followed by quantitative assessment, adopting either specialists, or data, or both.

This is an integral Bns construction process for the living environment field, which has critical and direct significance for future research. Considering that the comprehension of the living environment of the Chinese CCRCs is restricted (we were unable to travel to the destination due to the impact of the global pandemic), we acknowledge that the variables derived from literature instead of field research, might lack practicality. Nevertheless, we argue that it is feasible for researchers to refer to and apply this method and its instruments, to other research studies.

Acknowledgement

This study was funded by the China Scholarship Council.

References

- Aviles, J., Porter, G.C., Estabrooks, P.A., Alexander, N.B. Madigan, M.L., 2020. Potential implementation of reactive balance training within continuing care retirement communities. *Translational Journal of the American College of Sports Medicine*, 5 (6), 51.
- Ayalon, L., 2015. Perceptions of old age and aging in the continuing care retirement community. *International Psychogeriatrics*, 27 (4), 61-620.
- Ayalon, L., Green, V., 2013. Social ties in the context of the continuing care retirement community. *Qualitative Health Research*, 23 (3), 396-406.
- Ayalon, L., Yahav, I., 2019. Location, location, location: close ties among older continuing care retirement community residents. *Plops one*, 14 (11), e0225554.
- Ayalon, L., Yahav, I. and Lesser, O., 2018. From a bird's eye view: Whole social networks in adult day care centers and continuing care retirement communities. *Innovation in aging*, 2 (3), 024.
- Amin, M.T., Khan, F. and Imtiaz, S., 2019. Fault detection and pathway analysis using a dynamic Bayesian network. *Chemical Engineering Science*, 195, 777-790.
- Boeder, J., Hwang, S., Chan, T., 2020. Engagement with life among the oldest-old in assisted living facilities: enriching activities and developmental adaptation to physical loss. *Ageing and Society*, 1-22.
- Bowes, S., 2017. *Leisure and Social Continuity: The Secret to Successful Aging for Oldest-Old in Long-Term Care?* Thesis (PhD). Bowling Green State University.

- Campbell, N.M., 2015. Third place characteristics in planned retirement community social spaces. *Journal of Architectural and Planning Research*, 32, 55-67.
- Chen, S.H. and Pollino, C.A., 2012. Good practice in Bayesian network modelling. *Environmental Modelling and Software*, 37, 134-145.
- Colistra, J., 2019. Innovations in housing for smart cities. *Journal of Architectural Engineering*, 25 (4), 06019001.
- Doron, I. and Lightman, E., 2003. Assisted-living for older people in Israel: market control or government regulation? *Ageing and Society*, 23 (6), 779-795.
- Dorner, B. and Friedrich, E.K., 2018. Position of the Academy of Nutrition and Dietetics: Individualized Nutrition Approaches for Older Adults: Long-Term Care, Post-Acute Care, and Other Settings. *Journal of the Academy of Nutrition and Dietetics*, 118 (4), 724-735.
- Dempster, A.P., 1967. Upper and lower probabilities induced by a multivalued mapping. *Annals of Mathematical Statistics*, 38, 325-339.
- Glass, A.P., 2014. Innovative seniors housing and care models: what we can learn from the Netherlands. *Seniors Housing and Care Journal*, 22 (1), 74-81.
- George, P.G. and Renjith, V.R., 2021. Evolution of Safety and Security Risk Assessment methodologies to use of Bayesian Networks in Process Industries. *Process Safety and Environmental Protection*, 149, 758-775.
- Goulding, R., Jayasuriya, N. and Horan, E., 2012. A Bayesian network model to assess the public health risk associated with wet weather sewer overflows discharging into waterways. *Water research*, 46 (16), 4933-4940.
- Hou, S.I., 2018. A Taiwan study abroad program on aging, culture, and healthcare. *Educational Gerontology*, 44 (1), 18-27.
- Hu, X., Xia, B., Hu, Y., Skitmore, M. and Buys, L., 2019. What hinders the development of Chinese continuing care retirement community sector? A news coverage analysis. *International Journal of Strategic Property Management*, 23 (2), 108-116.
- Hu, X., Xia, B., Skitmore, M., and Buys, L., 2018. Providing a sustainable living environment in not-for-profit retirement villages. *Facilities*, 36 (5-6), 272-290.
- Hwang, E., Parrott, K., Brossoie, N., 2019. Research on housing for older adults: 2001 to 2018. *Family and Consumer Sciences Research Journal*, 47 (3), 200-219.
- Jiang, Y. E., Liu, J., 2017. Health monitoring system for nursing homes with lightweight security and privacy protection. *Journal of Electrical and Computer Engineering*, 2017, 1360289.
- Jester, D.J., Thomas, K.S., Peterson, L.J., Dosa, D.M., Andel, R. and Hyer, K., 2021. Effect of Hurricane Irma on daily direct care nurse staffing in nursing homes. *Journal of the American Geriatrics Society*, 69 (8), 2298-2305.
- Kaikkonen, L., Parviainen, T., Rahikainen, M., Uusitalo, L. and Lehtikainen, A., 2021. Bayesian networks in environmental risk assessment: A review. *Integrated environmental assessment and management*, 17 (1), 62-78.
- Korb, K.B. and Nicholson, A.E. 2004. *Bayesian artificial intelligence*. London: CRC Press.
- Koren, C., Ayalon, L., 2019. "Not living together yet all the time together": The construction of living apart together in continuing care retirement communities from perspectives of residents and CCRC staff. *Journal of Social and Personal Relationships*, 36 (11-12), 3855-3874.
- Kaikkonen, L., Parviainen, T., Rahikainen, M., Uusitalo, L. and Lehtikainen, A., 2021. Bayesian networks in environmental risk assessment: A review. *Integrated environmental assessment and management*, 17 (1), 62-78.
- Kemperman, A. and Timmermans, H., 2014. Green spaces in the direct living environment and social contacts of the aging population. *Landscape and Urban Planning*, 129 (129), 44-54.
- Kennedy, D.J. and Coates, D., 2008. Retirement Village Resident Satisfaction in Australia: A Qualitative Enquiry. *Journal of Housing For the Elderly*, 22 (4), 311-334.
- Korb, K.B., Hope, L.R., Nicholson, A.E. and Axnick, K. 2004. Varieties of causal intervention. Berlin, Heidelberg, 2004, 322-331.
- Lam, T.Y., Yan, J., 2021. Continuing care retirement community senior housing in Shanghai: an analysis of the development barriers. *International Journal of Housing Markets and Analysis*.
- Li, M., Wang, D. and Shan, H., 2019. Risk assessment of mine ignition sources using fuzzy Bayesian network. *Process Safety and Environmental Protection*, 125, 297-306.
- Liu, W., Yue, K., Yue, M., Yin, Z. and Zhang, B., 2018. A Bayesian network-based approach for incremental learning of uncertain knowledge. *International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems*, 26 (01), 87-108.
- Lu, J., Zhang, L. and Zhang, K., 2021. Care preferences among Chinese older adults with daily care needs: individual and community factors. *Research on Aging*, 43 (3-4), 166-176.
- Lam, T.Y., Yan, J., 2021. Continuing care retirement community senior housing in Shanghai: an analysis of the development barriers. *International Journal of Housing Markets and Analysis*.

- LeBard-Rankila, K., 2021. Stiffness, Pain, and Function of Police Officers: Duty-Belts and the Use of Donuts. *Archives of Physical Medicine and Rehabilitation*, 102 (10), 96-97.
- Lee, J.E., 2020. Stronger Impact of Interpersonal Aspects of Satisfaction Versus Tangible Aspects on Sustainable Level of Resident Loyalty in Continuing Care Retirement Community: A Case Study. *Sustainability*, 12 (21), 8756.
- Li, J., Zhao, Y. J., Li, H., Li, L.F., 2011. Barrier-free interior design for the disabled people. *2011 IEEE International Symposium on IT in Medicine and Education*, 1, 363-367.
- Laskey, K.B. and Mahoney, S.M., 2000. Network engineering for agile belief network models. *IEEE Transactions on knowledge and data engineering*, 12 (4), 487-498.
- Lee, J.-E., 2020. The Six Dimensions of Resident Satisfaction and Their Impact on Word-of-Mouth (WOM) Intention in a Continuing Care Retirement Community (CCRC): A Case Study. *Asia-Pacific Journal of Business*, 11 (4), 49-63.
- Lee, J.-E. and Severt, D., 2018. Diagnostic assessments of service quality in a continuing care retirement community (CCRC): An exploratory study. *Journal of Quality Assurance in Hospitality and Tourism*, 19 (1), 91-111.
- Lu, H. 2021. *The Collaboration Models of Practices of Aging in Community in Different Contexts*. Thesis (PhD). New York: Columbia University.
- Murty, S., 2017. Encouraging community in a continuing care retirement community. *Journal of Gerontological Social Work*, 60 (1), 3-6.
- Misuri, A., Khakzad, N., Reniers, G. and Cozzani, V., 2018. Tackling uncertainty in security assessment of critical infrastructures: Dempster-Shafer Theory vs. Credal Sets Theory. *Safety science*, 107, 62-76.
- Mohammadfam, I., Ghasemi, F., Kalatpour, O. and Moghimbeigi, A., 2017. Constructing a Bayesian network model for improving safety behavior of employees at

Appendix

Table 4: 77 Measurement scales of well-being

Author(s), year	Name of measurement scale (abbreviation)	Domains
Nieboer, 2005	Social production function (SPF-IL)	Universal goals affection, behavioural confirmation, status, comfort and stimulation
Ryff, 1995	Ryffs Scales of Psychological Well-being-84 (RPWB)	Self-acceptance, positive relations, autonomy, environmental mastery, purpose in life, personal growth
Tellegen, 1996	Multidimensional Personality Questionnaire Well-being Scale (MPQ-WB)	Social potency, achievement, social closeness, stress reaction, alienation, aggression, control, harm avoidance, traditionalism, absorption
Mezzich, 1994	Multicultural Quality of Life Index (MQLI)	Physical SWB, psychological SWB, self-care, independent functioning, occupational functioning, interpersonal functioning, social-emotional support, community and services support, personal fulfillment, spiritual fulfillment, overall quality of life
Neugarten 1961	Life Satisfaction Rating Scale (LSR)	Zest, resolution and fortitude, congruence between desired and achieved goals, positive self-concept, and mood tone.
Hills, 2001; Eysenck, 1985; Rosenberg, 1989; Diener, 1985	OHI+ Eysenck Personality Questionnaire (EPQ)+ Rosenberg's Self-esteem Scale (RSS)+ Satisfaction with Life scale (SLS)	Satisfaction with life, personal efficacy, sociability/empathy, a positive outlook, physical well-being, cheerfulness and self-esteem.
Supranowicz, 2014	PMSW-21	Physical domain, mental domain, social domain
Bradburn, 1969	Affect Balance Scale (ABS)	Positive, negative affects
Kinderman, 2011	BBC Well-being Scale (BSC)	Life satisfaction, personal growth, relationships
Katerndahl, 2007	Bio-psycho-socio-spiritual Inventory (BioPSSI)	Health, emotions, relationships, spirituality, life satisfaction

Cummins, 1983	Comprehensive Quality of Life Scale (COMQOL-A4)	Material SWB, health, productivity, intimacy, safety, place in community, affects
Kahnemann, 2004	Day Reconstruction Method (DRM)	Life satisfaction, feelings
Kovess, 2001	Energy and Vitality Index (EVI)	Affects, vitality
Prince, 1999	Euro-D	Affective suffering, motivation
EuroQoL Group, 1990	EuroQOL-EQ-5D	Mobility, self-care, usual activities, pain, anxiety/depression
Csikszentmihalyi, 1987	Experience Sampling Method (ESM)	Affect, arousal, cognitive efficiency, motivation
Deaton, 2008	Gallup-Healthways Well-being Index (GHWBI)	Life satisfaction, emotional health, physical health, healthy behaviours, work environment, access to health care
Goldberg, 1979	General Health Questionnaire-12 (GHQ-12)	Positive, negative affects
Dupuy, 1977	General Well-being Schedule (GWB)	SWB, self-control, vitality, anxiety, depression, general health
Tibblin, 1990	Gothenburg Quality of Life Measurement Scale (GQL)	Affects, social SWB, physical health, life satisfaction
Al Naser, 2005	Kuwaiti Raha Scale (KRS) 2010	Religiosity, happiness, stability, confidence, likable
Scheier, 1994	Life Orientation Test of Optimism and Pessimism-Revised (LOT-R)	Optimism, pessimism
Neugarten, 1961	Life Satisfaction Index (LAI-A)	Zest, congruence between desired and achieved goals, positive self-concept, affects
Neugarten, 1961	Life Satisfaction Index (LAI-B)	Zest, congruence between desired and achieved goals, positive self-concept, affects
Neugarten, 1961	Life Satisfaction Index (LAI-Z)	Zest, congruence between desired and achieved goals, positive self-concept, affects
Watson, 1995	Mood and Anxiety Symptom Questionnaire-90 (MASQ)	General distress, anxiety, depression
Watson, 1995	Mood and anxiety Symptom Questionnaire-62 (MASQ)	General distress, anxiety, depression
Ware, 1990	MOS 36-Item Short Form Health Survey-12 (SF-36)	Physical function, role physical, general health, social functioning, pain, mental health, vitality
Peterson, 2005	Orientation to Happiness Scale (OTH)	Meaning, pleasure, engagement
Watson, 1988	Positive and Negative Affect Schedule (PANAS)	Positive, negative affects
Rothmann, 2007	Perceived Wellness Survey (PWS)	Health spirituality, affects, relationships, emotions, cognition
Ruta, 1994	Patient Generated Index General Well-being Scale (PGI.)	Health, affects, relationships
Lawton, 1975	Philadelphia Geriatric Center Morale Scale-22 (PGC)	Agitation, loneliness, attitudes towards aging
Lawton, 1975	Philadelphia Geriatric Center Morale Scale-17 (PGC)	Agitation, loneliness, attitudes towards aging
Vaingankar, 2011	Positive Mental Health Measurement Scale (PMH)	Coping, emotional support, spirituality, relationships, personal growth, affects
Bann, 2012	Public Health Surveillance Well-being Scale (PHS-WB)	Life satisfaction, meaning in life, autonomy, competence, relatedness, affects, relationships, health, energy
Hyde, 2003	Quality of Life Scale (CASP-19)	Control, autonomy, affects, self-realization
Ferrans, 1985	Quality of Life Index (QLI)	Family relations, health, resources, spiritual WB
Kaplan, 1997	Quality of Well-being Scales (QWB-SA)	Health, mental health, mobility, physical activity, relationships
Ryff, 1995	Ryffs Scales of Psychological Well-being-54 (RPWB)	Self-acceptance, positive relations, autonomy, environmental mastery, purpose in life, personal growth
Ryff, 1995	Ryffs Scales of Psychological Well-being-18 (RPWB)	Self-acceptance, positive relations, autonomy, environmental mastery, purpose in life, personal growth
Bringsen, 2009	Salutogenetic Health Indicator Scale (SHIS)	Affects, relationships
Diener, 1985	Satisfaction with Life Scale (SWLS)	Positive affect, absence of negative affect, life satisfaction
Antonovsky, 1987	Sense of Coherence Scale (81)-29	Comprehensibility, manageability, meaningfulness
Antonovsky, 1987	Sense of Coherence Scale (81)-13	Comprehensibility, manageability, meaningfulness

Antonovsky, 1987	Sense of Coherence Scale (81)(81)-9	Comprehensibility, manageability, meaningfulness
Vendegot, 2003	Self-evaluation of Quality of Life (SEQOL)	Well-being, life satisfaction, happiness, family, fulfillment of needs, satisfaction with relationships, releasing life potential, objective factors, quality of life
Ingersoll-Dayton, 2004	Thai Well Being Scale	Life satisfaction, relationships
Tennant, 2007	Warwick-Edinburgh Mental-Well-being Scale (WEMWBS)	Optimism, purpose in life, relaxed, cognition, relationships, feeling loves
Bech, 1993	WHO (Five) Well-being Index	Cheerful, calmness, activity, rest, interest
WHOQUOL, 1998	WHOQOL-100	Physical health, psychological health, social relationships, level of independence, environment, spirituality
WHOQOL, 1998	WHOQOL-Bref	Physical, psychological, health, social relationships, environment
Kozma and Stones, 1980	Memorial University of Newfoundland Scale of Happiness (MUNSH)	Positive affect (PA), negative affect (NA), positive experience (PE), negative experience (NE).
Radloff, 1977	Depression: Center for Epidemiologic Studies Depression Scale (CES-D)	
Spitzer, 1999	The Patient Health Questionnaire 9 (PHQ-9)	
Beck, 1996	Beck Depression Inventory-II (BDI-II)	
Eaton, 2004	Center for Epidemiologic Studies-Depression Scale-Revised (CES-D-R)	
Zigmond, 1983	Anxiety: Cranial electrotherapy stimulation (CES-Anxiety)	
Pachana, 2007	Anxiety: Geriatric Anxiety Inventory (GAI)	
Kirsch, 2013	Anxiety: Hospital Anxiety and Depression Scale (HADS-A)	
Quinn, 2009	Health: Activities of Daily Living (ADL)	
Katz, 1963	Health: 12-Item Short Form Health Survey (SF-12): Physical Component Summary (SF-12Physical) + Mental Component Summary (SF-12Mental); 12-Item General Health Questionnaire (GHQ-12)	
Mackenzie, 2004	Health: Inventory of Attitudes Towards Seeking Mental Health Services (IASMHS)	
Laidlaw, 2007	Subjective representation of aging and old age: Attitudes to Aging Questionnaire (AAQ)	
Sarkisian, 2005	Subjective representation of aging and old age: Expectations Regarding Aging Survey-12 (ERA-12)	
Diener, 1985	Satisfaction with Life: Satisfaction with Life Scale (SWLS)	
Watson, 1988	Satisfaction with Life: Positive and Negative Affect Schedule (PANAS)	
Cantril, 1966	Satisfaction with Life: Cantril Self-Anchoring Striving Scale (CL)	
Choudhary, 2010	Satisfaction with Life: Question on Life Satisfaction (QS)	
Scheier, 1994	Optimism: Life Orientation Test-Revised (LOT-R)	
Kempen, 1996	Self-esteem: the Groningen Activity Restriction (GARS)	
Suurmeijer, 1994	Self-esteem: Scale self-esteem scale (Rosenberg, 1965)	
Rosenberg, 1965	Self-esteem: Rosenberg-Self-Esteem-Scale (SES)	
Körner, 2008	Personality: NEO-Five Factor Inventory (NEO-FFI-30)	

Steger, 2006	Meaning in Life: Meaning in Life Questionnaire (MLQ)	
Kamman, 1983	Affect: Affectometer (AA)	
Russell, 1982	Loneliness: The UCLA Loneliness Scale The de Jong Gierveld Loneliness Scale (UCLA)	

Comparative analysis of air-conditioners and energy consumption levels towards green retrofitting in Ghana

John Dadzie^{1*}, Philip Ansah², Kingsley Apraku¹, Isaac Pratt¹

¹Department of Building Technology, Kumasi Technical University, Kumasi

²Department of Chemical Engineering, Kumasi Technical University, Kumasi

*Corresponding author: john.dadzie@kstu.edu.gh

Abstract

Indoor discomfort triggers demand and installation of air-conditioners in buildings. Available estimates show that over 1.6 billion air conditioners (ACs) have been installed globally. The estimated figure of 1.6 billion is expected to increase to 5.6 billion by 2050 with increasing greenhouse gas emissions. The aim of the study is to identify various air conditioners installed in universities buildings, the energy consumption patterns and energy retrofit implications. Thus, a case study approach was adopted to understand the state of air-conditioners and energy consumption levels of two public universities in Ghana. The study covered a period of 6 months; 3 months for each university. There are four sections in all: onsite visits, categorisation of data, analysis to establish the various air conditioners and related energy use, concluding with energy conservation renovation actions. Overall, 733 air-conditioners were identified with close to 36% being unrated, 44% (1-star), another 11% (2-star) and 9% of being 3-star. In all the cases, the study presents no evidence of the 4-star and 5-star air-conditioners. Thus, energy retrofit actions were estimated using a 4-star energy efficient air-conditioner. Energy savings after retrofit analysis of the unrated air conditioners presents energy savings between 20-30%. The results contribute to policy formulation to ensure actions towards environmental sustainability are achieved.

Keywords

Indoor discomfort, energy retrofit, air-conditioners, energy savings, environmental sustainability

Introduction

Climatic conditions and poor selection of materials affect indoor thermal comfort. The features of a design that promote energy reduction such as orientation, envelope selection, glazing ratio, shading devices and installation of energy efficient technologies are lacking (Majid *et al.* 2014; Dadzie *et al.* 2018). Poor orientation contributes to indoor discomfort and related high energy demand as a result of uncontrolled heat transfer. Also, high glazing to wall ratio to some extent negatively impact energy management actions (Alghoul *et al.* 2017). The International Energy Agency (IAE) reports of a rise in the installation of air conditioners and linked that to improved economic conditions. Demand for ACs is associated with encouraging financial positions as household income tend to support decisions to buy and install in buildings (Al-Qawasmi and Tlili 2018). Installation of air-conditioners over the years has caused increased demand for energy often higher than supply (Raji *et al.* 2015; Winkler *et al.* 2020). Air-conditioning (AC) equipment represents nearly \$100 billion (100 million-unit per year for the global market) and accounting for 4.5 exajoules (4.26 quadrillion Btus) of site energy consumption per year (IEA 2018). Clearly the pattern is not showing any sign of improvement as the main drivers of indoor

discomfort exist or keep increasing. Available estimates show adoption of ACs in developing economies particularly countries in the tropical regions, contributing close to 31% of the total energy consumption (Oh *et al.* 2016).

Improving energy saving of ACs is the main driving factor of improved environmental sustainability. Given that energy consumption and greenhouse gas emissions keep rising, actions are needed to address the problem. Energy efficient air-conditioners continue to improve year after year as attempts to improve energy savings continue (Shah *et al.* 2017). Shah (2021) identifies “best-in-class” high-efficiency room air-conditioners components and products. The findings show that manufacturers tend to minimize production costs by using room air-conditioners designs that are readily available or standardized and share components across various models. High energy demanding ACs are manufactured and supplied although the effects of emissions are severe (Opoku *et al.* 2019). Manufacturers are focused on improving demand without necessarily matching that with improved energy saving potentials. Opoku *et al.* (2020) posit that electricity consumption of such air-conditioners is relatively high, in the range of 3000–5400 kWh/yr per air conditioner depending on the brand and the cooling capacity. Over 85% of air conditioners used in Ghana exist in the lowest energy efficiency ratio category (1-star) and the remaining percentages are in the next lower categories (2 and 3-stars). However, there are other categories of air-conditioners that were not considered in the study by Opoku *et al.* (2020); such ACs consume above present benchmarks, thereby contributing to high emissions. Adopting sustainable construction materials and systems can reduce the high indoor discomfort and improve wellbeing. This study seeks to investigate air-conditioners installed in public universities, the level of energy demand and assess energy conservation retrofit options. This seeks to strengthen actions towards environmental sustainability to reduce emissions.

Literature Review

Studies on air-conditioners and energy consumption in developing economies

Energy demand and supply in many developing economies has been a major challenge due to varying factors particularly the use of air-conditioners. The other factors include tropical weather conditions that cause indoor discomfort as well as poor selection of materials and construction. The deficiencies in the construction sector have placed extra burden not only on the supply but contributed to wastage and excessive energy demand. Developing economies rely heavily on thermal plants that run on fossil fuel for electricity generation. This contributes to the release of greenhouse gases into the environment. Estimates show between 60-80% of electricity consumed in buildings is used to run air-conditioners to provide indoor thermal comfort. Energy efficient air-conditioners are ignored for cheaper models with low efficiency ratings. Energy efficiency and cost saving opportunities in public and commercial buildings in a developing country was studied by Opoku *et al.* (2019). The authors used raw data from a national survey conducted on air-conditioning equipment for the study. Also, to achieve the research objectives, a power quality clamp meter was used to monitor the actual power consumptions of stratified samples of the conventional air-conditioners in offices, as well as that of an inverter air-conditioner installed in an office. The results from the study show that over 85% of air-conditioners used in Ghana exist in the lowest energy efficiency ratio category (1-star) and the remaining percentages are in the next lower categories (2 and 3-stars). It has been determined that enforcing energy efficiency regulations to shift the market structure of air conditioners in Ghana into the higher energy efficiency ratio (EER) categories has huge benefits for the country (Opoku *et al.* 2019).

Opoku *et al.* (2018) focused on air-conditioners powered by solar systems in Ghana and presented economic analysis of a hybrid solar PV-grid powered air-conditioner for daytime office use in hot humid climates. As air-conditioners are the highest energy consuming appliances in buildings, investigating and presenting solutions to address the problem is appropriate for a developing economy. The authors relied on a survey approach and reports of findings that indicate 60–80% of electricity used in offices and commercial buildings is for air-conditioning. In line with the research questions, the authors also studied the performance of a hybrid solar PV-grid powered air-conditioner for daytime office cooling in hot humid climates. Thus, an office building of 30 m² floor area (105 m³ office space) in a building with three of the sides sharing walls with adjacent offices, and the front side facing north was used for the study, with the air-conditioner set at a temperature of 20 °C. In the experiment, the pure sine wave hybrid inverter with integrated PWM charge control system was set to solar energy priority and supported by utility grid electricity when solar energy is not sufficient. Initial results indicate that a 1040 Wp solar PV system with 200 Ah, 24 V battery configuration has a monthly mean solar fraction of 51% ± 9% for an air-conditioner with nominal cooling capacity of 2.5 kW and maximum power consumption of around 1.19 kW. The energy generation of the 1040 Wp solar PV system has been determined to be around 1211 kWh per year. Adoption of the hybrid solar PV-grid powered air-conditioner presents a financial gain of US\$ 1600 compared to 100% utility grid electricity in 10 years. In another study, Arthur and Fiano (2020) explored knowledge and understanding of energy efficiency in air-conditioning by focusing on the manufacturing sector. The study investigated energy efficiency (EE) measures and practices from the perspectives of Ghana's manufacturing sector. A mixed methods approach that applied both qualitative and quantitative strategies were applied. The authors explained that a quantitative approach is relevant to establish statistical inferences and the qualitative methods used to provide further in-depth understanding to statistic(s) provided by the quantitative analysis. The study used close to 750 respondents although actual analysis was done with a sample size of 260. The shortfall is often due to errors and late submission of questionnaires. The authors concluded that knowledge about EE awareness and practices occurring at the departmental levels was mixed but clear on servicing and cleaning of air-conditioning. Also, the findings identified failure to clean the heating, ventilating and air-conditioning systems, to close doors and windows while ACs were on and avoidance of the use of efficient refrigerants and new ACs are major factors that negatively impact EE for the manufacturing industries. The findings are consistent with similar studies conducted by Kubota *et al.* (2011) on energy consumption of air-conditioners in Malaysia.

Drivers of energy efficiency development in lighting and air-conditioning systems was presented by Arthur and Fiano (2019). The study used a survey approach to assess the drivers to energy efficiency in lighting and air-conditioning systems from the perspective of two manufacturing industries. The results show that staff of manufacturing industries consider the availability of information on energy efficiency measures, staff awareness and knowledge and the availability of funds as leading drivers to energy efficiency development. Also providing incentives in the form of awards to employees drives energy efficiency. The inferential statistics showed that employees' gender, department and job position predict the barriers to energy efficiency in the manufacturing industries. However, drivers of energy efficiency are not dependent on gender, department of work and job position. Uba *et al.* (2013) proposed a simplified procedure for estimating air-conditioning cooling load. The study argues that undersized or oversized air-conditioning equipment leads to high operational cost, frequent breakdowns and accelerated wear of equipment. Wrong sizing of equipment is often the result of inaccurate procedures employed to estimate the cooling load of the air-conditioned space. The Transfer Function Method (TFM), a well-known cooling or heating load estimation procedure that has been adopted by ASHRAE, was applied. The tool predicted the hourly and

daily average cooling load due to different types of walls, roofs and fenestration that are typically found in buildings. This has been used to develop cooling load factors that simplify load estimation with a worksheet. The outputs of the worksheet were compared with the result of the cooling load estimated using a computer program and were found to be satisfactory. Duggal and Singh (2016) investigated and conducted an energy audit of 109 air conditioners. The performance of air conditioners was evaluated using operating parameters - air flow rate and enthalpy difference across the evaporator coil as described by Bureau of Energy Efficiency. The findings show that 55 units did not conform to star labelling specifications and 50% units performed below 75% of their rated capacity. Common air-conditioning issues such as low refrigerant charge, unclean filters, non-evident insulation, infrequent maintenance and improper installation.

Ahadzie *et al.* (2019) attempted to understand occupant behaviour in the use of ACs towards combating climate change. The study identified occupant behaviour that contributes to efficient use of ACs in public buildings and how that can be factored into developing energy efficiency guidelines. The study by Ahadzie *et al.* (2019) is consistent with that undertaken by Arthur and Fiano (2019). The only deviation is the focus of the study, the sample and the sectors considered for data collection. Drawing on the theory of planned behaviour (TPB), survey questionnaire was used to collect data from office buildings. Partial least squares–structural equation modelling (PLS-SEM) analysis was employed for the analysis. The results show that switching on fan(s) as alternative to ACs has a path coefficient of 0.527 and opening windows for natural ventilation accounting for 0.351 significant path coefficient. Wearing of light or heavy clothing as a means of conserving energy achieved 0.174 impact coefficient while occupant behaviour of switching off ACs when leaving the room came last in the ranking, with an impact coefficient of 0.146. Similar studies indicate that switching off ACs when leaving a space has recorded high impact compared to wearing of lighting clothes. Gyamfi *et al.* (2017) in presenting the energy efficiency situation in Ghana discussed many issues including the country's electrical appliance market, which has been flooded with imports of used low-efficiency appliances from overseas. The research provides a review of energy efficiency initiatives undertaken by agencies responsible for energy generation, transmission, and distribution. It discusses the current energy efficiency status of three household appliances, namely refrigerators, air-conditioners and lighting systems. The review indicates that EE measures carried out especially in the replacement of incandescent lamp with compact fluorescent light (CFL) made significant savings that offset the national electricity peak demand by 200–240 MW. Thus, the study aligns to the theory of environmental sustainability and reduction of emissions through energy retrofit.

Research Methodology

The research methodology section discusses case studies as the data collection approach and the nature of data collected for the study. A case study methodology as proposed by Yin (2018) was adopted and applied for the purpose of this study. It commenced with a description of the cases and the data collected from two cases (that is public universities) in the middle part of Ghana - The Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development (AAMUSTED) and Kumasi Technical University. Majority of the programs are aligned to technical training, technology development and transfer. There are over 30 blocks on the main campus, construction is in 5” solid sandcrete blocks with 25mm cement sand mortar as plaster on both external and internal surfaces and finished with paint. The windows are generally sliding louver glass, fixed in hardwood timber frames, with aluminium sheeting as roof finish. In all the buildings, the ceiling is finished with plywood sheets nailed to

hardwood noggings, painted, with heights less than 3m. A large percentage of the buildings are poorly oriented, contributing to high indoor thermal discomfort. In Kumasi Technical University (KsTU), there are over 20 blocks on the main campus and many other similar blocks on the second campus. The style and nature of construction of the buildings on campus are similar to that of AAMUSTED, again with close to 40% of the buildings poorly oriented, thereby contributing to high indoor thermal discomfort. Data collection consisted of identifying the type of air conditioners and manufacturers, taking details of energy consumption on labels, and studying hours of consumption. Data collection starts from 9am to 5pm except weekends and lasted months. The approach is consistent with similar studies on university buildings all over the world. Pazouki *et al.* (2021) used a university as a case study in presenting a mathematical model to find the best strategy for building energy retrofit. The multi-objective optimization model takes into account economic criteria such as profit, initial cost, and payback period, as well as environmental objectives such as energy-saving and the use of clean and renewable energy. Also, Ascione *et al.* (2015) conducted a feasibility study of energy savings and respect of the historical value of educational buildings using three main approaches. They include performance assessment, in situ monitoring and documental information. Assimakopoulos *et al.* (2020) applied a case study approach in discussing a holistic approach in energy retrofiting. Energy saving estimates are based on the energy efficiency ratings of the various air conditioners and the average hours of consumption.

Findings and Discussion

The results of the level of installation of air-conditioners as presented in Tables 1 and 2 are consistent with the objectives of the study. There are about 20% of air-conditioners in AAMUSTED compared to KsTU. This aligns to the total students admitted, number of buildings, size buildings and availability of space for development.

Table 1: Classification of air-conditioners

Case study	Types of air-conditioners				Total
	Unrated	1-star	2-star	3-star	
KsTU (Case 1)	89	118	13	6	226
% of distribution	39	52	6	3	100
AAMUSTED (Case 2)	139	158	62	48	407
% of distribution	34	39	15	12	100

Table 1 presents an overview of air-conditioners installed in the two universities. For the first case, the results show that 89(39%) air-conditioners are unrated, 1-star are 118(52%), 2-star presents 13(6%) and 6 (3%) for 3-star. Case 1 shows the university has installed more 1-star than the unrated air conditioners. In case 2, 139(34%) of conditioners are unrated, 158 (39%) are 1-star, 62(15%) 2-start and 48(12%) for 3-star air-conditioners. Thus, in both cases the 1-star air conditioners are more compared to the other types. Also, there are more unrated air-conditioners than the 2-start and 3-start models as the study recorded no 4-star and 5-star air-conditioners. The results are consistent with the findings of Opoku *et al.* (2019) indicating high installation of 1-star and other low rated air conditioners in Ghana. The findings show that energy consumption patterns of the 1-star and unrated air conditioners are almost the same as indicated in Table 2. Thus, energy retrofit calculations are based on the unrated air conditioners as that address all 1-start air conditioners as well. Details of the savings are presented in figures 1 and 2.

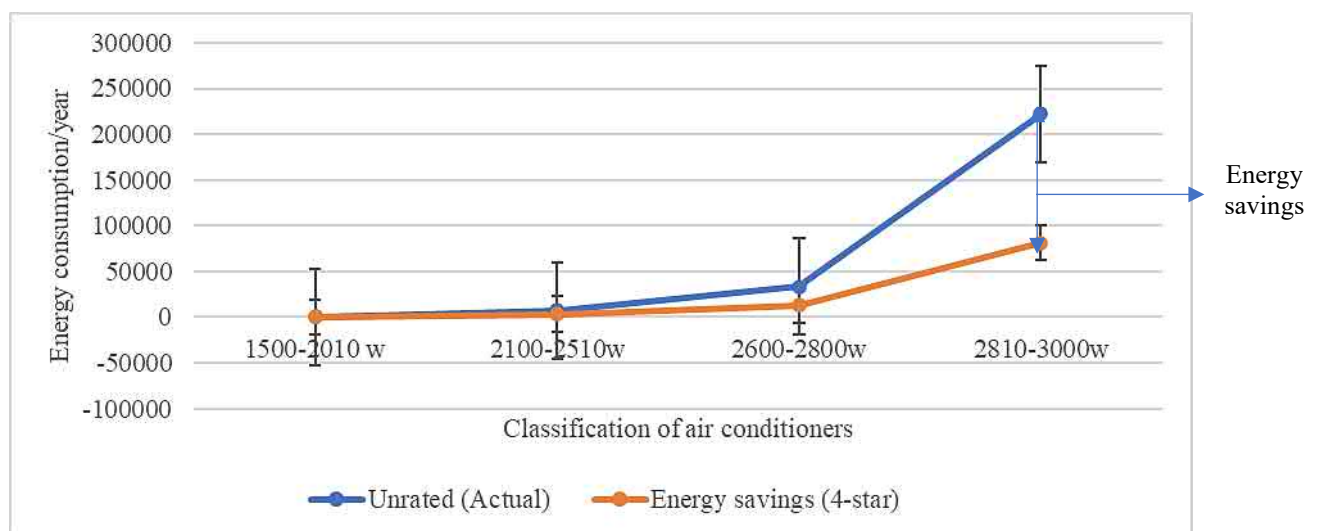
Table 2: Energy rating patterns

CASE 1				
	Energy Rating			
Air-conditioners	1500-2010 w	2100-2510w	>2800w	>3000w
Unrated	0	0	15	74
1-star	0	73	33	12
2-star	2	10	1	0
3-star	5	1	0	0
CASE 2				
Air-conditioners	1500-2010 w	2100-2510w	>2800w	>3000w
Unrated	0	0	75	64
1-star	0	92	45	21
2-star	36	22	4	0
3-star	37	11	0	0

To estimate the energy consumption and likely retrofit actions, the study grouped the air-conditioners using the energy ratings. The ranges were established using the data obtained onsite with details indicating a minimum of 1500w to a maximum of more than 3000w. In the case of unrated air-conditioners, majority as identified are over the 2800w and 3000w levels of energy demand.

Energy saving towards retrofit with 4-star inverter air-conditioner

The average power consumption of the inverter air-conditioner is determined to be about 1100W (1.10 kW), classified as a 4-star. An inverter air-conditioner consumes 33% less electricity on average compared to a conventional air-conditioner (Duggal and Singh 2016). The measured weighted average power consumptions were compared with their respective name plate power inputs for the different energy efficiency ratio (EER). Thus, the study adopted and applied the rating of a 4-star inverter for energy saving estimates and retrofit actions.

**Figure 1: Actual and predicted energy savings – CASE 1**

Figures 1 and 2 present energy saving potential of retrofitting unrated air-conditioners as identified in Case 1 and Case 2. In both analysis, energy savings between 20-30% of the total annual consumption can be achieved using the 4-star inverter air conditioner.

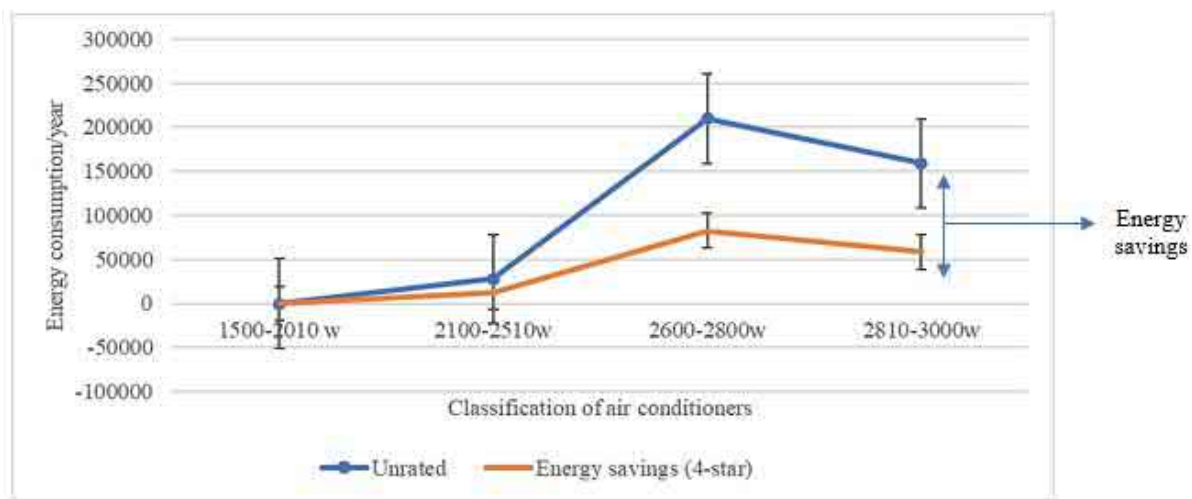


Figure 2: Actual and predicted energy savings – CASE 2

Conclusion

Many past studies identified the main air-conditioners as 1-star, 2-star, 3-star, 4-star with other studies discussing the 5-star models. However, this study has identified another type known as the unrated air-conditioners. This type of air-conditioner presents no classification with a large proportion not retrofitted. The energy consumption is higher than that of the other types of air-conditioners. The analysis shows that retrofitting the unrated air-conditioners could deliver energy savings between 20-30%. Also, retrofitting the 1-star and the unrated air-conditioners could yield a combined energy savings of more than 35%. This presents reductions in emissions as attempts to reduce the impact of construction activities on the environment is consistent with the theoretical framework of the study.

Acknowledgement

The authors acknowledge the support of facility managers of Kumasi Technical University and The Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development for the support during the onsite field study.

References

- Ahadzie, D.K., Opoku, R., Ware, S.N.O. and Mensah, H., 2020. Analysis of occupant behaviour in the use of air-conditioners in public buildings in developing countries: evidence from Ghana. *International Journal of Building Pathology and Adaptation*.
- Alghoul, S.K., Rijabo, H.G. and Mashena, M.E., 2017. Energy consumption in buildings: A correlation for the influence of window to wall ratio and window to wall ratio and window orientation in Tripoli, Libya. *Journal of Building Engineering*, 11, pp. 82-86.
- Al-Qawasmi, A.R. and Tlili, I., 2018. Energy efficiency and economic impact investigations for air-conditioners using wireless sensing and actuator networks. *Energy Reports*, 4, pp.478-485.
- Arthur, J.L. and Fianu, J., 2019. Drivers to energy efficiency development in lighting and air-conditioning systems in manufacturing industries in Ghana for 2018. *Journal of Geography and Regional Planning*, 12(3), pp.34-42.

- Ascione, F., Cheche, N., De Masi, R.F., Minichiello, F. and Vanoli, G.P., 2015. Design the refurbishment of historic buildings with the cost-optimal methodology: The case study of a XV century Italian building. *Energy and Buildings*, 99, pp.162-176.
- Assimakopoulos, M.N., De Masi, R.F., Fotopoulou, A., Papadaki, D., Ruggiero, S., Semprini, G. and Vanoli, G.P., 2020. Holistic approach for energy retrofit with volumetric add-ons toward nZEB target: Case study of a dormitory in Athens. *Energy and Buildings*, 207, p.109630.
- Dadzie, J., Runeson, G. and Ding, G., 2018, May. Sustainable technologies as determinants of energy efficient upgrade of existing buildings. In *2018 International Conference on Smart Grid and Clean Energy Technologies (ICSGCE)* (pp. 145-149). IEEE.
- Duggal, B. and Singh, D.P., 2016, November. Energy audit of individual air conditioners: A case study. In *2016 7th India International Conference on Power Electronics (IICPE)* (pp. 1-5). IEEE.
- Gyamfi, S., Diawuo, F.A., Kumi, E.N., Sika, F. and Modjinou, M., 2018. The energy efficiency situation in Ghana. *Renewable and Sustainable Energy Reviews*, 82, pp.1415-1423.
- International Energy Agency (IEA). The Future of Cooling: Opportunities for energy-efficient air conditioning. Technical report, International Energy Agency (IEA); 2018
- Kubota, T., Jeong, S., Toe, D.H.C. and Ossen, D.R., 2011. Energy consumption and air-conditioning usage in residential buildings of Malaysia. *Journal of International Development and Cooperation*, 17(3), pp.61-69.
- Majid, N.H.A., Takagi, N., Hokoi, S., Ekasiwi, S.N.N. and Uno, T., 2014. Field survey of air conditioner temperature settings in a hot, dry climate (Oman). *HVAC&R Research*, 20(7), pp.751-759.
- Opoku, R., Mensah-Darkwa, K. and Muntaka, A.S., 2018. Techno-economic analysis of a hybrid solar PV-grid powered air-conditioner for daytime office use in hot humid climates—a case study in Kumasi city, Ghana. *Solar Energy*, 165, pp.65-74.
- Opoku, R., Edwin, I.A. and Agyarko, K.A., 2019. Energy efficiency and cost saving opportunities in public and commercial buildings in developing countries—the case of air-conditioners in Ghana. *Journal of Cleaner Production*, 230, pp.937-944.
- Pazouki, M., Rezaie, K. and Bozorgi-Amiri, A., 2021. A fuzzy robust multi-objective optimization model for building energy retrofit considering utility function: A university building case study. *Energy and Buildings*, 241, p.110933.
- Raji, B., Tenpierik, M.J. and van den Dobbelsteen, A., 2015. The impact of greening systems on building energy performance: A literature review. *Renewable and Sustainable Energy Reviews*, 45, pp.610-623.
- Shah, N.K., Park, W.Y. and Gerke, B., 2017. Assessment of commercially available energy-efficient room air conditioners including models with low global warming potential (GWP) refrigerants.
- Shah, N., Park, W.Y. and Ding, C., 2021. Trends in best-in-class energy-efficient technologies for room air conditioners. *Energy Reports*, 7, pp.3162-3170.
- Uba, F.A. and Sarsah, Y.K., 2013. Simplified procedure for estimating air conditioning cooling load in Ghana. *International Journal of Scientific & Technology Research*, 2(9).
- Winkler, J., Das, S., Earle, L., Burkett, L., Robertson, J., Roberts, D. and Booten, C., 2020. Impact of installation faults in air conditioners and heat pumps in single-family homes on US energy usage. *Applied Energy*, 278, p.115533.
- Yin, R.K., 2018. *Case study research and applications*. Sage.

The humble curtain: a cheap and cheerful insulator?

Britta Basse* and Kerry Mulligan and Daphne Robson

Engineering and Architecture, Ara Institute of Canterbury, Christchurch, New Zealand.

*Corresponding author: Britta.Basse@ara.ac.nz

Abstract

Poor thermal performance of houses is an ongoing topic in New Zealand, where outside temperatures can be cold and historically, houses were built with little insulation. Nowadays, minimally insulated houses are predominantly occupied by low-income earners who tend to only heat the living area. Here we use log-linear multiple regression analysis to investigate the effects of installing curtains on bedroom doors as a cheap method to improve interior comfort. What impact does this installation have on the thermal performance of a typical New Zealand house? We found that installation of curtains on bedroom doors provided an effective barrier to heat transfer. However, at low outside temperatures, isolating heat sinking bedrooms in this way did not correspond to average temperature gains in the Kitchen/Living areas.

Keywords

insulation, interior comfort, thermal performance, time-period, regression

Introduction and background

In New Zealand, where average annual outdoor temperatures range from 10 °C in the south to 16 °C in the north (National Institute of Water and Atmospheric Research, 2019), the most commonly heated room is the living room (French et al., 2006). However, in a typical house the highest average temperature was 17.8 °C in the evening (as recorded by temperature loggers in various rooms, time-periods and heights and described in detail by French et al. (2006)). This does not reach the World Health Organization (WHO) guideline minimum indoor house temperature of 18 °C for temperate and cold climates (World Health Organization, 2018). The WHO guidelines exist because cold housing is related to poor health outcomes and is a worldwide problem (Daniel et al. 2021, Gouveia and Mahoney 2021, World Health Organization 2007).

In general, low income occupants in New Zealand (i.e. students, beneficiaries and single parent families) are more likely to live in uninsulated or minimally insulated rental properties and report their homes as cold (Statistics New Zealand, 2015). In response, the Residential Tenancies (Healthy Homes Standards) Regulations 2019 (New Zealand Government, 2018) require landlords to install heating for the main living area and underfloor and ceiling insulation with the intention of improving indoor comfort. However the implementation has been slow in some instances (New Zealand Government 2018, 2021, Radio New Zealand 2021).

In this study, we investigate whether we can improve indoor comfort by thermally isolating bedrooms from the remainder of a (minimally insulated) house with a simple low-cost installation of curtains on the bedroom door frames. The motivation came from post-earthquake anecdotal reports that curtains covering doorframes - where doors could no longer be closed -

were better insulators compared to closed wooden doors. Fabric curtains, fitted well, may be preferable to wooden doors because they can cover the whole door frame (no gaps); are less likely to be left open; and have been shown to provide thermal insulation when used as a window covering (Fitton et al. 2017, Abdallah and Abdelfattah 2014). A literature search suggests that this study has not been replicated elsewhere and is a novel idea. Research on using curtains as insulation has focused on their use on windows, and we did not find any studies on their use between rooms.

The fact that the house is unoccupied is both a blessing and a limitation of this study. On one hand, presumably human occupation would have a big effect on both temperature and humidity. However, this is also a unique opportunity to measure insulation effects on baseline temperatures - without the complication of human occupation.

After curtain installation, the two questions investigated were:

- Did bedrooms become colder because they are no longer heated by a living room heat pump. If yes, then by how much?
- Did living and kitchen areas become warmer because cold bedrooms are no longer acting as a heat sink? If yes then by how much?

Research Methodology

Initial setup and data collection

In early 2016, 30 temperature sensors (ITEAD, 2017), (accuracy ± 0.5 °C) were installed (6-8 sensors per room) recording air temperature at two heights (low 200 mm and medium 1500 mm from the floor respectively) in three bedrooms and the connected open plan living and kitchen area of a minimally insulated 100 m² 1960s weatherboard house in central Christchurch, New Zealand (Mulligan et al. 2020a, 2020b). A wall mounted air source heat pump (Daikin, model FVXS50LVMA_t), located centrally in the house, in the living room, is programmed to automatically turn on when an internal temperature sensor detects a temperature less than 18 °C. Fig.1 shows a floor plan of the house.

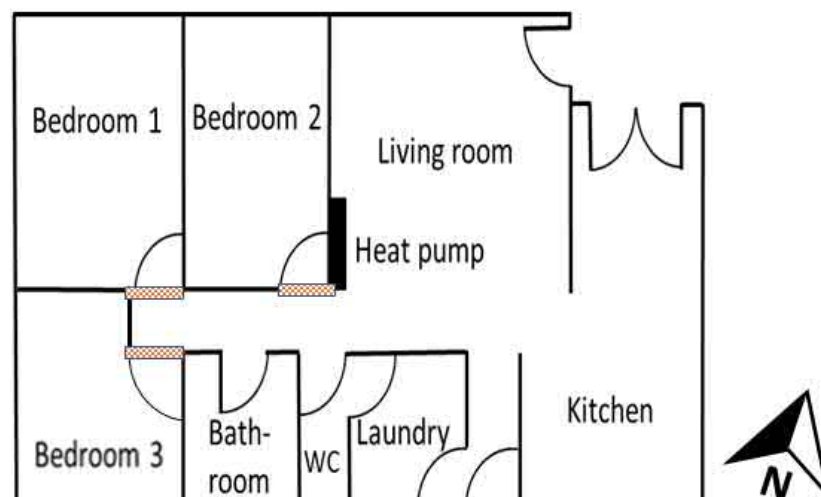


Figure 1: Floor plan of house and position of the curtains for each bedroom

Temperatures were logged at 5 minute intervals from 1st June until 31st October in 2016 (153 days). Curtains were installed in the doorways of Bedrooms 1, 2 and 3 for the same

months of the year in 2020. Curtains were made of heavy cotton material without linings and were fitted to cover the entire door frame with no gaps. Wooden doors were left on hinges and kept open. Because the house is unoccupied, it was not subject to the Residential Tenancies (Healthy Homes Standards) Regulations 2019 (New Zealand Government, 2018) and so there were no further insulations installed.

Outside hourly temperatures were obtained from the closest appropriate National Institute of Water and Atmospheric Research (NIWA) weather station in Kyle Street, Christchurch (approximately 3 km from the house) (National Institute of Water and Atmospheric Research, 2013).

Data analysis

The data were checked and analysed using R software (R Core Team, 2019). Temperatures were averaged for the time periods: morning (7 – 9 am), day (9 am – 5 pm), evening (5 – 11 pm), and night (11 pm – 7 am) (French et al., 2006). Statistical tests and models discussed in the subsections below are not the only way of analysing the data but were chosen because they are standard methods of analysis, details of which can be found either online or in many intermediate statistical textbooks.

Comparison of outside temperatures in 2016 and 2020

Welch two sample *t*-tests were used to determine whether there were any significant differences between outside temperature time-period averages in 2016 and 2020. An *F*-test was used to determine whether outside temperature time-period averages were equally variable in both years.

Quantifying curtain, time-period and room effects on indoor temperature

Log-linear multiple regression analyses with interaction terms were used to explore relationships between medium or low interior time-period average temperatures (°C) and outside temperatures (°C) while quantifying the effects of: curtains (installed or not installed), room (Bedroom 1, 2, 3, Living, and Kitchen), and time-period (morning, day, evening, night). The base regression model equation is:

$$\text{indoor\_sensor\_temp} = \beta_0 \times \exp(\beta_1 \times \text{outside\_temp}) \quad (1)$$

where the indoor sensor could be either medium or low height. This regression model is applied to the grouped combinations “Living/Kitchen” area and “Bedrooms 1, 2 & 3”.

Findings and Discussion

Comparison of outside temperatures in 2016 and 2020

There was no significant difference in the 2016 and 2020 outside temperature time-period averages and variances (Fig. 2), ($p > 0.01$).

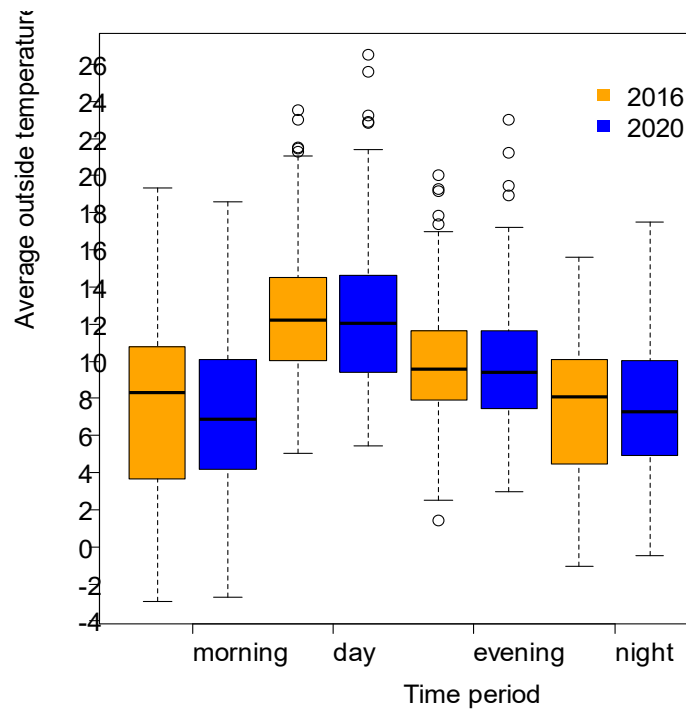


Figure 2: Comparison of 2016 and 2020 average outside temperatures

Regression results for Bedrooms 1, 2 & 3

The percentage of variation in medium and low sensor average temperatures explained by the regression model (1) was 78% and 82% respectively ($p < 2.2 \times 10^{-16}$). The results for Bedroom 1, during the day without curtain installation are first presented as the default in section 3.2.1. In subsequent subsections curtain, time period and room effects are presented.

Bedroom 1, during the day without curtain installation

During the day in Bedroom 1 without curtains installed on bedroom doors, when the outside temperature was zero degrees, the average interior temperature was 14.9 °C (medium) and 10.9 °C (low) (Fig. 3). For each increase of one degree in the outside temperature, medium sensors increased by approximately 2.1% and low sensors increased by approximately 3.2% ($p < 2 \times 10^{-16}$).

Curtain effects in Bedrooms 1, 2 & 3

When the outside temperature was zero degrees, the installation of curtains on bedroom doors significantly decreased interior sensor average temperatures in the bedrooms by approximately 34% (medium) and 21% (low) (p -values $< 2 \times 10^{-16}$) (see Fig. 3 for this effect illustrated in Bedroom 1 only), implying that the curtain installation isolates the bedrooms from the Living area heat pump and has a cooling effect on bedrooms when outside temperatures are cold. This cooling effect is greater on medium sensor average temperatures compared to low sensor average temperatures.

As outside temperatures increase (Fig. 3), the impact of a lack of heating reaching the bedrooms lessens and eventually (when outside temperatures reach approximately 15-20 degrees) the isolation of the bedrooms from the heating source has a warming effect on bedroom temperatures most likely due to solar heat gains from the bedroom windows not being lost to the Living/Kitchen area.

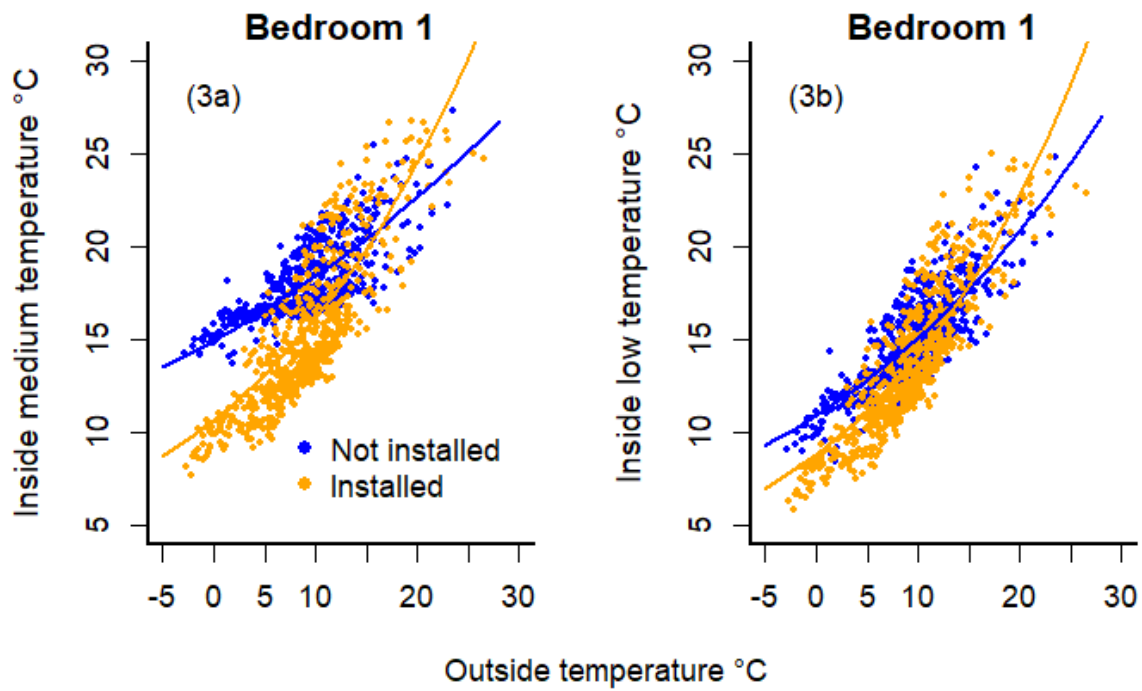


Figure 3: Bedroom 1 interior sensor average daytime temperatures (medium (3a) and low (3b)) related to outside average temperatures, coloured to show curtain effects. Regression lines are also plotted

Time period effects in Bedrooms 1, 2 & 3

Fig. 4 shows inside temperatures versus outside temperatures for Bedrooms 1, 2 & 3; all time periods and curtains both installed and not installed. It can be seen that daytime and evening temperatures were mostly warmer than night and morning temperatures for both low and medium sensors.

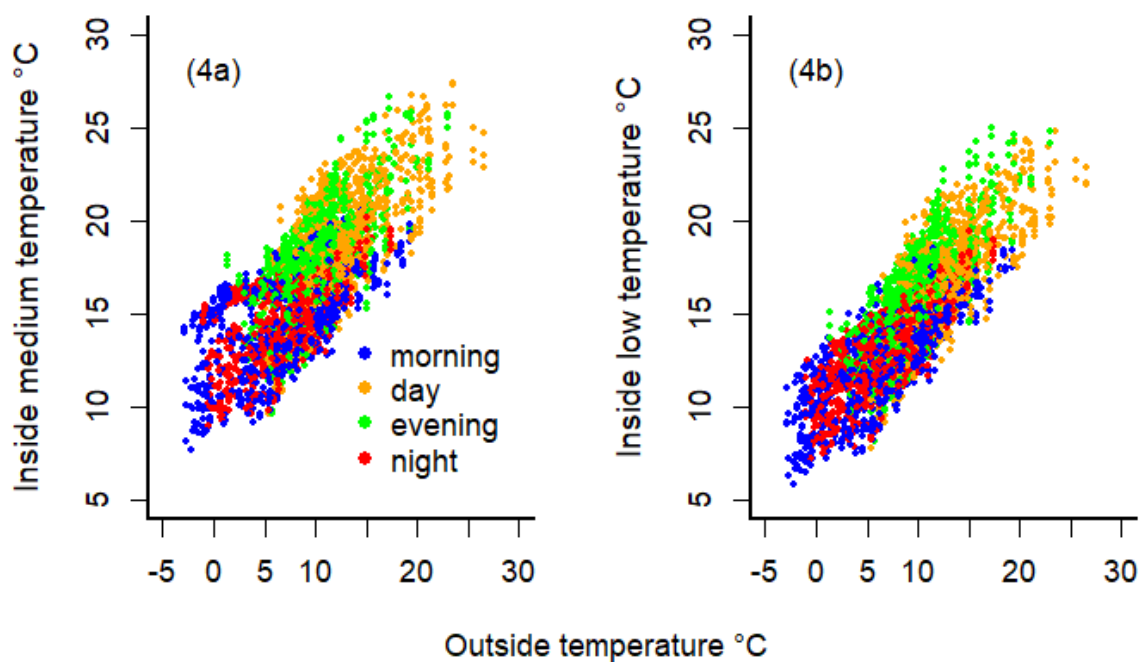


Figure 4: Bedrooms 1, 2 and 3 interior sensor average temperatures (medium (4a) and low (4b)) related to outside average temperatures, coloured to show time period effects. Data include curtains both installed and uninstalled

Bedroom effects in Bedrooms 1, 2 & 3

Room effects are depicted in Fig. 5. When the outside temperature was zero degrees, Bedroom 2 was generally warmer than the other rooms. Medium sensors on average were 11% warmer in Bedroom 2 compared to Bedroom 1 ($p < 2 \times 10^{-16}$). For low sensors, Bedroom 2 was 21% warmer than Bedroom 1 ($p < 2 \times 10^{-16}$). This effect lessened as outside temperatures increased and inside temperatures became more variable.

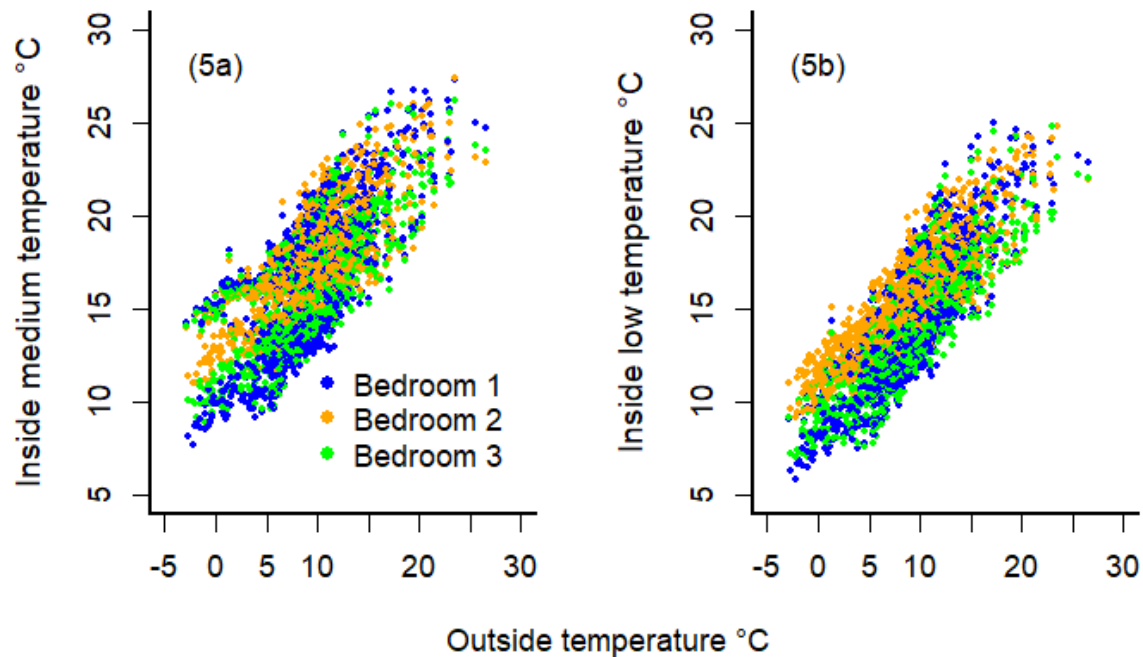


Figure 5: Bedrooms 1, 2 and 3 interior sensor average temperatures (medium (5a) and low (5b)) related to outside average temperatures, coloured to show room effects. Data include curtains both installed and uninstalled

Regression results for the Living/Kitchen area

The percentage of variation in medium and low sensor average temperatures explained by the regression model (1) was 71% and 80% respectively ($p < 2.2 \times 10^{-16}$). The results for the Kitchen, during the day without curtain installation are first presented as the default in section In subsequent subsections curtain, time period and room effects are presented.

Kitchen, during the day without curtain installation

During the day in the Kitchen area without curtains installed on bedroom doors, when the outside temperature was zero degrees, the average interior temperature was 17.3 °C (medium) and 13.4 °C (low) (Fig. 6). For each increase of one degree in the outside temperature, medium sensors increased by approximately 1.4% and low sensors increased by approximately 2.4% ($p < 2 \times 10^{-16}$).

Curtain effects in the Living/ Kitchen area

When the outside temperature was zero degrees, the installation of curtains on bedroom doors significantly decreased Living/Kitchen area medium interior sensor average temperatures by approximately 6% ($p < 2 \times 10^{-16}$) (see Fig. 6a for this effect illustrated in the Kitchen only). Curtains on the bedroom doors did not significantly affect Living/Kitchen area low average temperatures ($p > 1\%$) (see Fig. 6b for this effect illustrated in the Kitchen only).

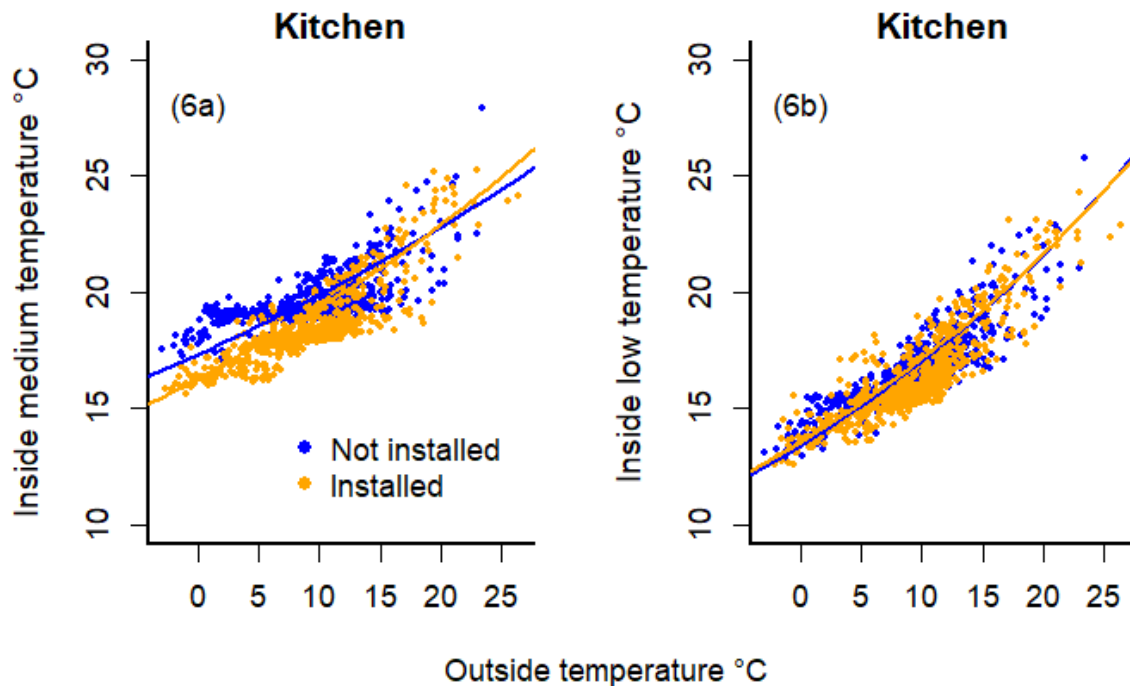


Figure 6: Kitchen area interior sensor daytime average temperatures (medium (6a) and low (6b)) related to outside average temperatures, coloured to show curtain effects. Regression lines are also plotted

Medium and low sensor time period and room effects in the Living/Kitchen area

Fig. 7 shows inside temperatures versus outside temperatures for the Living/Kitchen area; all time periods and curtains both installed and not installed. It can be seen that daytime and evening temperatures were mostly warmer than night and morning temperatures for both low and medium sensors.

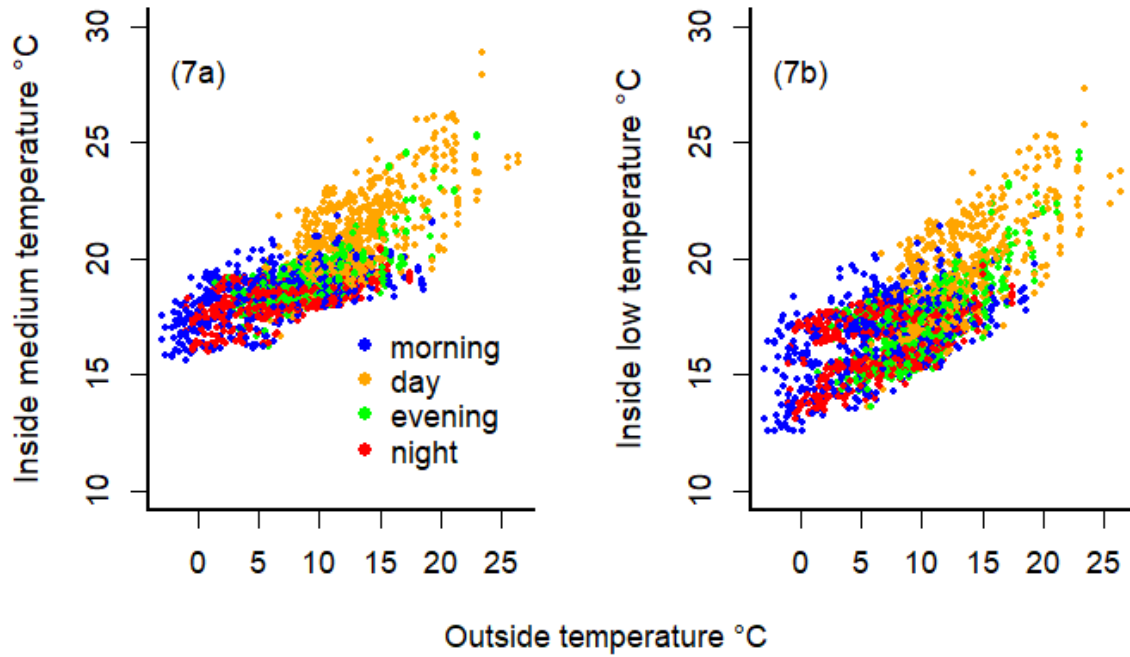


Figure 7: Living/Kitchen area interior sensor average temperatures (medium (7a) and low (7b)) related to outside average temperatures, coloured to show time-period effects. Data include curtains both installed and uninstalled

In addition, low sensor average temperatures were approximately 17% warmer in the Living area compared to the Kitchen area when the outside temperature was zero degrees (Fig. 8). This difference lessened as outside temperatures increased.

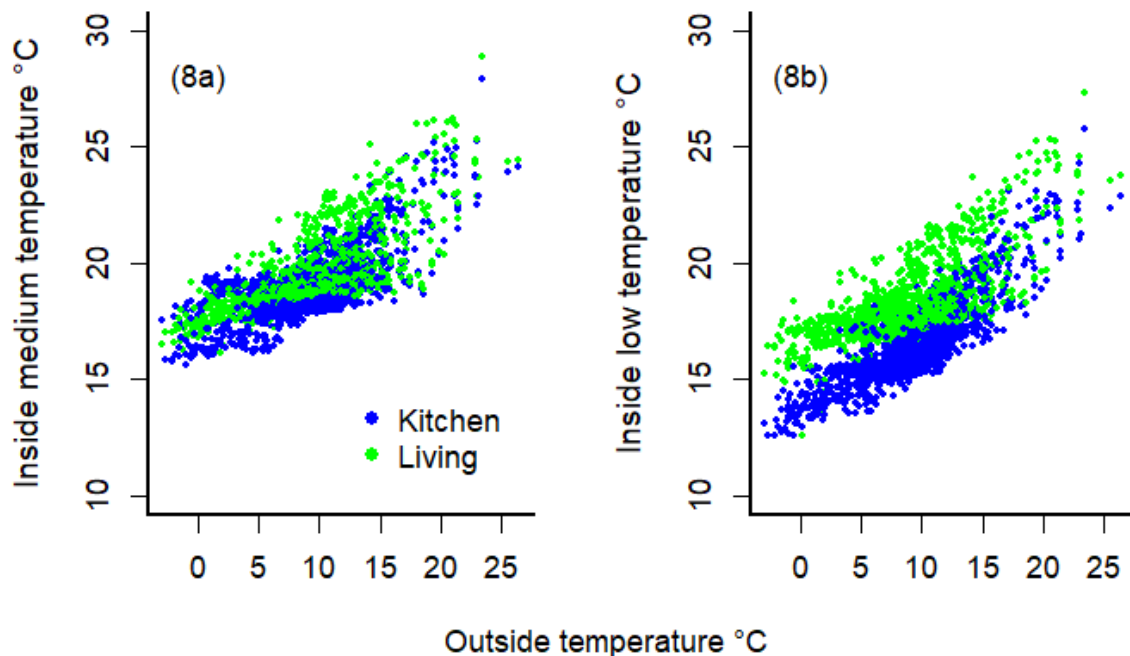


Figure 8: Living/Kitchen interior sensor average temperatures (medium (8a) and low (8b)) related to outside average temperatures, coloured to show room effects. Data include curtains both installed and uninstalled

Conclusion

At low outside temperatures, the heat pump acts as a heat source for the whole house (not just the Living/Kitchen area) and consequently bedrooms act as a heat sink away from the Living/Kitchen area. After curtain installation on bedroom doors, this heat source is effectively cut off from the bedrooms and consequently their average temperatures decrease. One could then expect a corresponding increase in the length of time that the Living/Kitchen area stays at an approximately constant temperature of 18 °C (the thermostat setting on the heat pump), but this was not an outcome of the analysis presented here. In fact, when outside temperatures were cold, medium sensor average temperatures in the kitchen end of the Living/Kitchen area dropped after the installation of curtains on Bedroom doors (see section 3.3.2 and Fig. 6). These unexpected results could be due to a leakage of heat throughout the house, for example through unsealed windows and doors.

At higher outside temperatures, inside temperatures are more variable and quantifying the thermal effects of curtain installation on bedroom doors becomes more difficult. Without curtains, bedrooms could become the heat source due to sun shining through north/west facing bedroom windows for example. Correspondingly the Living/Kitchen area would act as the heat sink. One would then expect that the addition of curtains on bedroom doors to lower the average temperature in the Living/Kitchen area but this was also not seen in the analysis.

Our installation of curtains on bedroom doors provided an effective barrier to heat transfer throughout the house and it was reasonable to use curtains as a cheap form of isolation. However they did not improve the overall comfort in the Living/Kitchen area. Future plans include quantifying the effects of draft-stopping the house, including energy analysis.

References

- ABDALLAH, H. A. A. & ABDELFAATTAH, A. 2014. Standards design for some pile fabrics used as curtains to achieve comfortable properties. *Life Science Journal*, 7, 11.
- DANIEL, L., BAKER, E., BEER, A. & PHAM, N. T. A. 2021. Cold housing: evidence, risk and vulnerability. *Housing Studies*, 36, 110-130.
- FITTON, R., SWAN, W., HUGHES, T. & BENJABER, M. 2017. The thermal performance of window coverings in a whole house test facility with single-glazed sash windows. *Energy Efficiency*, 10, 1419-1431.
- FRENCH, L. J., CAMILLERI, M. J. T., ISAACS, N. P. & POLLARD, A. R. 2006. Winter temperatures in New Zealand houses. *Windsor Conference: Comfort and energy use in buildings - getting them right*. Windsor, UK: Building Research Association New Zealand.
- GOUVEIA, J. P. & MAHONEY, K. 2021. *Perspective on cold homes during the winter period in the policy debate of the UK* [Online]. UK: CENSE – Center for Environmental and Sustainability Research, Department of Science and Environmental Engineering. Available: <https://www.eppedia.eu/article/cold-homes-during-winter-period-uk> [Accessed 25/01/2022].
- ITEAD. 2017. *ITEAD digital thermometer DS18B20 specifications* [Online]. Available: <https://www.itead.cc/ds18b20-digital-thermometer-gauge.html> [Accessed 17/06/2021].
- MULLIGAN, K., BASSE, B. & ROBSON, D. Bubble Wrap or Slippers? That Is the Question: From Hamlet to Home Insulation. In: ASKARINEJAD, H., SINGH, A. & YAZDANI, S., eds. *Proceedings of International Structural Engineering and Construction*, 2020a.
- MULLIGAN, K., BASSE, B. & ROBSON, D. Using a single source heat pump to achieve WHO recommendations for healthy indoor temperatures: Measuring the baseline in an uninhabited, minimally insulated, timber frame house in Christchurch, New Zealand. 2020 International Conference on Civil, Architectural and Environmental Engineering (ICCAEE 2020), 2020b Christchurch, New Zealand. AIP Publishing.
- NATIONAL INSTITUTE OF WATER AND ATMOSPHERIC RESEARCH 2013. National Climate Database.
- NATIONAL INSTITUTE OF WATER AND ATMOSPHERIC RESEARCH. 2019. *Overview of New Zealand's climate* [Online]. Available: <https://www.niwa.co.nz/education-and-training/schools/resources/climate/overview> [Accessed 17/06/2021].
- NEW ZEALAND GOVERNMENT 2018. Residential Tenancies (Healthy Homes Standards) Regulations.

- NEW ZEALAND GOVERNMENT 2021. Updating the Healthy Homes Standards - heating regulations. New Zealand: Te Tūāpapa Kura Kāinga – Ministry of Housing and Urban Development (HUD).
- R CORE TEAM 2019. R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing.
- RADIO NEW ZEALAND. 2021. *Councils downplay powers to enforce healthy homes standards* [Online]. New Zealand: Radio New Zealand. Available: <https://www.rnz.co.nz/national/programmes/summer-days/audio/2018779254/councils-downplay-powers-to-enforce-healthy-home-standards> [Accessed 24/01/2022 2022].
- STATISTICS NEW ZEALAND. 2015. *Perceptions of housing quality in 2014/2015* [Online]. New Zealand: Statistics New Zealand. Available: <https://www.stats.govt.nz/reports/perceptions-of-housing-quality-in-201415> [Accessed 17/06/2021].
- WORLD HEALTH ORGANIZATION 2007. Housing, energy and thermal comfort. Geneva.
- WORLD HEALTH ORGANIZATION 2018. WHO Housing and health guidelines. Geneva.

Methods for assessment of space heating energy use in buildings: A literature review

Isabel Andrade^{1*}, V. Vishnupriya², Sid Becker¹

¹Department of Mechanical Engineering, University of Canterbury, Christchurch

²School of Built Environment, Massey University, Auckland

*Corresponding author: mariaisabel.andradebeltran@canterbury.ac.nz

Abstract

The COP21 Paris Agreement and the Glasgow Climate Pact require urgent abatement of the current fossil-based energy consumption. In 2021, the Global Status for Buildings and Construction Report pinpointed buildings as responsible for 36% of the global energy consumption; 36% of this energy consumption by end-use of commercial buildings corresponds to space heating. Heating loads in commercial buildings can be reduced by building envelope retrofits, efficiency upgrades of heating equipment, energy management, and influencing energy users' behaviour. Traditional engineering assessment methods use capacity metrics such as the building load coefficient (BLC) for the building infrastructure or the coefficient of performance (COP) for heating and cooling equipment to measure how far the improvements can go. In office buildings, one way to optimize operation systems for space heating is to modify set points, but the set parameters constrain the associated savings; for example, changes to the indoor temperature are limited, to maintain a safe indoor environmental quality (IEQ). However, these capacity metrics and constraints do not reflect the interaction between building occupants and the heating system, nor the resultant capacity for energy reductions. This paper reviews the literature on energy assessment tools focused on occupant heating behaviour. The findings suggest the need for a standard method to assess occupants' behavioural aspects related to the final energy use in commercial buildings and the consequent potential for energy conservation.

Keywords

Building Energy, Energy Assessment Methods, Occupant Behaviour, Space Heating

Introduction

In 2021, the Global Status for Buildings and Construction Report pinpointed buildings as responsible for 36% of the global energy consumption (UNEP, 2021). Despite need for urgent action to achieve global net zero by mid-century and to limit the global average temperature rise to 1.5 °C set out by the Paris Agreement (UNFCCC, 2015) that was recently reinforced in the Glasgow Climate Pact (UNFCCC, 2021), the global energy demand and emissions by the building sector in 2020 only dropped one per cent from an all-time high of 10 Gigaton equivalent of CO₂ Gtoe (IEA, 2020) set the previous year. And still, 36% of energy consumption by end-use of commercial buildings is attributed to space heating, see Figure 1.

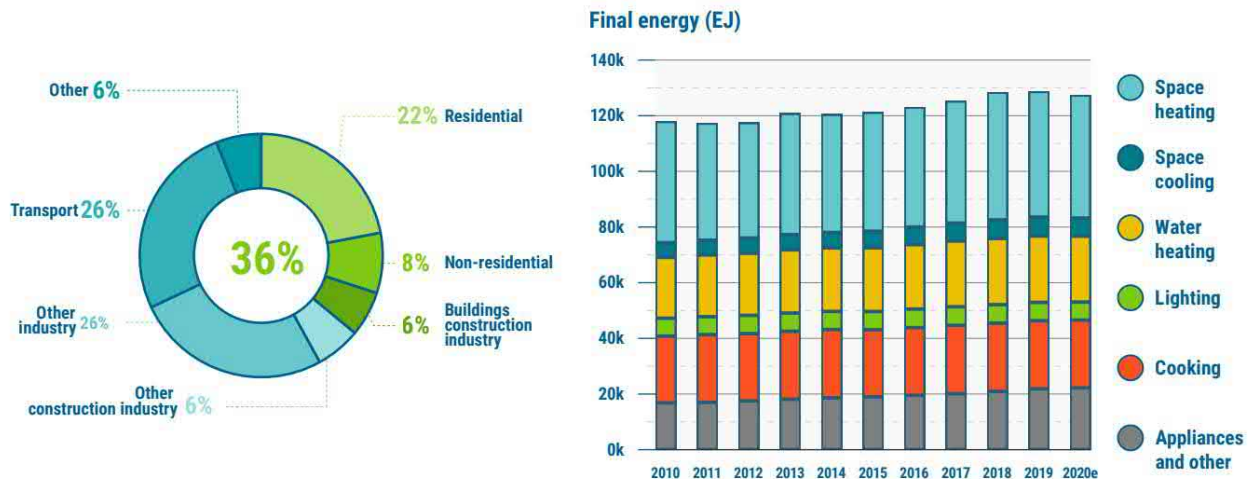


Figure 1. World final energy consumption (UNEP, 2021)

Measures to increase energy efficiency along with demand side management programs that emerged in response to the 1970s oil crisis contributed to large improvements in the building sector, especially in the 1980s (ASE, 2013). Through the implementation of resolutions and energy policy objectives (first formal documents in 1975), equipment performance directives (first in 1978) and building acts and codes (first formal documents in 1984) (Economidou et al., 2020) the building engineering and management field quickly acted on the challenge of delivering more efficient systems. Since the OPEC oil embargo in 1973 precipitated the energy crisis, integrated building design and demand side management have been developed as ways to deal with power supply issues and reduce reliance on fossil fuels (Krumdieck, 2019). Hence, carbon emission reductions have been achieved in an incremental manner since then, i.e. small percentages of the energy baseline are curtailed through modifications of the current serviced infrastructure and/or user behaviour. The current response to global emissions reductions targets in the building energy research sector is mainly focused on green building design methods and materials selected in building design (MacGregor, 2018) for new construction.

The methods for energy auditing and energy management of existing buildings are relatively mature and primarily centred on the large part of the energy used that is wasted due to outdated construction practices, use of inefficient equipment and lack of effective technical control systems (Economidou et al., 2020). These often lead to engineered retrofits of the building infrastructure that are conducted on envelope (e.g. insulation, glazing, weather stripping, and shades), equipment (replacement/upgrade) and system operation (e.g. Building Management System BMS). These traditional engineering practices have achieved energy use reductions in existing buildings in the range of 25-50% (IPCC, 2014). Energy management and

efficiency retrofits can produce cost savings, but the rate of retrofitting may not be sufficient and rapid to make the urgently needed contribution to carbon emissions reductions. HVAC energy reductions through occupant behaviour can be achieved if the current demand of heat is quantified for individual office users, since energy-related behavioural interventions at the occupant level need to be tailored (Abrahamse et al., 2007). Different standard approaches are reviewed in this paper, as a basis for future research on occupant behaviour of energy use for space heating in office buildings.

Literature Review

An integrative literature review was conducted with the use of two Engineering Databases: Compendex and Scopus. These databases were accessed through the online collection at the University of Canterbury Library. The search was initiated with a combination of the key words “building energy” and “occupant behaviour”. The first search yielded 281 records that were filtered by additional keyword requirements, including: heating, commercial buildings, office buildings, and analysis or assessment. Thirty one journal articles, and twelve conference articles were found as relevant to this research; they were selected for analysis. Three research categories were generated from the review, these are: (i) Energy Assessment focused on Building Infrastructure, (ii) Energy for HVAC systems and Occupant Behaviour, and (iii) Methods of Occupant-Focused Energy Assessment in Commercial Buildings.

Research Findings and Discussion

Energy Assessment focused on Building Infrastructure

Current engineering practices of reducing energy consumption in commercial buildings comprise Assessment and Intervention (A&I) on the building envelope, on the equipment and on the operation systems (IPCC, 2014). Little attention has been given to the focus on A&I on the occupants. Traditional engineering assessment methods use capacity metrics such as the building load coefficient (BLC) for the building infrastructure or the coefficient of performance (COP) for heating and cooling equipment, as a measure of how far the improvements can go. One way to optimize operation systems for space heating is to modify set points but the associated savings are limited by set parameters; for example the changes to the indoor temperature are limited in order to maintain a safe indoor environmental quality (IEQ). Such constraints dictate the system’s capacity for energy reductions. The assessment of energy savings measures for the building infrastructure has been well studied for both the commercial and residential sectors. The methods used in detailed energy audits comprise building and utility data analysis, walk-through surveys, energy baseline models, energy conservation measures and cost-effectiveness analysis. The ISO 13790:2008 standard (ISO, 2008) provides calculation methods for assessment of the annual energy consumption for space heating and cooling. The standardized methods include calculations of heat transfer to determine the energy needs to maintain certain set-point temperature under other relevant system standards. This standards also gives alternative methods that include fixed user schedules for the calculations of the annual energy use.

Verification-focused methods of post-retrofit energy savings are mostly used in commercial and industrial buildings; this comprehensive verification uses techniques such as regression models and time variant models (Krarti, 2000). Furthermore, evaluation methods of net zero energy retrofits of existing buildings employ annualized energy-related cost

analyses to identify the cost optimum point and measures with highest potential of energy reductions (Goswami and Kreith, 2017). Cost-effectiveness values of energy conservation interventions are estimated through calculations and numerical models based on either forward or inverse models, often in conjunction with ratio-based methods. The output of forward models is the building energy use while that for inverse models are BLC, base load and building time constant (thermal storage). Ratio-based methods are used to evaluate energy/cost densities pre-audit based on performance metrics such as energy use intensity (EUI). Borgstein et al. (2016) reviewed existing building performance evaluation methods that are based on physical infrastructural characteristics. The authors identified 5 main categories:

- Engineering calculations
- Simulation
- Statistical methods
- Machine learning
- Other techniques (dynamic/real-time analysis, load-curve analysis, energy audits)

The application of engineering techniques support the implementation of energy interventions and energy efficiency programmes. Typical energy performance assessment types are summarized by (Wang et al., 2012) as environmental assessment, building energy certification, whole-building benchmarking and hierarchical assessment and diagnosis. Commercial buildings in New Zealand often go under assessment that follows guidelines from organizations such as the Chartered Institution of Building Services Engineers (CIBSE), the Carbon and Energy Professionals New Zealand (CEP) and the Building Research Association of New Zealand (BRANZ). These entities provide referential methods to assess building conditions and energy consumption through the use of performance measurements. International protocols such as the US DoE's International Performance Measurement and Verification Protocol or the Building Research Establishment Environmental Assessment Method (BREEAM) are also used in New Zealand as guidelines to determine energy savings in buildings as per ASHRAE standards. Some building owners and managers opt to use performance assessment tools and certification from the New Zealand Green Building Council (NZGBC), the Leadership in Energy and Environmental Design (LEED), or the International Organization for Standardization ISO 50001 Energy Management Systems, among others. These tools are mainly used to assess the building hard infrastructure.

Energy for HVAC systems and occupant behaviour

Energy uses include space conditioning (HVAC), domestic hot water, lighting and plug loads. The occupants' activities and use type have a huge impact on the quality and quantity of energy services needed. The building users that have control over their HVAC systems directly influence the building energy performance; their interaction with the building energy system depends on conditions of the indoor and outdoor environment, and certain predispositions of the occupants (Akimoto et al., 2010, Brager and de Dear, 1998). Greater understanding of the human input in heating energy use may provide not only reductions in operating costs, but also enhanced comfort conditions and productivity for building users (D'Oca et al., 2018). Occupants' behaviour has been broadly studied and identified as target for energy conservation interventions (Rafsanjani et al., 2018, Yousefi et al., 2017, Hong et al., 2015). However, the effects and outcomes of behavioural interventions in different contexts are very diverse (Lehner et al., 2016) as behavioural influence factors can range extensively. Research efforts have

linked contextual/environmental and personal psycho-social factors, with occupant's willingness and capability to save energy.

Behavioural aspects of building energy conservation have been mostly studied in dwellings. For example, Andersen (2012) analysed 11 years of heating consumption data from 35 apartments in Copenhagen that had heat cost allocators; additionally, heating consumption data from 290 identical townhouses was investigated with the aim of estimating the influence of occupants' behaviour. Pritoni et al. (2016) used smart thermostats to record data about occupancy, room temperature, comfort set point, active setback temperature, and fan-coil run time in every bedroom in a residence hall. They compared heating energy consumption from each period to outside temperature to develop a model for baseline heating energy consumption in each building. Outside air temperature, cooling energy consumption, and heating energy consumption were measured for each building through the university's energy management and control system. Gauthier (2016) gathered qualitative data via questionnaires, interviews, diaries, and visual records taken by wearable cameras, in addition to measured indoor conditions. They investigated the behavioural responses to cold thermal discomfort in households, but the energy usage was not assessed. Several occupant traits and behavioural facilitating conditions have been associated to heating consumption (Guerra-Santin and Itard, 2010, Cui et al., 2017, D'Oca et al., 2017, Paço and Lavrador, 2017). Nonetheless, these factors are yet to be integrated into energy intervention design and implementation in commercial buildings (Kosonen and Kim, 2017).

Methods of Occupant-Focused Energy Assessment in Commercial Buildings

Despite being recognized as a critical point for the estimation of the energy-saving potential in buildings (Brøgger and Wittchen, 2018), behavioural aspects are often excluded from traditional A&I of commercial buildings. Discrepancies between the anticipated vs. the actual energy consumption in buildings have been explained. Fedoruk et al. (2015) attributed the energy performance gap to technical factors (e.g. equipment tuning/operation) and the human element. These are findings that other review studies corroborate (Zou et al., 2018, Dronkelaar et al., 2016, Menezes et al., 2012), in which the user side is acknowledged for its big (but not quantified) potential.

The link between occupant behaviour and energy savings in commercial buildings has increasingly gained attention. Simulation of occupant behaviour is the main tool to capture the variability of operating buildings. Gaetani et al. (2018) for example, estimated the variability of the effects of occupant behaviour on heating and cooling energy demand based on simulations and impact indices for blind use, equipment use and indoor temperature set points management. The impact indices were designed to ponder contributing loads to the total heating/cooling energy demand. Changes in temperature differences marked by modified set points were also analysed. Several building variants and operation parameters were evaluated by applying sensitivity analysis against the calculated primary energy with the use of EnergyPlus to obtain the impact indices. The assessment method was tested in a case study by the same authors, and demonstrated to link 85-95% of the variations of heating/cooling loads to behavioural aspects. Although the user behaviours were successfully simulated and the variations of energy use were explained as dependent of building characteristics and climate, similar to what Nicol et al. (2004) had concluded, the real effect of the various aspects of occupant behaviour was not grasped.

In the field of Demand Response, which addresses load shifting and shedding (Chen et al., 2018), the metric Demand Flexibility serves as an assessment tool to quantify the building flexibility potential to move the load peaks. Hurtado et al. (2017) for example, developed a method to quantify the capacity of demand flexibility of buildings. They simulated the effects of various physical building conditions on energy consumption. This simulation is similar to the one conducted by Ghahramani et al. (2016) who modelled office buildings using the software EnergyPlus to understand the influence of temperature set points, operational (schedules) and environmental (climate zones) parameters on HVAC energy consumption. The authors estimated energy savings ranging from 6.78% to 37.03% depending on climate conditions, for selected optimal temperature set points. Occupancy schedules in 16 climate zones were included in the analysis but the variability of schedules and behaviours was identified as a limitation for estimating accurate heat loads. The choice of temperature set points is a behaviour by itself and it is variable between occupants, but in this study fixed optimal ranges were used for the simulation. Simulation of occupant behaviour in the software EnergyPlus was also used by Sun and Hong (2017) to estimate savings potential. The authors found a maximum potential of overall energy savings of 22.9% for individual measures that included user interaction with all types of equipment in four different climate zones. Despite these efforts, assuming fixed temperature ranges or occupancy levels may lead to uncertainty of the models.

Previous research has shown improved understanding of the interaction between occupants' behavioural aspects and their final energy use. Yan et al. (2017) proposed an interdisciplinary framework that integrated data-driven analysis techniques with social science aspects to understand occupant behaviour, preferences and needs as indicators of energy-saving potential of innovative technologies. The framework offers an evaluation method that starts by measuring occupancy through sensing and data transmission, followed by computational simulation. The programme designed under this framework was called IEA EBC Annex 66 where occupant behaviour modelling tools (obXML and obFMU) were developed to assess the impacts of users' actions on energy demand under the consideration of personal socio-cognitive drivers. The types of interventions proposed by the Annex 66 assessment methodology are based on behavioural-based energy efficiency solutions. The literature research has found that Annex 66 is the only approach that includes both A&I design components in the scope of the research. Notwithstanding, potential interventions based on the results from their approach are not necessarily intended to modify behaviours towards energy reduction but instead to accommodate the existing or newly designed systems to possibly flexible comfort requirements of the occupants.

Currently, there exists no method that can provide a quantitative measure of the energy saving potential resulting from occupant behaviour assessment in commercial buildings. The inability to link contextual/environmental and personal psycho-social factors to behavioural interventions in commercial buildings has made it difficult to identify and reward consistent behaviour towards energy conservation, as recognized by Gulbinas et al. (2015), hence the importance of this literature review.

Conclusion

The standard approaches to assess energy use for space heating in office buildings have been reviewed. Three research categories emerged from the review: (i) Energy for HVAC systems and Occupant Behaviour, (ii) Energy Assessment focused on Building Infrastructure, and (iii)

Methods of Occupant-Focused Energy Assessment in Commercial Buildings. All of the published research that considers assessment on occupants consists in post-occupancy surveys. These surveys are aimed at checking if serviced buildings meet their purpose, but are not directly related to energy usage. This literature review has identified an opportunity for future research on building energy assessment with a focus on occupants. Research efforts in this area may provide guidance for implementation of strategies to impact the occupants' carbon footprint at the workplace.

References

- ABRAHAMSE, W., STEG, L., VLEK, C. & ROTHENGATTER, T. 2007. The effect of tailored information, goal setting, and tailored feedback on household energy use, energy-related behaviors, and behavioral antecedents. *Journal of environmental psychology*, 27, 265-276.
- AKIMOTO, T., TANABE, S.-I., YANAI, T. & SASAKI, M. 2010. Thermal comfort and productivity - Evaluation of workplace environment in a task conditioned office. *Building and Environment*, 45, 45-50.
- ANDERSEN, R. The influence of occupants' behaviour on energy consumption investigated in 290 identical dwellings and in 35 apartments. 2012 2012. 2279-2280.
- ASE 2013. The History of Energy Efficiency. In: POLICY, A. C. O. N. E. E. (ed.).
- BORGSTEIN, E. H., LAMBERTS, R. & HENSEN, J. L. M. 2016. Evaluating energy performance in non-domestic buildings: A review. *Energy and buildings*, 128, 734-755.
- BRAGER, G. S. & DE DEAR, R. J. 1998. Thermal adaptation in the built environment: a literature review. *Energy & Buildings*, 27, 83-96.
- BRØGGER, M. & WITTCHEN, K. B. 2018. Estimating the energy-saving potential in national building stocks – A methodology review. *Renewable & sustainable energy reviews*, 82, 1489-1496.
- CHEN, Y., XU, P., GU, J., SCHMIDT, F. & LI, W. 2018. Measures to improve energy demand flexibility in buildings for demand response (DR): A review. *Energy and buildings*, 177, 125-139.
- CUI, Y., YAN, D. & CHEN, C.-F. 2017. Exploring the factors and motivations influencing heating behavioral patterns and future energy use intentions in the hot summer and cold winter climate zone of China. *Energy and buildings*, 153, 99-110.
- D'OCA, S., CHEN, C.-F., HONG, T. & BELAFI, Z. 2017. Synthesizing building physics with social psychology: An interdisciplinary framework for context and occupant behavior in office buildings. *Energy Research & Social Science*, 34, 240-251.
- D'OCA, S., HONG, T. & LANGEVIN, J. 2018. The human dimensions of energy use in buildings: A review. *Renewable and Sustainable Energy Reviews*, 81, 731-742.
- DRONKELAAR, C. V., DRONKELAAR, C. V., DOWSON, M., SPATARU, C. & MUMOVIC, D. 2016. A review of the regulatory energy performance gap and its underlying causes in non-domestic buildings. *Frontiers in mechanical engineering* U6 - ctx_ver=Z39.88-2004&ctx_enc=info%3Aofi%2Fenc%3AUTF-8&rft_id=info%3Aid%2Fsummon.serialssolutions.com&rft_val_fmt=info%3Aofi%2Ffmt%3Akev%3Amtx%3Ajournal&rft.genre=article&rft.atitle=A+review+of+the+regulatory+energy+performance+gap+and+its+underlying+causes+in+non-domestic+buildings&rft.jtitle=Frontiers+in+mechanical+engineering&rft.au=Chris+van+Dronkelaar&rft.au=Chris+van+Dronkelaar&rft.au=Mark+Dowson&rft.au=Catalina+Spataru&rft.date=2016-01-01&rft.pub=Frontiers+Media+SA&rft.eissn=2297-3079&rft.volume=1&rft_id=info:doi/10.3389%2Ffmech.2015.00017&rft.externalDBID=DOA&rft.externalDocID=oai_doaj_org_article_67b18770f3f24308b9fd55573c8583b6&paramdict=en-US U7 - Journal Article, 1.
- ECONOMIDOU, M., TODESCHI, V., BERTOLDI, P., D'AGOSTINO, D., ZANGHERI, P. & CASTELLAZZI, L. 2020. Review of 50 years of EU energy efficiency policies for buildings. *Energy and buildings*, 225, 110322.
- FEDORUK, L. E., COLE, R. J., ROBINSON, J. B. & CAYUELA, A. 2015. Learning from failure: understanding the anticipated-achieved building energy performance gap. *Building research and information : the international journal of research, development and demonstration*, 43, 750-763.
- GAETANI, I., HOES, P.-J. & HENSEN, J. L. M. 2018. Estimating the influence of occupant behavior on building heating and cooling energy in one simulation run. *Applied energy*, 223, 159-171.
- GAUTHIER, S. 2016. Investigating the probability of behavioural responses to cold thermal discomfort. *Energy and buildings*, 124, 70-78.

- GHAHRAMANI, A., ZHANG, K., DUTTA, K., YANG, Z. & BECERIK-GERBER, B. 2016. Energy savings from temperature setpoints and deadband: Quantifying the influence of building and system properties on savings. *Applied energy*, 165, 930-942.
- GOSWAMI, D. Y. & KREITH, F. 2017. *Energy management and conservation handbook*, Boca Raton, CRC Press.
- GUERRA-SANTIN, O. & ITARD, L. 2010. Occupants' behaviour: determinants and effects on residential heating consumption. *Building research and information : the international journal of research, development and demonstration*, 38, 318-338.
- GULBINAS, R., KHOSROWPOUR, A. & TAYLOR, J. 2015. Segmentation and Classification of Commercial Building Occupants by Energy-Use Efficiency and Predictability. *IEEE Transactions on Smart Grid*, 6, 1414-1424.
- HONG, T., D'OCA, S., TURNER, W. J. N. & TAYLOR-LANGE, S. C. 2015. An ontology to represent energy-related occupant behavior in buildings. Part I: Introduction to the DNAs framework. *Building and environment*, 92, 764-777.
- HURTADO, L. A., RHODES, J. D., NGUYEN, P. H., KAMPHUIS, I. G. & WEBBER, M. E. 2017. Quantifying demand flexibility based on structural thermal storage and comfort management of non-residential buildings: A comparison between hot and cold climate zones. *Applied energy*, 195, 1047-1054.
- IEA 2020. Tracking Buildings 2020. IEA.
- IPCC 2014. Fifth Assessment Report.
- ISO 2008. BS EN ISO 13790:2008: Energy performance of buildings. Calculation of energy use for space heating and cooling. British Standards Institute.
- KOSONEN, H. K. & KIM, A. A. 2017. Advancement of behavioral energy interventions in commercial buildings. *Facilities*, 35, 367-382.
- KRARTI, M. 2000. *Energy audit of building systems: an engineering approach*, Boca Raton, FL, CRC Press.
- KRUMDIECK, S. 2019. *Transition engineering: Building a sustainable future*, CRC Press.
- LEHNER, M., MONT, O. & HEISKANEN, E. 2016. Nudging – A promising tool for sustainable consumption behaviour? *Journal of cleaner production*, 134, 166-177.
- MACGREGOR, D., JAQUES, BINT, BERG 2018. The built environment and climate change: A review of research, challenges and the future. BRANZ.
- MENEZES, A. C., CRIPPS, A., BOUCLAGHEM, D. & BUSWELL, R. 2012. Predicted vs. actual energy performance of non-domestic buildings: Using post-occupancy evaluation data to reduce the performance gap. *Applied energy*, 97, 355-364.
- NICOL, J. F., HUMPHREYS, M. A. & OLESEN, B. A stochastic approach to thermal comfort - Occupant behavior and energy use in buildings. 2004 2004. 554-568.
- PAÇO, A. & LAVRADOR, T. 2017. Environmental knowledge and attitudes and behaviours towards energy consumption. *Journal of environmental management*, 197, 384-392.
- PRITONI, M., WOOLLEY, J. M. & MODERA, M. P. 2016. Do occupancy-responsive learning thermostats save energy? A field study in university residence halls. *Energy and buildings*, 127, 469-478.
- RAFSANJANI, H. N., AHN, C. R. & CHEN, J. 2018. Linking building energy consumption with occupants' energy-consuming behaviors in commercial buildings: Non-intrusive occupant load monitoring (NIOLM). *Energy and buildings*, 172, 317-327.
- SUN, K. & HONG, T. 2017. A simulation approach to estimate energy savings potential of occupant behavior measures. *Energy and buildings*, 136, 43-62.
- UNEP 2021. 2021 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector. Nairobi: United Nations Environment Programme.
- UNFCCC 2015. Paris Agreement.
- UNFCCC 2021. The Glasgow Climate Pact. UK.
- WANG, S., YAN, C. & XIAO, F. 2012. Quantitative energy performance assessment methods for existing buildings. *Energy and buildings*, 55, 873-888.
- YAN, D., HONG, T., DONG, B., MAHDAVI, A., D'OCA, S., GAETANI, I., FENG, X. & LAWRENCE BERKELEY NATIONAL LAB, B. C. A. 2017. IEA EBC Annex 66: Definition and simulation of occupant behavior in buildings. *Energy and buildings*, 156, 258-270.
- YOUSEFI, F., GHOLIPOUR, Y. & YAN, W. 2017. A study of the impact of occupant behaviors on energy performance of building envelopes using occupants' data. *Energy and buildings*, 148, 182-198.
- ZOU, P. X. W., XU, X., SANJAYAN, J. & WANG, J. 2018. Review of 10 years research on building energy performance gap: Life-cycle and stakeholder perspectives. *Energy and buildings*, 178, 165-181.

Theme 3: Sustainability

A Parametric Study of Passive House Strategies in a Cooling Dominated Climate – A Case Study of Algeria.

Damiloju Lydia Adeyina^{1*}, Timothy Anderson¹ and Ali Ghaffarian Hoseini²

¹Department of Mechanical Engineering, Auckland University of Technology, Auckland, New Zealand

²Department of Built Environment Engineering Auckland University of Technology, Auckland, New Zealand

*Corresponding author: damiloju.adeyina@aut.ac.nz

Abstract

The Passive House has emerged as a de facto standard for ultra-low energy buildings in recent times. Passive House leans heavily on the idea of reducing heat transfer through the building envelope using super-insulation, thermal bridge free design, airtight construction, highly insulated windows, and heat recovery ventilation. The application of these Passive House strategies has proved effective in heating-dominated climates and, as a result, has seen its growth worldwide. Despite this, few examples of Passive House buildings are in cooling-dominated climates. Hence, there is a need to explore the application of the Passive House approach in these climates.

To this end, this study undertook a parametric analysis of Passive House strategies applied to a 'typical' building in Algeria's hot and arid climate, where nine months of continuous cooling is often needed. The study showed that although Passive House recommends super-insulating the envelope of the building, with a thermal transmittance of 0.10- 0.15 W/m²K, this level of insulation might not be required in cooling dominated climate. As it was found that insulation applied to the building envelope, particularly the roof, simultaneously reduced the heating and cooling demand. Similarly, double glazing would significantly reduce the heating demand but was less effective in reducing cooling needs. Most tellingly, it was found that the peak cooling load was reduced by 10%, whereas a 54% peak load reduction was observed for heating. In summary, although Passive House strategies are useful in reducing overall energy demand in buildings, they appear to favour heating loads. Therefore, there is a need to understand further the Passive House framework in a cooling dominated climate and how it can be adapted to suit these environs.

Keywords

Algeria, Cooling-dominated climate, Energy Efficient Building, Passive House, Super-Insulation.

Introduction

Growth in sustainable buildings and energy efficiency is expected to be the principal driver of new and existing buildings in many climates. Currently, about 40% of the world's energy is consumed within buildings, mainly for heating and cooling purposes, to achieve a conducive indoor thermal environment (International Energy Agency and the United Nations Environment Programme, 2018) (Yang et al., 2014). Having explored different strategies, Passive House (PH) buildings have achieved heating/cooling energy savings of up to 90% compared to a conventional building and 75% compared to low energy buildings (Passipedia, 2020) (Waq et al., 2020). The buildings achieve these savings without compromising on the occupant's thermal comfort but focus heavily on the idea of reducing heat transfer through and within the building envelope.

The Passive House relies on five fundamental strategies: (i) super-insulation, (ii) thermal bridge free construction, (iii) airtight construction, (iv) high-performance windows, and (v) mechanical ventilation with heat recovery (Passipedia, 2020) (Han *et al.*, 2021). This concept traces its origin to buildings designed for the Central European climate, such as Germany, but has now been significantly adopted worldwide (Passive House Institute US (PHIUS), 2021). Despite this development, there are only a few examples of Passive House buildings in cooling dominated climates (i.e. the tropics and equatorial region), as shown in Figure 1 (Passivhaus Institut, 2019). Therefore, this case study aims to ascertain if the Passive House standard of energy efficiency and thermal comfort is achievable in cooling dominated climate.

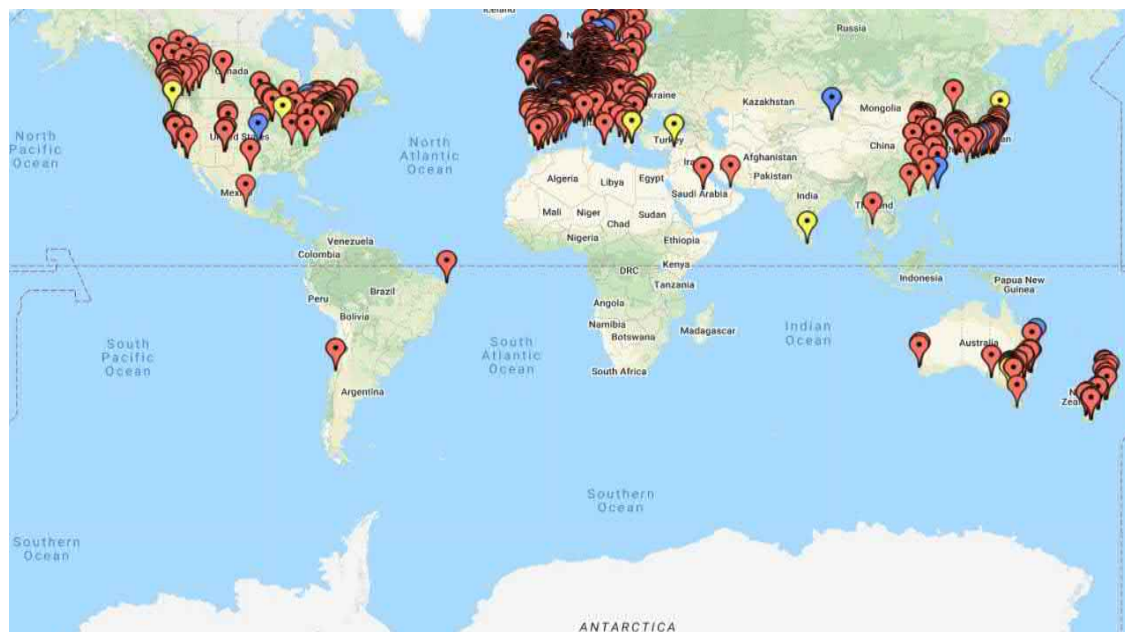


Figure 1: Map of certified Passive House (The International Passive House Association (iPHA), 2021)

Literature Review

It is unclear why Passive House buildings have not been more widely adopted in cooling dominated climates; however, a performance review on a number of Passive Houses has reported some thermal comfort issues, particularly the problem of overheating, even in cold climates. Examining this point, a post-occupancy evaluation of nine Passive Houses built in

Linköping (Sweden) reported that occupants complained of thermal discomfort in the building, including issues relating to high temperatures during the summer period (Rohdin *et al.*, 2014). The principal cause of overheating in the buildings was attributed to the super-insulation and airtightness. Likewise, in another study carried out on the first Passive House office in Romania, Badescu *et al.* (2010) discovered that overheating and cooling load occurrences were higher for a Passive House building than a conventional building.

More recently, Udrea *et al.* (2016) confirmed that overheating in this building was due to wall thickness and the influence of internal gains. Ridley *et al.* (2013) also stated that overheating is a major issue in climate zones characterised by hot summers and mild winters. Noting that the Camden Passive House, which exhibited good space heating in winter, displayed an overheating risk in summer. Similarly, in a performance analysis carried out by Fokaides *et al.* (2016) on the Tseri Passive House, in the semi-tropical climate of Cyprus, the issue of overheating was also reported. Post-occupancy internal heat gain and heatwaves were cited as contributing factors to the high temperature experienced/measured in the building.

The overheating issue pointed out in these buildings is a major concern and can pose an obstacle for the Passive House framework in cooling dominated climates (characterised by high temperature). To this end, Schnieders *et al.* (2015) carried out a study to show the applicability of Passive House in relevant climates of the world represented by Yekaterinburg, Tokyo, Shanghai, Las Vegas, Abu Dhabi, and Singapore. This study concluded that the Passive House standard is achievable in all climates. Thus, implying that the energy demand standard (15kWh/m²a for both heating and cooling), as well as the thermal comfort requirements (temperature not exceeding 25°C for more than 10% of the year, or alternatively through meeting the ASHRAE 55 and EN15251 standard) (Schneider, 2009), can be met in all climate. Although, this was not the case for the cooling dominated climate of Singapore as the study showed that, to meet the thermal comfort standard, total energy demand for sensible and latent cooling may exceed 70 kWh/m²a. This energy demand was considered acceptable because total energy savings of over 75% was achieved in the Passive House compared to a similar conventional building.

In summary, the applicability of the Passive House fundamental design concept in cooling dominated climates is largely unclear. Moreover, there are limited documented examples to substantiate the suitability and efficiency of Passive House strategies in achieving an energy-efficient, thermally conductive building in cooling dominated climates. Furthermore, the occurrence of overheating in heating-dominated climates suggests that achieving the Passive House requirements in a cooling dominated climate is not a straightforward task. Therefore, the objective of this study is to clarify the pertinence and effectiveness of the Passive House strategies (super-insulation, advanced window technology) in reducing energy demand, especially cooling demand, whilst providing a conductive indoor thermal environment in a cooling dominated climate. Also, as achieved in heating dominated climate, can these strategies significantly contribute towards saving at least 75% of a building's cooling demand and total energy when compared to a conventional building.

Method

The study follows a parametric simulation case study approach, where Passive House strategies (super-insulation, advanced window technology) were applied to a typical building in a cooling dominated climate. This method was chosen to evaluate the impact of each PH strategies on the energy demand and thermal comfort of the building. For this study, it was assumed that the building would be located in Ghardaia, Algeria. Ghardaia's climate is characterised by

pronounced temperature differences between day and night and summer and winter. The winter season begins in December and lasts until the end of February; the summer season extends from March until the end of November. The hottest month is July, with an average temperature of 32.5°C (91°F), while the coldest month is January, with an average temperature of 11°C (52°F).

The energy utilised in conditioning the building was simulated and analysed using the building modelling tool, Integrated Environmental Solutions-Virtual environment (IES-VE). IES-VE provides an environment for a detailed evaluation of building and system designs, allowing them to be optimised for comfort criteria and energy use. IES-VE has also been utilised in other Passive house studies, such as the work of Buijze and Wright (2021).

The construction parameters for the baseline building in this case study were taken from documented secondary sources by Sami-Mecheri et al., (2015) and Ali-Toudert and Weidhaus (2017). The data includes the architectural layout of the building, as shown in Figure 2, with its corresponding building material, occupancy profile, internal load, and energy analysis results. In summary, the building is a single-story family house with no basement. The main façade is oriented towards the south; the living area is approximately 70 m² with a total window area of 13m².

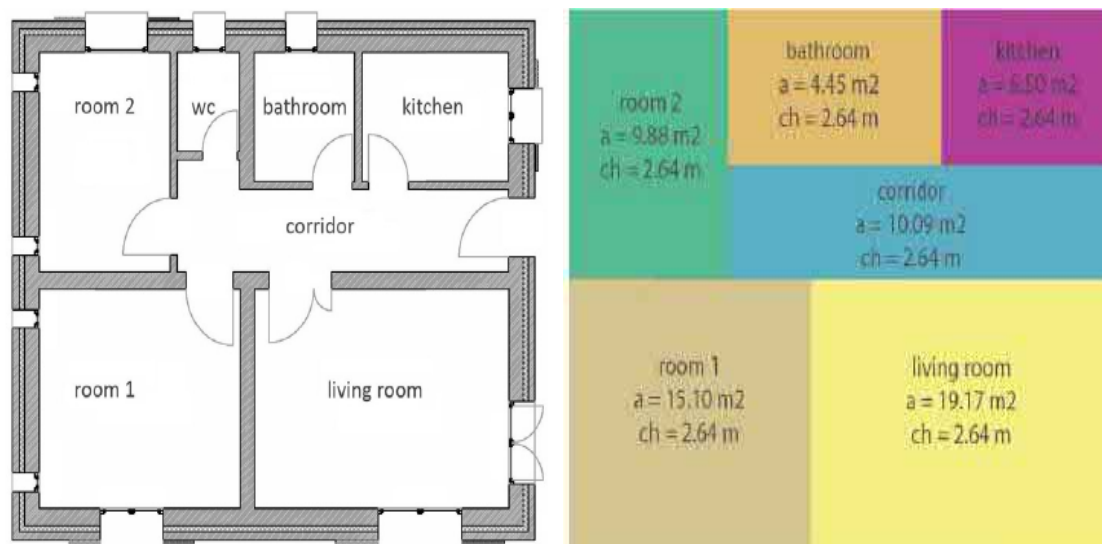


Figure 2: Architectural layout and dimension of the case study building (Ali-Toudert and Weidhaus, 2017).

The building is typical of a residential building in Algeria, with a flat roof and an un-insulated building envelope. The thermal transmittance of the façade elements is shown in Table 1. During its regular operation, the buildings heating setpoint for rooms one and two, the living room and the bathroom is 18°C, while the living room is maintained at 21°C. Conversely, the cooling setpoint is 24 °C. In saying this, the simulation profile assumes the building's uncontrolled ventilation rate is 0.5 ACH (air changes per hour) with an additional 1.4 ACH of controlled ventilation to prevent overheating in the daytime and 2.4 ACH at night during the summer period (May 15-September 15). Also, the building is subject to an internal heat gain due to continuous equipment use in both the kitchen and living room of 50 W. From 6 am to 10 pm, the lighting adds 19 W/m² for Room 1, Room 2, and the bathroom, and 13W/m² for the kitchen and corridor. Additionally, the occupancy profile assumes one person per space, except for the corridor (seated at rest, as per DIN EN ISO 7730). More detailed information about the quantitative data for the building components and layers can be found in Ali-Toudert and Weidhaus (2017).

Table 1: Thermal Transmittance of the Building Components.

Building Component	U-value (W/m ² K)
Floor construction	2.6355
Ceiling Construction	2.9331
External Wall	1.1493
Internal Wall	1.8864
Window	5.4739

Results

Validation of Reference Model- Base Case.

Having outlined the thermal design of the baseline building, IES-VE was used to simulate the heating and cooling demand. In Figure 3, it can be seen that the results are broadly comparable to those reported by Ali-Toudert and Weidhaus (2017) for the identical building. The differences in heating and cooling demand can be attributed to the difference in the software package, weather data and minor assumptions (such as the glazing size) in the modelling and simulation settings used in this study.

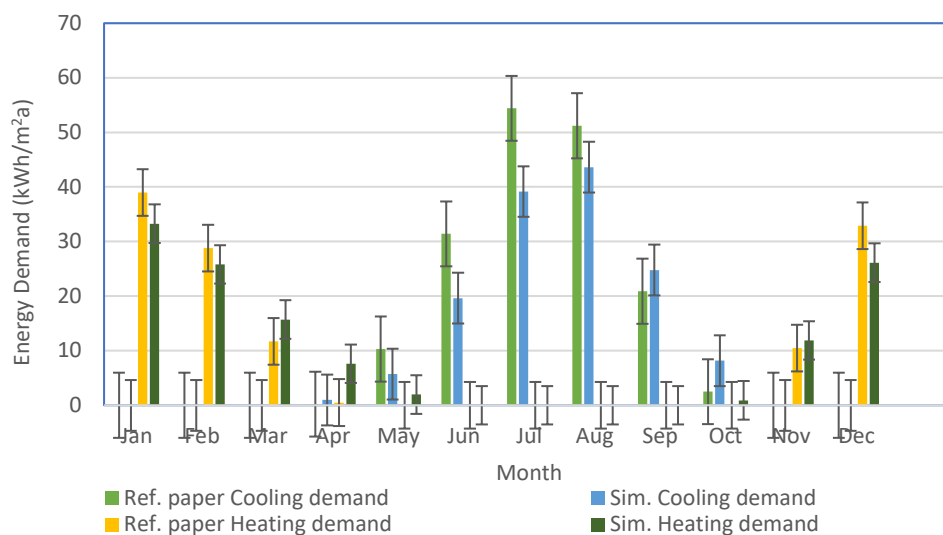


Figure 3: Monthly heating & cooling demand of the reference building.

Parametric Exploration

Having shown that the simulation software could predict the thermal environment, it was decided to examine how changes to the building design would subsequently affect its performance. In Algeria, no minimum level of insulation is currently enforced by regulations

(Kerfah et al., 2020). However, Passive House recommends that buildings be super-insulated to meet, thermal transmittance value of 0.10-0.15 W/m²K, with values of up to 0.30 W/m²K having been used in warmer climates (Passipedia, 2018) (Schnieders et al., 2015). On this basis, it was decided to examine how changes to the façade would impact the heating and cooling load for the building.

External Wall Analysis

As noted previously, Algeria has no mandated requirement for insulation in buildings. However, Figure 4 shows that the application of just 2cm of insulation (0.60 W/m²K) results in a 24% reduction in the building's peak heating load. Furthermore, a 6% decrease in the heating demand is also observed because the insulating material reduces the heat loss in the building. On the other hand, it is important to note that the insulation only slightly minimises the building's peak cooling load and cooling demand.

Since the insulation reduces heat transfer between internal and external boundaries, its minimal effect on cooling load could connote energy gained by the wall from the external environment is insignificant. Thus, the building's heat gain (i.e., internal heat gain and solar gain) remains somewhat unchanged. Accordingly, translating to a relatively small change in cooling demand with less than 5% energy savings at a maximum thickness of 10cm (0.20 W/m²K).

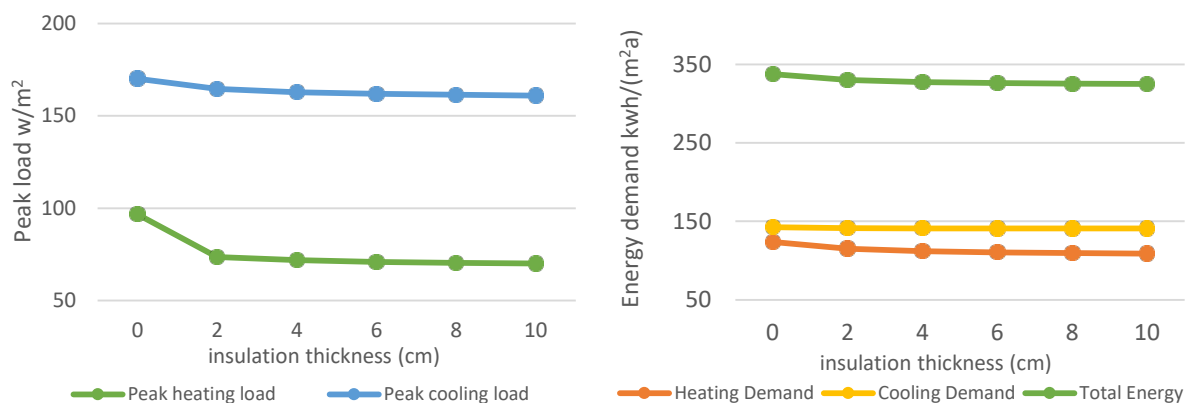


Figure 4: Energy demand for wall insulation.

Ground Floor Analysis

Considering that the insulated wall, mostly exposed to the external environment, has no significant influence on cooling demand. It is necessary to investigate the impact of insulation on the ground floor not directly exposed to the sun. The result in Figure 5 shows insulation isolates the internal environment, conversely impeding conductive heat transfer from the ground while preventing heat loss in the building. Notably, minimum insulation of 2cm (0.80 W/m²K) reduced the peak heating and cooling load by 18% and 14% simultaneously. Also, as insulation increases, peak heating and cooling loads continuously decreases. An additional decline of 4% for peak heating and 2.5% for peak cooling load is observed as the insulation is increased to 4cm (U-value 0.47 W/m²K). Resulting in a significant 40% decline in heating

demand compared to the reference building and only about 2.4% reduction observed for cooling demand. However, beyond 4cm insulation, energy transfer is diminished; thus, insulation has no significant effect on the peak load. The cooling demand then begins to slightly increase as insulation slows the removal of heat energy (internal heat gain). So, more heat is retained in the building, thereby increasing the cooling demand.

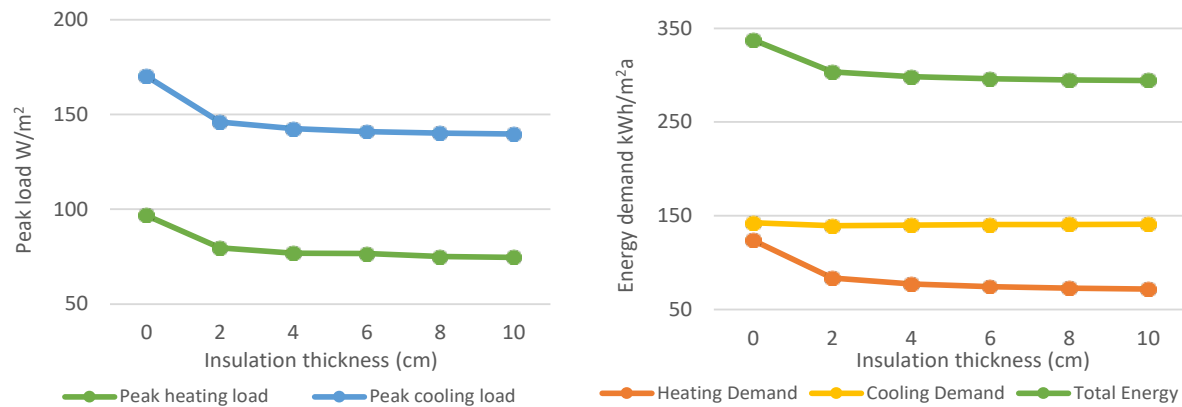


Figure 5: Energy demand for floor insulation.

Roof Analysis

The un-insulated roof is directly exposed to the sun and, as such, allow significant heat gain, which may be excellent for heating. However, the influence of insulation on the building's cooling energy demand is established in Figure 6. The result shows that although significant heat could be gained via the roof, heat gained could also be lost quickly. Thus, even the minimum insulation thickness of 2cm ($0.87 \text{ W/m}^2\text{K}$) keeps excessive heat out and reduces heat loss from the building. Its impact on the cooling load shows that significant heat is gained from the sun; therefore, applying insulation diminishes the cooling load by 19%. Likewise, heat gain, including those from other sources (i.e., internal gain), is prevented from being lost, thereby reducing peak heating load by 24%. The reduction of peak loads consequently results in energy savings of 29% and 20% for heating and cooling simultaneously. More so, as the insulation increases, there is a continuous drop in peak load, energy demand for both heating and cooling and total energy. Though, beyond the insulation thickness of 6cm ($0.35 \text{ W/m}^2\text{K}$), the effect of insulation is insignificant. As it appears, this thickness of insulation is sufficient in sequestering the indoor environment from the external environment whilst maintaining the indoor condition, hence its diminished significance on the building's energy demand.

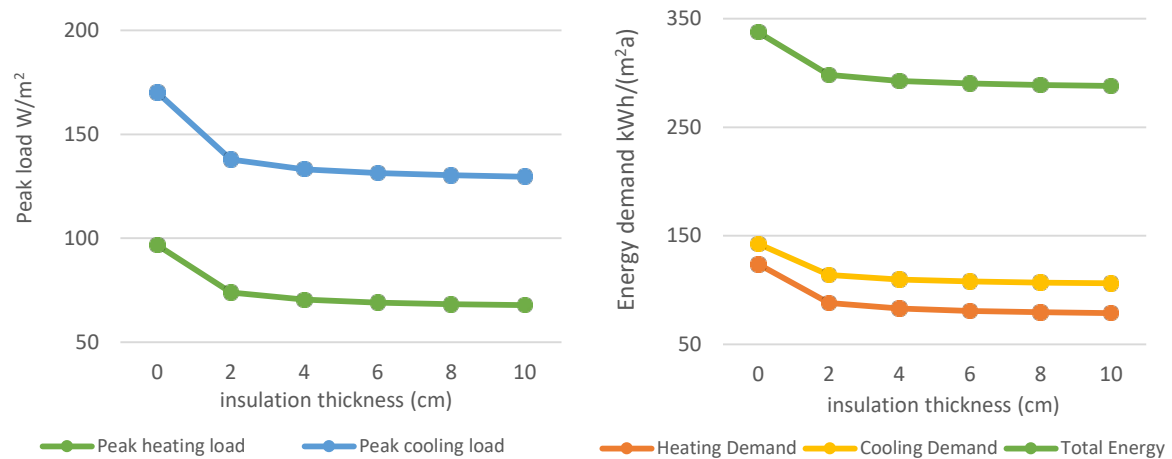


Figure 6: Energy demand for roof insulation

Advanced Window Analysis

Lastly, an integral part of evaluating the building envelope is the window glazing. The reference building with a wall to window ratio (WWR) of 15% uses a single glazed window of U-value of $5.5 \text{ W/m}^2\text{K}$. To evaluate the impact of low thermal windows, which can range from 0.7 to $1.8 \text{ W/m}^2\text{K}$ in triple and double-glazed windows; a double-glazed window with a thermal transmittance of $1.4 \text{ W/m}^2\text{K}$ and a Passive House standard window of $0.80 \text{ W/m}^2\text{K}$ is explored in the model building.

The result displayed in Figure 7 shows, the application of low thermal glazing to the conventional building proves beneficial to the heating load/demand. The double-glazed window of $1.4 \text{ W/m}^2\text{K}$ diminishes only 3% of the peak cooling load, while a substantial 26% was observed for the peak heat load. The less impact on the cooling demand can be due to insignificant solar gain based on windows size. However, the double-glazed window proves sufficient to exclude the negligible solar heat gain, saving 3% of cooling demand. On the other hand, the low thermal glazing prevents heat loss in the building, hence its influence on the peak heating load resulting in heating energy savings of 12% and 21% using the standard passive house window.

The Passive House standard window further insulates the indoor environment and causes heat to be trapped in the building. That way increases cooling energy demand by 7%, surpassing the need when single-glazed windows were used in the model. Consequently, rendering the passive house standard window undesirable in this cooling dominated climate.

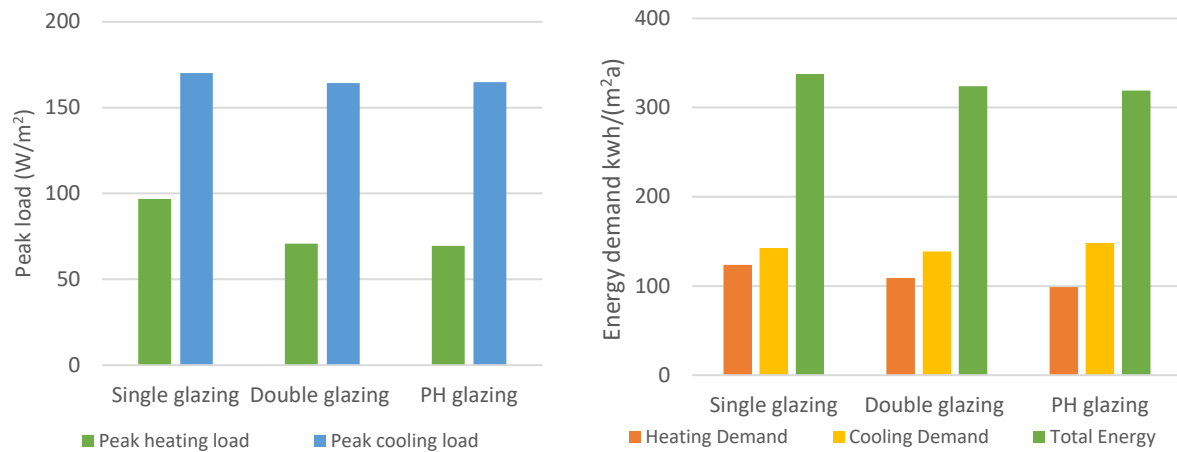


Figure 7: Energy demand for advanced window technology.

In conclusion, it can be observed that insulation isolates the internal environment, thereby limiting the influence of external conditions. However, certain thickness and thermal transmittance would negatively impact the cooling demand, which is undesirable in this climate of study.

Insulated Envelope (Wall, Roof, Floor) and Advanced Window Technology.

The preliminary analysis of the building envelope does provide clarity on the impact of the Passive House strategy on each component. It also informs the thermal value suitable in this climate to reduce cooling demand. However, to ascertain that this would provide the best result in energy demand and thermal comfort for building in this climate. It is pivotal to apply these thermal values to the building envelope simultaneously and its outcome compared to the Passive House recommendation. Consequently, the model building is analysed with two variations, Case 1 and 2. Based on the preceding analysis, Case 1 (“insulated envelope”) considers thermal value for each building component beneficial to heating with consideration for cooling demand. Whereas Case 2 (“Super-Insulated Envelope”) explores the highest thickness of 10 cm for all parts as in a Prototype Passive House with the Passive House standard window application, as shown in Table 2.

Table 2: Characteristics of the reference building and alternative case studies.

The Reference Building		Case 1		Case 2	
Building Component	U-value (W/m²K)	Insulation thickness (cm)	U-value (W/m²K)	Insulation thickness (cm)	U-value (W/m²K)
Roof	3.56	6	0.41	10	0.21
Wall	1.15	4	0.35	10	0.21
Floor	2.64	2	0.8	10	0.21
Glazing	5.4		1.4		0.8

Having analysed both variations, the result of the building’s energy demand and the indoor thermal condition is presented. In Figure 8, Case 1 shows that insulating the building component at the thickness beneficial to heating with attention to cooling demand resulted in a significant decline in the peak heating load by 91.5% and the peak cooling load by 51%. Hence, as in a Passive House, heating demand, if necessary, can be handled by a small system.

Accordingly, the cooling demand can be managed using a system half the size required for a conventional building. Overall, resulting in energy demand savings of 88% and 29% for heating and cooling, respectively and 31% of the building's total energy demand compared to the reference building.

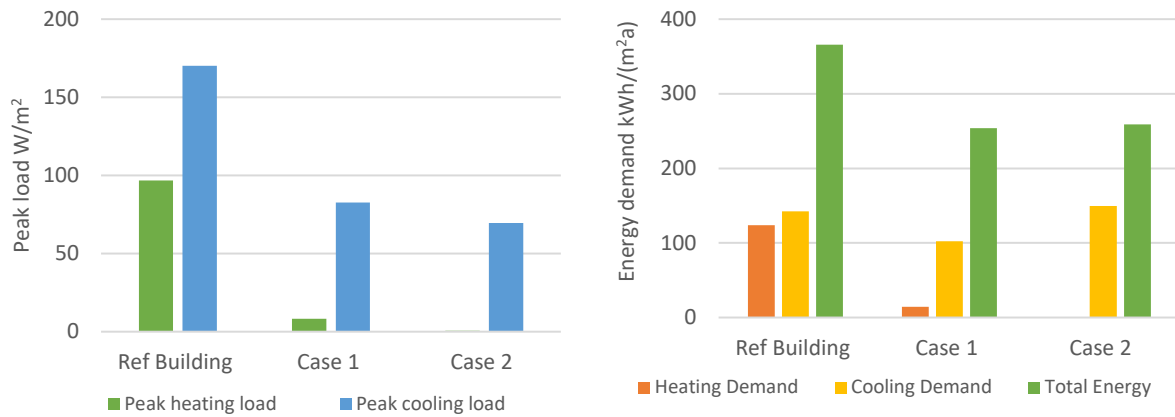


Figure 8: Energy Demand of Case 1 (Insulated Envelope) & Case 2 (Super Insulated Envelope)

On the other hand, in Case 2, as illustrated in Figure 8, heating demand has somewhat been eliminated in the building. It can also be seen that, although peak cooling load is reduced by about 60%, the cooling energy demand to maintain thermal comfort is fairly the same as the un-insulated reference building with an additional increment of 5%. As earlier mentioned, the lower the thermal value, the more isolated the indoor space is from external conditions. Meanwhile, heat gained in the building is trapped, and super-insulation hinders heat loss, thus increasing cooling demand to maintain indoor thermal comfort. As represented by the Passive House comfort graph, the indoor condition of both scenarios is shown in Figure 9.

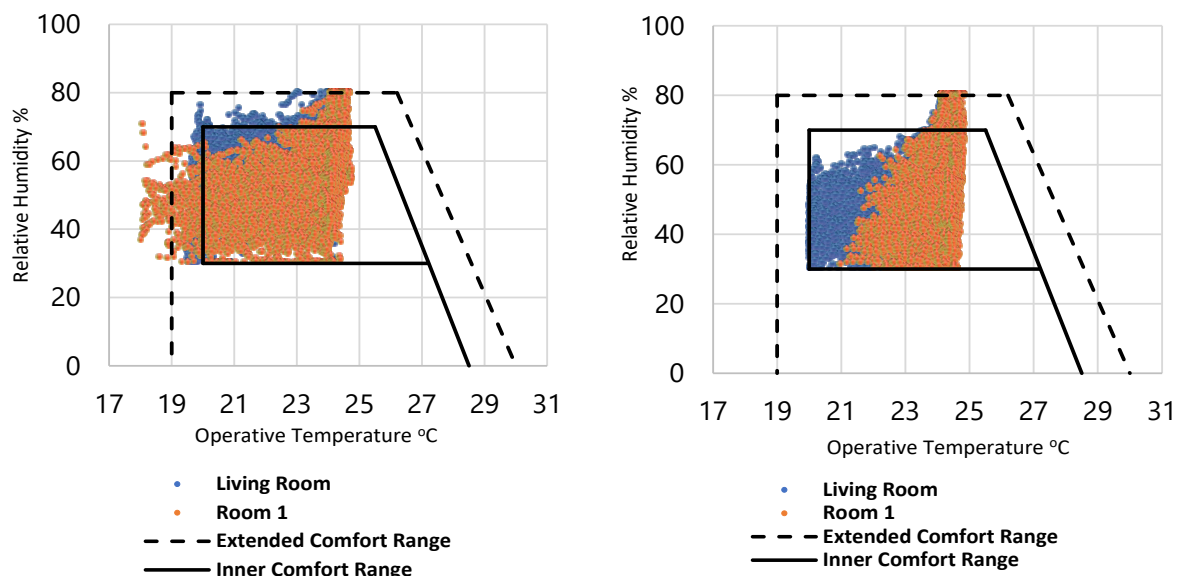


Figure 9: Indoor Operative Temperature & Relative Humidity for cases 1 (left) & 2 (right).

In Case 1, it is observed that the room temperature is presented to have some hours outside the graph's comfort/extended zone. Considering the room temperature was set to 18 °C, the temperature shown for Case 1 is deemed acceptable. However, regardless of the setpoint temperature, the Case 2 graph shows the room temperature seems to be higher than in Case 1, showing the effect of super-insulation in preventing heat loss. Thus, the comfort bandwidth, particularly for the room, seems higher and narrower (20-24.5 °C) in the super-insulated building than the temperature of 18-24.5 °C experienced in the less insulated building. This result also shows that the super-insulated building will likely overheat if the internal heat increases post-occupancy. However, based on this study, it can be concluded that both cases offer a conducive indoor solution, and preference will be dependent upon occupants, as the difference in total energy saved is only 2%, with the less insulated building saving more. Finally, it can be argued that both cases offer their own advantage, where in Case 1, even though both heating and cooling demand reduce significantly. There is a need for a mechanical system to maintain thermal comfort in both winters (although minimal) and summer seasons. In Case 2, the heating needs can be eradicated entirely, focusing only on cooling needs. In this case, cooling can then be delivered with a cooling system 50% less than the reference building requires.

Conclusion

The Passive House is rapidly becoming a standard for buildings in heating-dominated climates and has been recognised for saving energy and providing a conducive indoor environment. Considering that energy efficiency and thermal comfort are common issues in buildings. This study explores the fundamental Passive House strategies for possible adaptation in a cooling-dominated climate, with a view to establishing its effectiveness in this climate. Following a parametric approach, this study investigated two main Passive House strategies (super-insulation, advanced window technology) for a conventional building in Ghardaia, Algeria.

The simulations evaluated the building's energy demand for heating, cooling, and total energy, including the mechanical system's peak load to maintain the set temperature. It was observed that insulation and low thermal windows are primarily valuable for reducing heating demand. Saving up to 88% of the heating demand in Case 1 (insulated envelope) whilst almost eliminating the demand for heating in Case 2 (super-insulated envelope). However, with the primary focus of this study being the cooling demand, it was observed that the application of the PH strategies (Super-Insulation and low thermal windows) can minimise cooling load by isolating the indoor environment from external conditions. Although, its effect on the cooling demand is not as significant as the heating demand where only 31% savings was achieved in Case 1 and 29% in Case 2. Suggesting that less insulation than typically recommended for a Passive House can manage external influence without totally hindering heat loss in the building, as such reducing cooling energy demand and total energy up to 30%. This is almost half the targeted savings of 75%, hence, these strategies (super-insulation and advanced window technology) significantly contribute toward achieving a Passive House in a cooling dominated climate.

Additionally, it was observed that the application of these strategies resulted in a thermal conducive indoor environment. However, it is advisable to carefully consider the possibility of increasing internal heat gain post-occupancy in the scenario of the super-insulated envelope (Case 2) to prevent overheating risk. As shown above, heat loss in the super-insulated building is slower compared to the less insulated envelope. Therefore, presents a higher and narrower thermal bandwidth which can potentially lead to overheating if internal heat gains increase in the building.

Overall, insulation and low thermal window are advisable for this climate. Although, the preferred recommendation as to either lightly or super-insulation will be dependent on other factors. These factors would include the occupants' thermal preference, a potential increase in internal heat gain post-occupancy posing overheating risk, and viable alternatives (i.e., night ventilation) to meet cooling demand.

In this respect, the study is limited in that it is yet to consider the effect of other Passive House strategies, such as the effectiveness of using a recovery system in this building to reduce cooling demand further (as in a standard Passive House). In addition, several passive strategies, shading, energy-efficient appliances, and night ventilation to reduce cooling load and demand have not been explored. Therefore, future studies should examine whether these strategies are effective in insulated buildings to obtain a building comparable to the Passive House's energy efficiency and thermal comfort.

References

- Ali-Toudert, F. and Weidhaus, J. (2017) 'Numerical assessment and optimization of a low-energy residential building for Mediterranean and Saharan climates using a pilot project in Algeria', *Renewable Energy*, 101. doi: 10.1016/j.renene.2016.08.043.
- Badescu, V., Laaser, N. and Crutescu, R. (2010) 'Warm season cooling requirements for passive buildings in Southeastern Europe (Romania)', *Energy*, 35(8), pp. 3284–3300. doi: <http://dx.doi.org/10.1016/j.energy.2010.04.013>.
- Buijze, J. A. and Wright, A. J. (2021) 'The potential for the passive house standard in longyearbyen – The high arctic', *Building Service Engineering Research and Technology*, pp. 1–19. doi: DOI: 10.1177/0143624421996989.
- Han, F. et al. (2021) 'Verifying of the feasibility and energy efficiency of the largest certified passive house office building in China: A three-year performance monitoring study', *Journal of Building Engineering*, p. 103703. doi: 10.1016/j.jobbe.2021.103703.
- International Energy Agency and the United Nations Environment Programme (2018) *2018 Global Status Report: towards a zero-emission, efficient and resilient buildings and construction sector*. Available at: <https://www.worldgbc.org/news-media/2018-global-status-report-towards-zero-emission-efficient-and-resilient-buildings-and> (Accessed: 6 December 2021).
- Passipedia (2018) *Example - Passive House Database*. Available at: <https://passipedia.org/examples> (Accessed: 22 August 2018).
- Passipedia (2020) *What is a Passive House?* Available at: https://passipedia.org/basics/what_is_a_passive_house (Accessed: 20 July 2019).
- Passive House Institute US (PHIUS) (2021) *The History of Passive Houses and Passive Building*. Available at: <https://www.phius.org/what-is-passive-building/the-history-of-passive-houses> (Accessed: 27 March 2021).
- Passivhaus Institut (2019) *Introduction - Passive House buildings in different climates*. Available at: https://passipedia.org/basics/passive_houses_in_different_climates/introduction (Accessed: 5 October 2021).
- Ridley, I. et al. (2013) 'The monitored performance of the first new London dwelling certified to the Passive House standard', *Energy and Buildings*, 63, pp. 67–78. doi: <http://dx.doi.org/10.1016/j.enbuild.2013.03.052>.
- Rohdin, P., Molin, A. and Moshfegh, B. (2014) 'Experiences from nine passive houses in Sweden - Indoor thermal environment and energy use', *Elsevier-Building and Environment*, 71, pp. 176–185. doi:

- <http://dx.doi.org/10.1016/j.buildenv.2013.09.017>.
- Sami-Mecheri, S., Semmar, D. and Hamid, A. (2015) 'Determination of the Energetic Needs of Low Energy Housing and Integration of a Solar Water Heating Installation Located in Algeria', in *Energy Procedia*. Elsevier Ltd, pp. 854–863. doi: 10.1016/j.egypro.2015.07.821.
- Schnieders, J., Feist, W. and Rongen, L. (2015) 'Passive Houses for different climate zones', *Energy and Buildings*, 105, pp. 71–87. doi: 10.1016/j.enbuild.2015.07.032.
- The International Passive House Association (iPHA) (2021) *Map of Certified Passive House Buildings*. Available at: https://passivehouse-international.org/index.php?page_id=288 (Accessed: 20 July 2019).
- Udrea, I. et al. (2016) 'Thermal Comfort in a Romanian Passive House. Preliminary Results', *Energy Procedia*, 85, pp. 575–583. doi: <https://doi.org/10.1016/j.egypro.2015.12.247>.
- Was, K., Radoń, J. and Sadłowska-Sałęga, A. (2020) 'Maintenance of passive house standard in the light of long-term study on energy use in a prefabricated lightweight passive house in central europe', *Energies*, 13(11). doi: 10.3390/en13112801.
- Yang, L., Yan, H. and Lam, J. C. (2014) 'Thermal comfort and building energy consumption implications – A review', *Applied Energy*, 115, pp. 164–173. doi: 10.1016/j.apenergy.2013.10.062.

Self-reported occupant behaviours and multi-domain comfort preferences in New Zealand tertiary office buildings

Achini Shanika Weerasinghe*, Eziaku Rasheed and James Olabode Bamidele Rotimi

School of Built Environment, Massey University, Auckland, New Zealand.

*Corresponding author: A.Weerasinghe@massey.ac.nz;

Abstract

Often, building occupants compromise the energy savings of the building when they modulate their comfort through occupant behaviours. Significant energy impacts are possible through these occupant actions. Therefore, it is necessary to reduce energy consumption and emissions while considering the effects of occupant behaviour based on the occupants' comfort preferences. This study identifies the interrelation between occupants' indoor environment comfort preferences on occupant energy behaviours in New Zealand office buildings. The research used a case study approach with interviewing 25 participants and surveying 52 occupants selected from five educational office buildings. The data were analysed using content analysis and descriptive analysis to draw the findings. Results show that more than 50% of occupants adjust windows, lighting, shades, blinds, computers, heating appliances, drink hot/cold beverages, and adjust clothing to cope with indoor environmental discomfort. Amongst, drinking hot and cold beverages (77%) and opening and closing windows (73%) are most prominent. Specifically, more than 60% of occupants were expected to let in the fresh air, increase air movement, feel cooler, and feel warmer through opening/closing windows, drinking hot/cold beverages, adjusting clothing, and personal heaters. Therefore, air quality and thermal comfort preferences are more prominent than visual and acoustic preferences. The findings from the current study would assist design buildings that maintain occupant comfort. Energy modelers could also use this information to improve occupant energy models for accurate energy consumption prediction.

Keywords

Energy efficiency, indoor environment, comfort, occupant behaviours, offices, New Zealand.

Introduction

The energy behaviour of the occupants can influence the energy use of the building in many ways. The behaviour of occupants, such as operating heating, ventilation, and air conditioning (HVAC) systems and switching lights on and off for their comfort, also lead to considerable fluctuations in total building energy consumption (Harish and Kumar 2016). A recent study by Sun and Hong (2017) highlighted that setting the thermostat to keep the cooling set below 24 °C is a waste of energy. On the other hand, the willingness of occupants to switch off plug loads and HVAC systems when unoccupied or leaving the spaces contribute significantly to avoiding energy waste (Sun and Hong 2017). The occupant energy savings from their behaviour could vary from 5 to 30% in commercial buildings (Hong and Lin 2013, Pothitou et al. 2016). Another study, Hoes et al. (2009), showed that occupant behaviour is an essential input parameter influencing the whole building energy simulations; therefore, uncertainty in occupant behaviours may significantly affect such predictions. Accordingly, a growing number

of researchers have developed around understanding occupant behaviours, especially for energy use predictions at the design stage (He et al. 2021). A vast majority of researchers in this field classified factors influencing energy-driven occupant behaviour into various categories such as environmental, building, social, physiological, psychological, and time-related factors (Bavaresco et al. 2020, D'Oca et al. 2019, Fabi et al. 2012, O'Brien and Gunay 2014, Peng et al. 2012).

Besides the above factors, the comfort preferences of the occupants are also meaningful in this field. In fact, occupants are exposed to multi-domain sources of discomforts inside buildings that continually affect them (Heydarian et al. 2020). Recently, Bavaresco et al. (2021) presented the interrelations between multi-domain comfort preferences with human building interactions like windows, blinds/shades, HVAC, and lighting in office settings. The assessment of combined effects between comfort preferences and occupant energy behaviours is a ground-breaking approach to modelling occupant behaviour for Building Performance Simulations (BPS) (Carlucci et al. 2020). Nevertheless, most previous research lacks broader views and has been limited to specific behaviours like window operation and HVAC adjustments (Harputlugil and De Wilde 2021). Thus, studies investigating occupant behaviours based on multi-domain comfort support assess occupants' indoor environmental preferences (Day et al. 2020).

Along these lines, the purpose of this study is to empirically evaluate the interrelation between multi-domain comfort and occupant behaviour, developing a conceptual framework in New Zealand offices. Multi-domain comfort preferences and occupant energy behaviours were first identified through the interviews on the case study conducted. Second, the comfort preferences and occupant behaviours were further analysed through a survey and identified the interrelationships between these aspects. Finally, a conceptual framework was developed combining both analyses.

Literature Review

Occupant behaviours

Building occupants desire to control the environmental factors based on their living spaces and the outside environment (Burger, 1992). Usually, these reactions of occupants are possible when they are in discomfort and trying to create a comfortable environment (Nicol and Humphreys 2002). According to Bluysen (2019), the building occupants influence the indoor climate through their presence and adjust building systems and components. Such activities aimed to improve thermal, acoustic, visual, and aesthetic comfort in the indoor environment. Similarly, Schweiker (2010) defined energy-driven occupant behaviour as a "human beings' unconscious and conscious actions to control the physical parameters of the surrounding built environment based on the comparison of the perceived environment to the sum of past experiences." However, Fabi et al. (2012) pointed out that this definition is limited to defined occupant behaviours caused by adaptive triggers related to the physical environment such as temperature, humidity, air velocity, solar radiation, etc.

Often, occupants aim to reach their own personal desired comforts using various strategies driven by adaptive triggers. Accordingly, Hong et al. (2017) categorised occupant energy behaviours into two main clusters: adaptive and non-adaptive behaviours. Adaptive behaviours include adjusting windows, blinds, thermostats, lighting, and plug-ins (personal heaters, fans) to adapt the indoor environment to their preferences. Also include changing clothing levels, drinking hot/cold beverages, and moving through spaces to adapt to their environment (de Dear and Brager 1998). On the other hand, non-adaptive behaviours include occupant presence,

operation of plug-ins and electrical equipment (office and home appliances), reporting complaints regarding discomfort (O'Brien and Gunay 2014). Accepting the existing indoor environmental conditions when there is no access, awareness, and choice to control comfort (Deuble and de Dear 2012, Healey 2013) is also considered non-adaptive behaviour. Thus, these occupant actions directly depend on the occupants' comfort requirements and influence overall building performance in building energy consumption and comfort (Wang et al. 2016).

Multi-domain comfort preferences

The occupants cope with various sources of multi-domain discomforts at work, and the primary sources of these discomforts include thermal, visual, acoustic, and air quality aspects (Bavaresco et al. 2021). For example, occupants open windows and blinds to let more daylight in, closing them to reduce overheating in summer (Bavaresco et al. 2021). Thus, occupant behaviours depend on the comfort or discomfort levels (Ozcelik et al. 2019). As further explained by Ozcelik et al. (2019), under concurrent thermal and visual discomfort, occupants initially adjust the shades and blinds, whereas, in no-discomfort situations, they tend to adjust the desk fan first. Accordingly, blinds and shades are adjusted under multi-domain comfort preferences (O'Brien and Kapsis 2013). Additionally, the comfort aspects like indoor air quality and noise level as triggers of window adjustment behaviour are highlighted (Haldi and Robinson 2011, Fabi et al. 2012). Along these lines, Day et al. (2020) emphasised the need to assess how occupants use different building systems using knowledge on multi-domain comfort stimuli.

Research Methodology

This study aims to develop a conceptual framework based on the interrelation between New Zealand offices' multi-domain comfort and occupant behaviour. A case study approach was adopted, employing interviews and a survey for data collection. A university in Auckland, New Zealand, was selected as the case, and a building occupant from five buildings was recruited for data collection. In the first stage, a purposive sample of 25 building occupants were subjected to face-to-face semi-structured interviews and open-ended online questionnaires. In the next round, structured online questionnaires were sent to a sample of 52 building occupants out of 257 of the selected five buildings, making up a response rate of 20% from the building population. The data collection was conducted from October 2020 and January 2021. Table 1 presents the profile of participants in the current study.

Table 1. Profile of participants

Data Collection Round	Participant Type	Occupation	No. of Participants
Interview	Building professional	Facilities management	3
		Sustainability	2
	Building occupant	University staff	15
		PhD student	5
Survey	Building occupant	University staff	31
		PhD student	21

In the interview round, the respondents were asked to mention comfort preferences and occupant behaviours. In the surveying round, the building occupants were asked to select the occupant behaviours they practice and the expected comfort changes from these behaviours given 17 occupant behaviours and 14 comfort preferences. The collected qualitative data were analysed using content analysis, while the quantitative responses were analysed using

descriptive analysis. Finally, a conceptual framework was developed considering the links between occupant comfort preferences and energy behaviours.

Findings and Discussion

Occupants' indoor environmental preferences

Considering the current indoor environmental conditions of the office buildings, the occupants indicated which kind of indoor environment would be most comfortable for them. The majority (64%) responded that they prefer to avoid outdoor sound as it affects their concentration of work and productivity. Another 56% of occupants prefer increased daylight in the office due to lack of windows or unavailability of windows and openings to let in natural light. However, in some places, the occupants are exposed to too much daylight. An equal number of occupants (40%) prefer to let in the fresh air and to feel warmer in winter. At the same time, another 32% prefer to feel cooler in summer. The main reason for these comfort preferences is the inadequacy of heating/cooling appliances and building openings and the lack of control over these building systems. Furthermore, another set of occupants (32%) who are directly exposed to sunlight during sunrise or sundown prefer to avoid glare while working on computers.

Occupant Energy Behaviours

Based on employees' subjective responses through the interviews, the most frequent behaviour is turning lighting on/off with a 76% response rate, closely followed by opening/closing windows selected by 72% of respondents. Considering other behaviours, 44% of occupants mentioned adjusting room air conditioner/thermostat and personal heaters. 40% of occupants also revealed that they adjust shades and blinds. Further, very few occupants (24%) mentioned opening doors. Finally, most building professionals (4 out of 5) added that occupants adapt to the environment by adjusting clothing, drinking hot/cold beverages, and moving through spaces.

However, occupants mentioned that they do not have control over lighting in some offices where the lights are been operated by occupancy sensors or lighting schedules at daytime. Similarly, some offices were fully air-conditioned, and the occupants did not have control over windows. Additionally, some of the occupants explained the reasons for some of the behaviours. Table 2 summarises the responses given by the occupants.

Table 2. Occupant energy behaviours

Occupant energy behaviours	Reasons
Turning lighting on/off	Lack of daylighting
	Mood and habits
	Occupants' personal preferences
	Energy-saving attitude
Adjusting thermostats and personal heaters	No operable windows
	Inadequate heating and cooling
Adjust shades and blinds	To increase daylighting in the morning
	To avoid glare
Opening doors	To let the cool air in from corridors

Quantitative analysis on occupant behaviours and multi-domain comfort

The questionnaire sent to occupants included multiple-choice questions for occupant energy behaviours and multi-domain comfort preference, and the occupants were asked to select the behaviours and preferences they come across in their day-to-day work in the office. As per the responses received, Figure 1 and Figure 2 illustrate the frequency of each behaviour practice and comfort preferences.

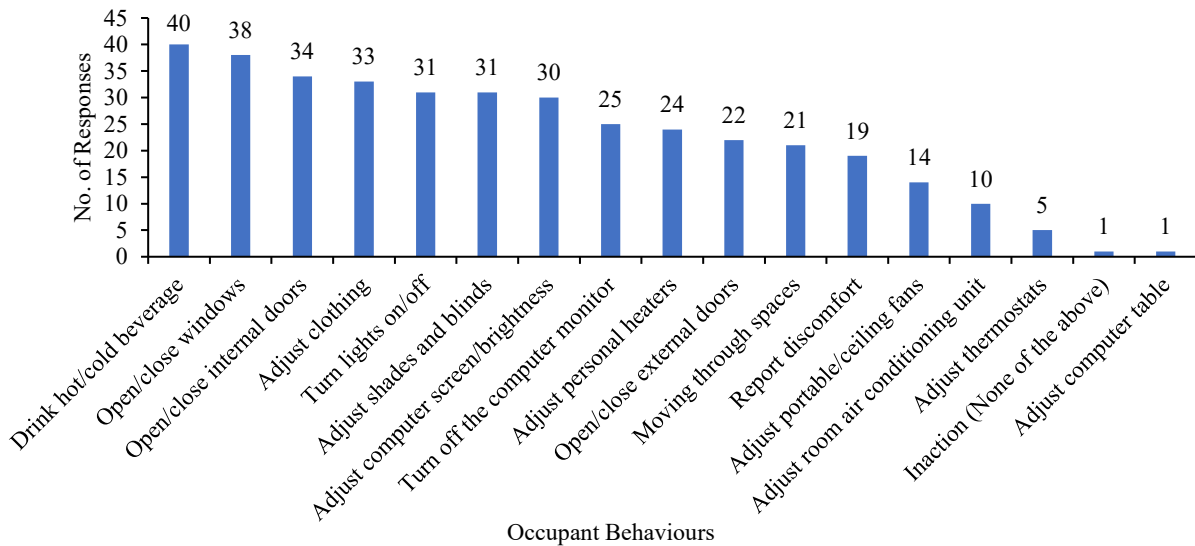


Figure 1. Energy behaviours by office building occupants

As seen from Figure 1, 77% of the respondents stated that they drink hot and cold beverages while working, whereas almost 73% of the occupants open and close windows at their workspace. Further, 65% and 63% of occupants open and close internal doors and adjust their clothing, respectively. Additionally, more than 50% of occupants indicated turning lights on/off, adjusting shades and blinds, and adjusting computer screen/brightness, while the response received to turn off the computer monitor is 50%.

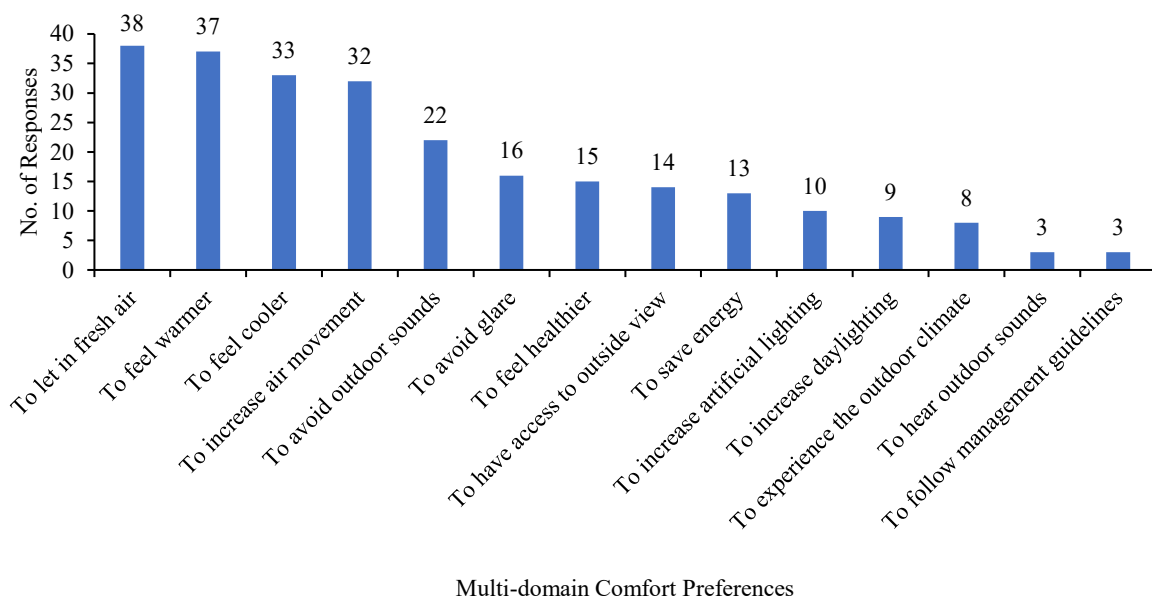


Figure 2. Multi-domain comfort preferences by office building occupants

As seen from Figure 2, most building occupants (73%) preferred to let in the fresh air along with these occupant behaviours. Other expectations that received more than 55% of the responses were to increase air movement, while 29% of the respondents prefer to feel healthier. The occupant behaviour on external doors that received 42% response can relate with the same comfort preferences as occupants' internal doors behaviours. These behaviours may link to avoiding and hearing outdoor sounds that have received 42% and 6% responses, respectively. Similarly, 71% and 64% of the respondents like to feel warmer or cooler depending on the temperature they experience.

Although occupants' lighting behaviour has received a considerable response, the concern on increasing artificial and daylighting received only 19% and 17% responses, respectively. Therefore, lighting behaviour may be linked to other preferences, such as saving energy and preferring a brighter or darker ambient to work. The results imply that occupants' comfort-related behaviour is influenced by their desire to save energy.

Additionally, adjusting portable/ceiling fans, room air conditioning units, and thermostats received responses between 10% - 30% due to the limited availability and accessibility to control these systems. In contrast, the building occupants mentioned non-adaptive behaviours such as moving through spaces and reporting discomfort to the building management by 40% and 37%, respectively. Only 2% of occupants indicated that they do not change the existing indoor environmental conditions or themselves.

In terms of adjustment preferences, only 25% of the occupants expected to save energy. Another 6% of the expected occupants to follow management guidelines through their occupant behaviours showed the significance of individual comfort preferences over managerial concerns.

Considering the behaviours that received 50% or more than 50% of occupants' responses, the survey findings highlight added comfort preferences of occupants, such as increasing air movement within the office while overriding the findings from the interviews. Also, added often practiced occupant behaviours such as drinking hot and cold beverages, adjusting their clothing, adjusting shades and blinds, adjusting computer screen/brightness, and turning off the computer monitor. This further highlights the occupants' unawareness of their behaviours and preferences in the first place; considering these behaviours and preferences is critical when it comes to modelling occupant behaviour for BPS.

The interrelation between occupant energy behaviours and multi-domain comfort

The above findings identified the link between behaviours and comfort preferences, and a conceptual framework was developed for these interrelationships. Figure 3 presents the developed conceptual framework.

According to the developed framework, occupant behaviours are related to multi-domain comfort such as thermal, air quality, acoustic and visual comfort. Occupants' windows and doors behaviour links to air quality and acoustic comfort preference. On the other hand, drinking hot and cold beverages, adjusting clothing, and adjusting personal heaters link with thermal comfort preferences. Considering visual comfort in terms of glare, lighting, and view preferences, adjusting shades and blinds, lighting, and computer screen and brightness link to these preference expectations. Furthermore, occupants' preference to save energy is not relating to their comfort. In contrast, occupants practice behaviours like adjusting the computer screen/brightness, turning off the computer monitor, and turning off lights when not needed, highlighting the building occupants' energy-saving attitude.

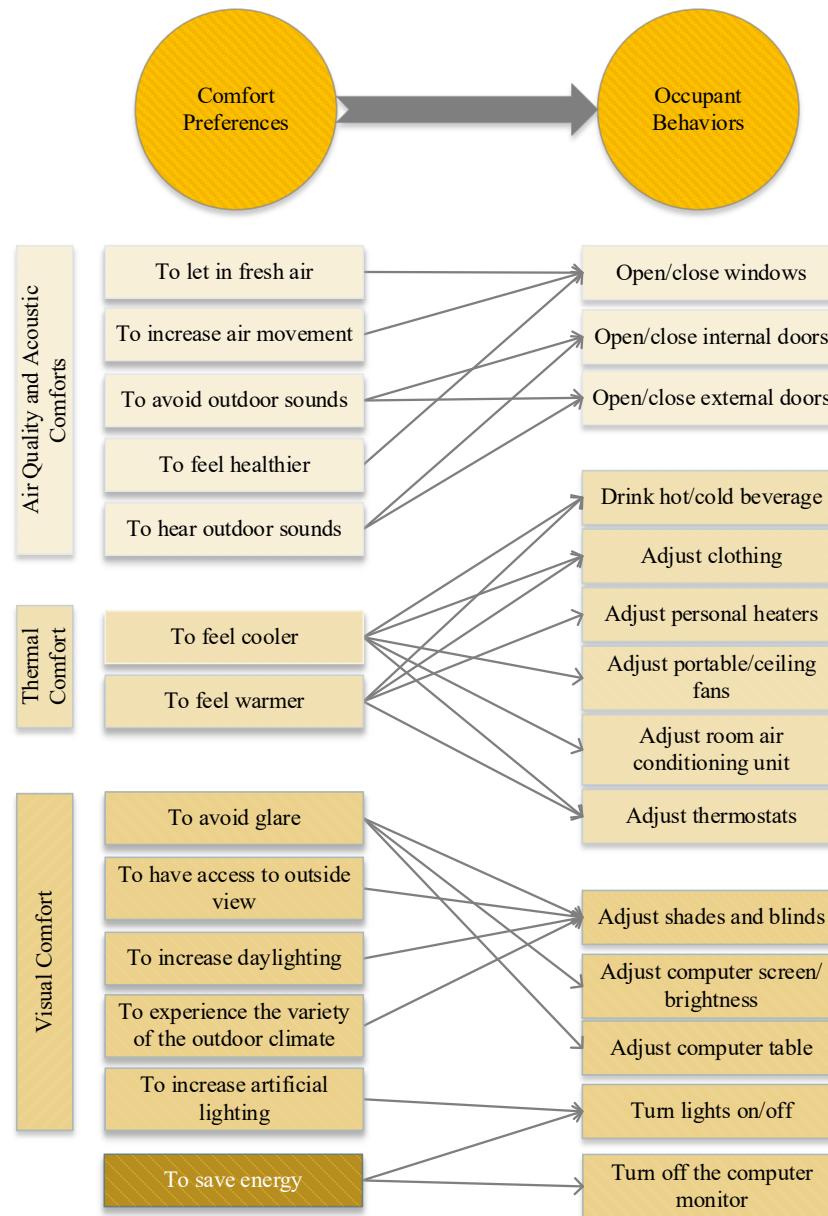


Figure 3. Conceptual framework on the interrelation of occupant energy behaviours and multi-domain comfort preferences

Discussion

This study's primary sources of comfort preferences are thermal and air quality preferences that arise due to multi-domain discomfort in the indoor environment. Along these lines, similar findings were highlighted in the previous empirical studies, indicating that the occupants are continually exposing to multi-domain discomfort (Day et al. 2020, Heydarian et al. 2020). Overall, the current study's occupants' comfort preferences expand the existing research by highlighting the interrelation between occupant behaviours relating to windows, doors, hot/cold beverages, clothing, personal heaters, fans, and air-conditioning systems thermostats, shades and blinds, computers, and lighting. As opposed to current findings, the study by Bavaresco et al. (2021) only highlights the relationship to behaviours such as opening/closing windows, opening/closing blinds, adjusting the thermostat, and adjusting lights.

The current study's most highlighted occupant energy behaviours are adjusting windows, lights, shades and blinds, computers, and personal heaters in their workspace, similar to

findings from Bavaresco et al. (2021) and He et al. (2021) studies. Moreover, other highlighted behaviours were adjusting internal doors, clothing, and drinking hot/cold beverages to deal with the indoor environment, while previous studies focused on the most apparent behaviours directly impacting energy (Harputlugil and De Wilde 2021). Also, the study revealed that occupants tend to do actions that indirectly affect energy consumption. This supports the views introduced in Hong et al. (2017) study, which explained that drinking beverages and occupant metabolic rate influence the comfort levels of individuals and their behaviour patterns, which eventually contribute to energy consumption.

Conclusion

The study reinforces the occupant behaviour association with indoor environmental conditions by identifying the primary sources of multi-domain discomfort and the occupants' perceived comfort preferences. Also, extend the interrelation of comfort preferences to prominent occupant energy behaviours. A better understanding of these relationships pinpoints the occupants' energy wasteful behaviours, supports the building design and operating team to make informed decisions on behalf of the building owners, and optimises building energy performance. The developed conceptual framework will be further extended using the environmental factors influencing occupant energy behaviours in office buildings.

Acknowledgement

This paper is part of a Ph.D. research project. The authors highly acknowledge Massey University, New Zealand, for providing the Doctoral Scholarship for research. The authors would like to thank all the interviewees who took part in this study.

References

- Bavaresco, M.V., D'Oca, S., Ghisi, E., and Pisello, A.L. 2020. Assessing underlying effects on the choices of adaptive behaviours in offices through an interdisciplinary framework. *Building and Environment*, 181 (2020), 107086.
- Bavaresco, M.V., Ghisi, E., D'Oca, S., and Pisello, A.L. 2021. Triggering occupant behaviour for energy sustainability: Exploring subjective and comfort-related drivers in Brazilian offices. *Energy Research and Social Science*, 74 (2021), 101959.
- Bluyssen, P.M. 2019. Towards an integrated analysis of the indoor environmental factors and its effects on occupants. *Intelligent Buildings International*, 12 (3), 199-207.
- Burger, J.M. 1992. *Desire for control. Personality, social and clinical perspectives*. Boston: Springer.
- Carlucci, S., De Simone, M., Firth, S.K., Kjærgaard, M.B., Markovic, R., Rahaman, M.S., Annaqeeb, M.K., Biandrate, S., Das, A., Dziedzic, J.W., Fajilla, G., Favero, M., Ferrando, M., Hahn, J., Han, M., Peng, Y., Salim, F., Schlüter, A., and van Treeck, C. 2020. Modeling occupant behavior in buildings. *Building and Environment*, 174 (2020), 106768.
- Day, J.K., McIlvennie, C., Brackley, C., Tarantini, M., Piselli, C., Hahn, J., O'Brien, W., Rajus, V.S., De Simone, M., Kjærgaard, M.B., Pritoni, M., Schlüter, A., Peng, Y., Schweiker, M., Fajilla, G., Becchio, C., Fabi, V., Spigliantini, G., Derbas, G., and Pisello, A.L. 2020. A Review of Select Human-Building Interfaces and Their Relationship to Human Behavior, Energy Use and Occupant Comfort. *Building and Environment*, 178 (2020), 106920.
- de Dear, R. and Brager, G. 1998. *Developing an adaptive model of thermal comfort and preference*. UC Berkeley: Center for the Built Environment.
- Deuble, M.P. and de Dear, R.J. 2012. Green occupants for green buildings: the missing link?. *Building and Environment*, 56 (2012), 21-27.
- D'Oca, S., Podjed, D., Vetršek, J., Dolinšek, S., and Op't Veld, P. 2019. Contextual and behavioural factors influencing human-building interaction in university offices: A cross-cultural comparison. In: S.I Tanabe, H.

- Zhang, J. Kurnitski, M.C. Gameiro da Silva, I. Nastase, P. Wargocki, G. Cao, L. Mazzarela, and C. Inard, eds. E3S Web of Conference, 26-29 May 2019 Bucharest. CLIMA 2019 Congress, 04064.
- Fabi, V., Andersen, R.V., Corgnati, S. and Olesen, B.W. 2012. Occupants' window opening behaviour: A literature review of factors influencing occupant behaviour and models. *Building and Environment*, 58 (2012), 188-198.
- Haldi, F. and Robinson, D. 2011. The impact of occupants' behaviour on building energy demand. *Journal of Building Performance Simulation*, 4 (4), 323-338.
- Harish, V.S.K.V. and Kumar A.A. 2016. Review on modeling and simulation of building energy systems. *Renewable and Sustainable Energy Reviews*, 56 (2016), 1272–1292.
- Harputlugil, T. and de Wilde, P. 2021. The interaction between humans and buildings for energy efficiency: a critical review. *Energy Research and Social Science*, 71 (2021), 101828.
- He, Z., Hong, T., and Chou, S.K. 2021. A framework for estimating the energy-saving potential of occupant behaviour improvement. *Applied Energy*, 287 (2021), 116591.
- Heydarian, A., McIlvennie, C., Arpan, L., Yousefi, S., Syndicus, M., Schweiker, M., Jazizadeh, F., Risetto, R., Pisello, A.L., Piselli, C., Berger, C., Yan, Z., and Mahdavi, A. 2020. What drives our behaviors in buildings? A review on occupant interactions with building systems from the lens of behavioral theories. *Building and Environment*, 179 (2020), 106928.
- Hoes, P., Hensen, J.L.M., Loomans, M.G.L.C., de Vries, B., and Bourgeois, D. 2009. User behavior in whole building simulation. *Energy and Buildings*, 41 (3), 295-302.
- Hong, T. and Lin H.W. 2013. Occupant Behavior: Impact on Energy Use of Private Offices. Berkeley: Ernest Orlando Lawrence Berkeley National Laboratory Report.
- Hong, T., Yan, D., D'Oca, S., and Chen, C.F. 2017. Ten questions concerning occupant behavior in buildings: The big picture. *Building and Environment*, 114, 518-530.
- Nicol, J.F. and Humphreys, M.A. 2002. Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy and Buildings*, 34 (2002), 563–572.
- O'Brien, W., Kapsis, K., and Athienitis, A.K. 2013. Manually-operated window shade patterns in office buildings: a critical review. *Building and Environment*, 60 (2013), 319–338.
- O'Brien, W. and Gunay, H.B. 2014. The contextual factors contributing to occupants' adaptive comfort behaviors in offices - A review and proposed modeling framework. *Building and Environment*, 77 (2014), 77-87.
- Ozcelik, G., Becerik-Gerber, B., and Chugh, R. 2019. Understanding human-building interactions under multimodal discomfort. *Building and Environment*, 151 (2019), 280-290.
- Peng, C., Yan, D., Wu, R., Wang, C., Zhou, X. and Jiang Y. 2012. Quantitative description and simulation of human behavior in residential buildings. *Building Simulation*, 50 (2012), 85-94.
- Pothitou, M., Kolios, A.J., Varga, L., and Gu, S. 2016. A framework for targeting household energy savings through habitual behavioural change. *International Journal of Sustainable Energy*, 35 (7), 686–700.
- Schweiker, M. 2010. Occupant behaviour and the related reference levels for heating and cooling. Thesis (PhD). Tokyo City University.
- Sun, K. and Hong, T. 2017. A simulation approach to estimate energy savings potential of occupant behavior measures. *Energy and Buildings*, 136 (2017), 43-62.
- Wang, C., Yan, D., Sun, H. and Jiang, Y. 2016. A generalized probabilistic formula relating occupant behavior to environmental conditions. *Building and Environment*, 95 (2016), 53-62.

Logistics management as a sustainability solution for New Zealand construction: A literature review based research framework

Kamal Dhawan*, John E. Tookey, Ali GhaffarianHoseini, Amirhosein GhaffarianHoseini

Auckland University of Technology, New Zealand.

*Corresponding author: kamal.dhawan@aut.ac.nz

Abstract

The New Zealand construction sector is conservative and highly fragmented, arguably due to its geographical isolation. Complex hierarchies, unwieldy project execution, and diverse and disjointed operational and sourcing methodologies typify its fragmentation. Multiple stakeholders, delineated design and construction, insularity of professions, and competitive tendering only compound the issue. Projects exemplifying design, technical, and social complexity driven by short timelines, high accountability, and bespoke delivery, exacerbate the situation.

Logistics is an interdisciplinary domain and forms a substantial component of the complex construction supply chain both in terms of project management and costs. Precluding continuity and an integrated approach, fragmentation manifests as poor coordination and ambiguous division of responsibility, leading to process inefficiency. The resulting increased resource overheads create sustainability concerns. Comprised of diverse elements from transportation to warehousing and management of stocks, logistics present substantial optimisation opportunity for the sector, through both strategic as well as operational mechanisms.

A long term collaborative alliance contract with construction consolidation centre (CCC) based logistics delivery for horizontal infrastructure in Auckland presents a potent research opportunity, being a maiden endeavour. The arrangement potentially provides long-term functional awareness, addresses resource flows, information management, and unifies intra/inter-organisational capabilities, creating a seamless work pipeline with upstream and downstream visibility.

The paper is a literature review based study highlighting the fragmentation issues and sustainability of the construction sector in general and New Zealand in particular. It examines logistics management as a tool for improved sustainability and presents a research framework for examining the impacts of 'Enterprise' alliance strategy and the CCC operational delivery mechanism on logistics management in the New Zealand construction sector. Research outcomes are likely to have fundamental impacts e.g., arriving at the contextual relevance of the concept, drawing and delivery of knowledge, influencing public policy, and producing outcomes transferrable to related domains.

Keywords Construction logistics, Fragmented construction, Sustainable construction, Logistics management, New Zealand construction

Introduction

New Zealand's construction sector is conservative, and responds slowly to improved philosophy. It faces multifarious challenges including limited research and development, amongst others. Notable governmental efforts for transforming the sector include Construction Sector Accord (2019) between industry leaders and the government, and a Construction Sector Transformation Plan (2020). A resultant initiative is a long-term NZ\$ 2.4bn contract between 'Watercare' (Auckland's water service deliverer) and its supply chain partners for capital water works delivery over a decade. It adopts 'Enterprise' alliance strategy and a Construction Consolidation Centre (CCC) as a logistics solution (Duncan, 2019; Ruth, 2019; Turner, 2019). Widely implemented internationally (Allen et al., 2012, 2014; Browne et al., 2005, 2012; DG Move EC, 2012; Lundesjo, 2011; Morana et al., 2014; Transport for London, 2008), both are without precedent in New Zealand. The CCC is a maiden implementation, while Enterprise 'programme alliance' (Klakegg and Artto, 2008) is a first for new infrastructure delivery (NZ InfraComm, 2020), the usual being project alliancing, where New Zealand is a pioneer (Ibrahim et al., 2015).

Though relational project delivery and CCCs have been extensively implemented and studied in Europe, North America, and Australia, New Zealand is an exception. A research gap regarding the logistics impacts under New Zealand's unique spatial, market, regulatory, and economic attributes (geographical isolation, import dependency, small regional expanse, long transits, small market/economy, and regulatory voids) exists.

The paper approaches a literature-based research framework for assessing the impacts of the unique research opportunity on construction logistics in New Zealand, through and examination of fragmentation and sustainability in construction in general and the New Zealand construction sector in particular, and logistics management as a tool for improved sustainability. The implementation of a CCC under long-term collaborative delivery as a logistics solution is a potent opportunity for assessing the contextual relevance of the concepts, as well as for creating contextual implementation benchmarks.

Literature Review

A Systematic Literature Review (SLR) on various aspects of consolidation, CCCs, and relational project delivery was undertaken. The scope the SLR was very wide since New Zealand contextual literature could not be found. SCOPUS, Google Scholar, Auckland University of Technology, University of Westminster, ScienceDirect and Elsevier databases were searched.

The following keywords were used: Construction Supply Chain, Construction Supply Chain Management, Freight Logistics, Urban Logistics, City Logistics, Construction Logistics, Consolidation, Consolidation Centre, Urban Consolidation Centre, Construction Consolidation Centre, Logistics Centre, Green Logistics, Sustainable Transport, Evaluation of Consolidation Centres, Relational Project Delivery, Alliance, Project Alliance, Programme Alliance.

Since the research aims at extending an existing body of knowledge, representative work has been included in the literature review. Backward and Forward searches were undertaken to prevent omission of literature with significant impact (Xiao and Watson, 2017).

The review yielded 136 papers/articles/reports pertaining to various aspects of CSCM, freight logistics/transport, consolidation, consolidation centres, and business models, and 21 pertaining to alliancing and its variants in the construction/infrastructure sector in general, and New Zealand in particular. A summary is at Table 1.

Table 1. Summary of Literature Review

Topic/Subject	Number of Papers/Articles/Reports
Alliancing	11
Alliancing in New Zealand	10
Business Models	15
Consolidation Centres	53
Construction Supply Chain/Management	9
Construction Logistics and Transport	17
Emissions and Transport Technology	16
Urban Freight and Vehicle Movement	13
Supply Chain/Logistics Evaluation	26

Inclusion criteria adopted were: Publication from 1990 to present; Domains as in Table 1; Reported outcomes (literature review, papers with concrete conclusions/outcomes, analysis of implementations); Research agenda; Case studies; Business models; and, Government reports). Literature pertaining to application of specific techniques was excluded.

Literature review has revealed the following significant issues: delivery models, business models for integration/collaboration, facility location principles, facility design, consolidation/distribution models, transport and its optimisation, economic, environmental and social outcomes, knowledge gaps, and similarities/potential impacts in domains such as transport/urban planning, land-use, and energy policy. These may broadly be categorised into four domains i.e., Design, Logistics, Impacts, and Spin-offs.

The Construction Industry

“Construction is the broad process/mechanism for the realisation of human settlements and the creation of infrastructure that supports development. This includes the extraction and beneficiation of raw materials, the manufacturing of construction materials and components, the construction project cycle from feasibility to deconstruction, and the management and operation of the built environment” (Du-Plessis 2002, p. 4).

The construction industry contributes significantly to economies, typically 6% of GDP in developed nations (UNECE n.d.). The sector has certain typical characteristics: Heterogeneity and fragmentation (dependence on a wide range of very different professions); Criticality of transport and logistical aspects; Non-transportability of the final product; Adaptability of the final product to a variety of uses; Built assets being amongst the most durable of human artefacts; Most construction projects being prototypes; Investments in machinery, tools and other elements need to be depreciated over a shorter period than other industrial sectors; Low entry-level for new contractors due to relatively small operational capital need; Close links to the economic cycle; Labour intensive, with high workforce mobility and growing skills needs; Contract duration linked to the length of the site construction phase; High accident rates; and, Generation of large quantities of waste (EC 1997).

Increasing inhabitants, visitors, urban complexity, and quality of life expectations require ever greater construction sector performance. The built environment (BE) continually sees increased demand for construction, repair, and renovation. Construction projects improve accessibility, functionality, and energy efficiency, leading to attractive, sustainable, economically viable, and vibrant urban areas (Balm and Ploos van Amstel 2017).

Project-centric by nature, construction generates employment, creates and improves infrastructure, and supports businesses (Shakantu et al. 2008). Individual uniqueness of

construction projects is exemplified by singularity of design, convergence of the supply chain (SC) on site, project bespoke operations and SCs with minimal standardisation, and repetitive reconfiguration of SCs through lifecycle stages (Wegelius-Lehtonen 2001, Dubois and Gadde 2002, Naismith et al. 2016). No projects are the same even if they are of the same type since factors such as locality, economy and policies highly affect the variables involved (Riazi et al. 2020).

Despite increasing competition, most construction businesses work on precedence without a systematic business strategy or process. Typically, the business models implemented are not well integrated and do not embody Supply Chain Management (SCM) best practice principles. This results in a heavy reliance on contractual sanction instead of participants agreeing on methods for achieving sound financial objectives, leading to adversarial relationships. All involved parties focus on achieving individual objectives and maximising their own profit margins. Such operating methods invariably create a competitive - arguably confrontational - and transactional environment for profit generation, leading to conflict and litigation, damaging the project at the fundamental level. Antagonistic relationships between developers and contractors undermine the project in the long run, and discourage responsible proponents. Anomalies lead to increased transactional costs and adversarial relationships, bringing out the 'best-for-individual' instead of the 'best-for-project' culture (Wegelius-Lehtonen 2001, Ekeskär and Rudberg 2016, Naismith et al. 2016, Fernandes et al. 2017, Navarro-Correcher et al. 2018).

The low cost and high volume characteristic of construction materials implies substantial movement of materials and resources even for small projects (Shakantu et al. 2003, Shakantu and Emuze 2012, Ying and Roberti 2013), underscoring the significance of logistics in construction.

Fragmentation in Construction

Fragmentation as a term describes two phenomena in the construction industry: The construction industry's structure (a relatively large number of small firms causing industry segregation); and, The activities and entities involved at the project level (delineation of design and construction, and limited coordination and integration within the project team). Literature cites the sequential nature of construction process, poor communication and coordination between various functional disciplines, lack of trust, and temporary collaboration of stakeholders as primary drivers of fragmentation (Alashwal and Fong 2015). It may be defined as the lack of coordination, collaboration, integration, poor communication, and diversity of specializations of contractual partners and various functional disciplines. It may refer to internal stakeholders (client, consultant, contractor etc.) or external stakeholders (local authority etc.) (Navi et al. 2014).

From the above, two levels of fragmentation may be interpreted *viz* Industry level or firm level (due to segregation of firms); and, Project level (due to disintegration of construction process and entities). Hierarchical boundaries between functional units of an organisation present a third level of fragmentation, however, this is insignificant owing to the process fragmentation being much deeper. While intra-organisational boundaries may be insignificant insofar as fragmentation is concerned, the project envelope around most projects environment exhibits certain boundaries that significantly impact it. These are project organisation boundaries *viz* expertise boundary, hierarchical boundary, and cultural-related boundary, and project management boundaries *viz* project social boundary, project knowledge boundary, and project action boundary (Alashwal and Abdul-Rahman n.d.). Project characteristics that lead to

fragmentation include *inter alia* project complexity, delivery requirements, high degree of specificity, location-based activities, regulation, complexity of services, and market segmentation (Alashwal and Fong 2015).

Fragmentation essentially involves two attributes: entities and processes. The entities dimension involves disintegration of expertise, situated knowledge, and specialists' inability to work together efficiently, while the process dimension involves the separation of construction process into several stages (initiation, design and planning, construction, and operation and demolition) (Alashwal & Abdul-Rahman n.d.). These translate to *inter alia* multiplicity of stakeholders and actors, delineated design and construction, insularity of professions, unwieldy hierarchies and project execution systems, competitive tendering, disjointed operating methodologies, project organisations, and adversarial relationships (Egan 1998, Wegelius-Lehtonen 2001, Dubois and Gadde 2002, Smith et al. 2004, Fernandes et al. 2017) within the enveloping project-based delivery model.

In construction, specialization in the project-based delivery model has led to fragmentation in three dimensions i.e., *Vertically*, a separation of firms and workers into different stages of project delivery (e.g., planning, design, product and process definition, construction, operation and maintenance); *Horizontally*, when different actors deliver complementary products and services (provided by specialists) at, approximately, the same stage of a process i.e., separation of firms and individuals into crafts, trades, and disciplines; and, *Longitudinally*, where continuity of teams is disrupted by reassignment at the end of a project, taking any tacit, accumulated knowledge with them, i.e., separation of firms and individuals into distinct projects (Shakantu and Emuze 2012, Sheffer and Levitt 2012, Ying et al. 2013, AUAS 2017, Jones et al. 2021). Figure 1 illustrates these.

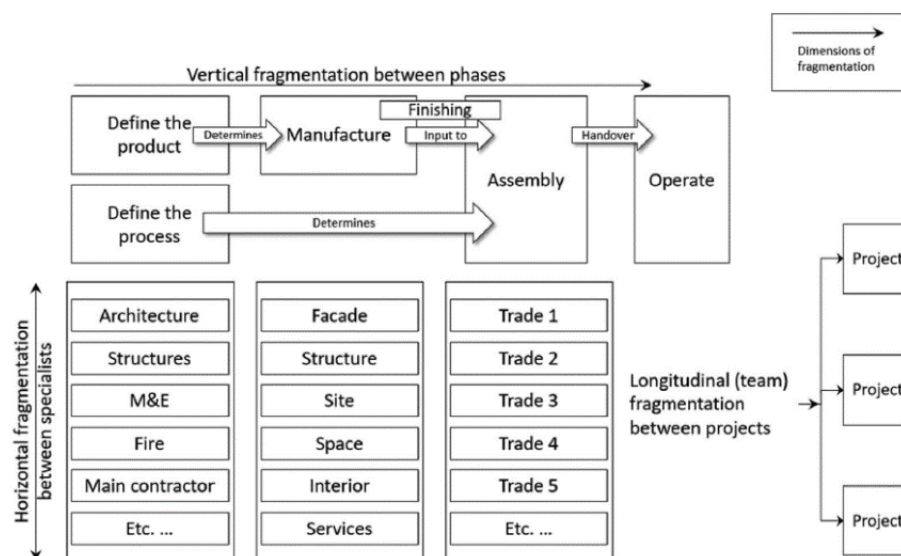


Figure 1. Fragmentation in Construction (Jones et al. 2021)

Table 2 brings out the five components of fragmentation in construction and associated variables/indicators.

Table 2. Components of fragmentation in Construction
(Anumba et al. 2002, Fong 2003, Baiden et al. 2006, Ratcheva 2009)

Component	Indicators
Integration	Single team focus and objectives, seamless operation, mutually beneficial outcomes, increased time and cost predictability, unrestricted cross-sharing of information, team flexibility and responsiveness to change, creation of single and co-located team, equal opportunity for project inputs, equitable team relationships and respect for all, and “No blame” culture.
Coordination	Lateral relationship, information technology, interpersonal relationships, and coordinator role
Collaboration	Common goal, trust, self-governing teams, end-user focus, and information exchange
Project boundaries and spanning knowledge	- Expertise boundaries, hierarchical boundaries, and cultural-related boundaries between professions - Project action boundary, project knowledge boundary, and project social boundary - Level of integrating occupational and contextual knowledge during the construction stage (sufficiency of information from previous stage). - Understanding information from other occupational or disciplinary team members
Decoupling diversity	Participating of different professionals in projects, adversarial relationship, misconception and misunderstanding, and design clashes, omissions and errors (due to data fragmentation)

Though the idea of fragmentation is equally applicable to all phases of a project from ideation, through concept development, design, construction, handover, operation, maintenance, and end of life management, the focus of this paper would be logistics which primarily participate during the construction phase and beyond.

Sustainability in Construction

The UN’s Habitat II Agenda identifies construction as a substantial contributor to socio-economic development in most regions. Statistically, construction contributes to more than half the total national capital investment, translating to circa 10% of GNP in most countries. As a corollary, the sector contributes substantially to the consumption of resources. As of 2019, while construction industry represented 35% of global energy consumption, it contributed to 38% of global emissions, producing 36% of global waste (Figure 2) (UNEP 2015, 2020).

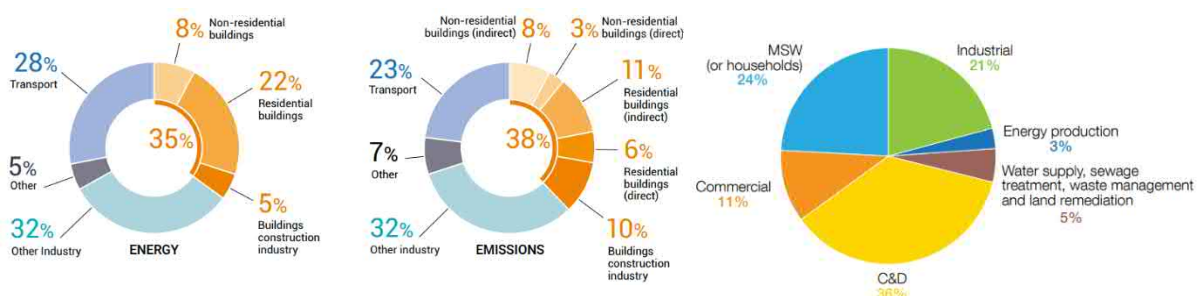


Figure 2. Energy consumption and emissions from the construction industry (L) (UNEP 2020) and Construction and demolition Waste generation (R) (UNEP 2015).

“The construction industry as a whole has to rapidly come to terms with the broader environmental and social agenda that is presented by the concept of sustainable development” (Curwell and Cooper 1998, p. 25).

As an introducer to sustainability and construction, Figure 3 presents positioning of the construction industry within the three sustainability domains.

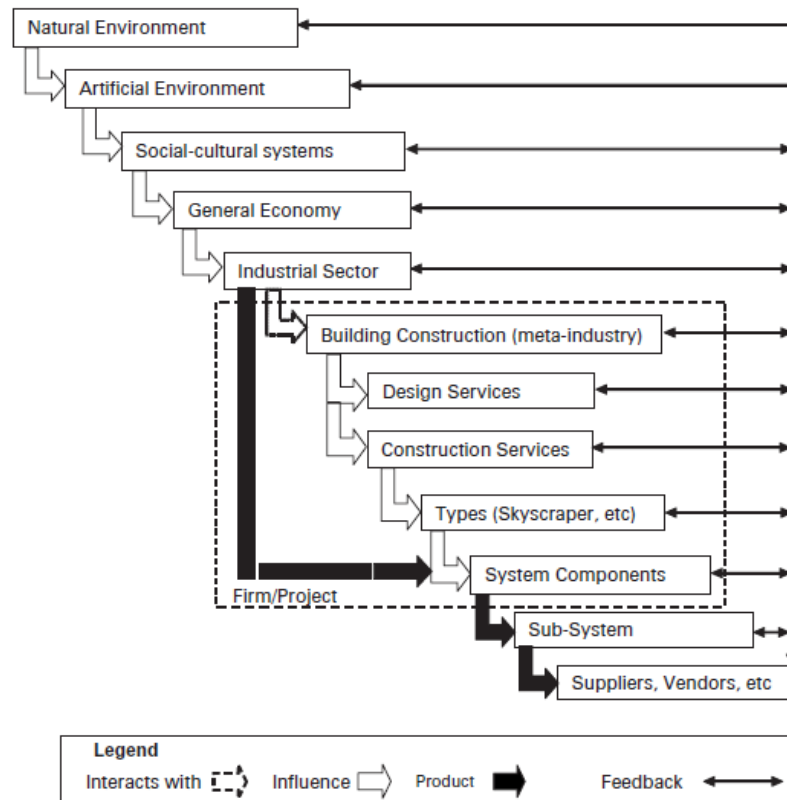


Figure 3. Positioning of Construction within Sustainability dimensions
(Fernández-Solís 2008)

Important definitions of sustainable construction from literature are:-

- *“The creation and operation of a healthy built environment based on ecological principles and resource efficiency”* (Kibert, 1994).
- *“A way of building which aims at reducing (negative) health and environmental impacts caused by the construction process or by buildings or by the built environment”* (Lanting, 1998).
- *“The sustainable production, use, maintenance, demolition, and reuse of buildings and constructions or their components”* (CIB, 2004).
- *“Sustainable construction refers to construction activities whose negative impacts are minimised and positive impacts maximised so as to achieve a balance in terms of environmental, economic and social performance”* (Hosseini et al. 2012).

These point to reduction of negative impacts, introduce the idea of restoration of the environment, highlight the social and economic aspects of sustainability, and define goals. Sustainable construction may be viewed as the contribution of the construction industry together with the built environment (BE) to Sustainable Development (SD), across multiple sectors of human activity and the economy. The need to address the fundamental ethical

dilemma of obligations to future generations is inherent. They serve to outline three aspects of sustainable construction:

- Broad interpretation of construction as a cradle to grave process, involving many more role players than just those traditionally identified as making up the construction industry.
- An emphasis on both environmental protection and value addition to the Quality of Life of individuals and communities.
- Encompassing not just technological responses, but also the non-technical aspects related to social and economic sustainability.

Sustainable construction stands at the intersection of sustainable processes, sources, and principles, and is executed over the three dimensions of the project life cycle, building systems and components, and performance attributes (Figure 4) (Kibert 2005, Nelms et al. 2007).

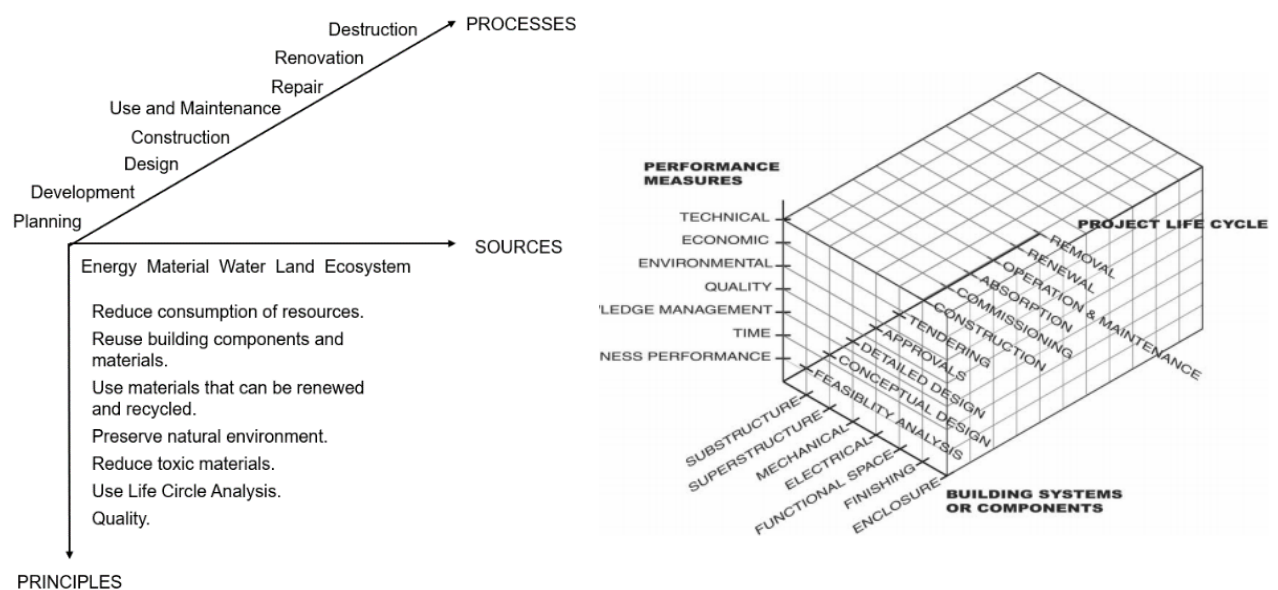


Figure 4. Elements of sustainable construction (Left) (Kibert 2005), and its execution dimensions (Right) (Nelms et al. 2007)

The construction sector has extensive physical boundaries, from extraction of materials, through manufacturing, assembly, construction, system maintenance/replacement, and disposal of waste, building systems, and finally the building structure. The physical distribution and relationships of built assets and infrastructure (and the resultant resource consumption profiles) to the planning decisions they are a result of, makes the paradigm even more complex (Kibert 2007). Table 3 illustrates the sustainability criteria across the lifecycle of a typical construction project.

Table 3. Sustainability criteria across the lifecycle of a typical construction project (Enshassi et al. 2018)

Sustainability Dimension / Project Phase	Inception	Design	Construction	Operation	Demolition
Economic	<i>Scale and Business Scope</i>	<i>Life Cycle Cost</i>	<i>Labour Cost</i>	<i>Training Costs</i>	<i>Labour Costs</i>
	<i>Effects on Local Economy</i>	<i>Standardisation</i>	<i>Materials Cost</i>	<i>Local Economy</i>	<i>Energy Consumption</i>
	<i>Capital Budget</i>	<i>Materials Choice</i>	<i>Water Cost</i>		<i>Waste Disposal Costs</i>
	<i>Finance Plan</i>		<i>Energy Consumption</i>		
			<i>Site Security</i>		
Social	<i>Employment</i>	<i>Safety Design</i>	<i>Direct Employment</i>	<i>Services</i>	<i>Communication to Public</i>
	<i>Infrastructure Capacity Building</i>	<i>Security</i>	<i>Working Conditions</i>	<i>Facilities</i>	<i>Operational Safety</i>
	<i>Community Amenities</i>		<i>Public Awareness</i>		<i>Job Opportunity</i>
	<i>Health and Safety</i>		<i>Infrastructure Improvement</i>		
Environmental	<i>Ecology Preservation</i>	<i>Designer</i>	<i>Noise Pollution</i>	<i>Chemical Waste</i>	<i>Environment Friendly</i>
	<i>Air Pollution</i>	<i>Life Cycle Design</i>	<i>Health and Safety</i>	<i>Water Pollution</i>	<i>Waste Treatment</i>
	<i>Water Pollution</i>	<i>Environmentally Conscious Design</i>	<i>Recyclable/Renewable Content</i>	<i>Waste Generation</i>	<i>Waste Recycling/Reuse</i>
	<i>Noise</i>	<i>Modular and Standardised Design</i>	<i>Legislation</i>		
	<i>Waste Generation</i>				

The New Zealand Construction Sector

By virtue of the geographical location of the country, its construction industry is isolated from the rest of the world (Naismith et al. 2016, Singer, 2018), and responds comparatively slowly to improved philosophy, resulting in delayed introduction of new ideas. New Zealand initiatives follow UK initiatives by almost eight years. The relevance of initiatives to upgrade the construction industry and the construction process, especially in the context of undertaking new business practices and bearing their cost, is contentious in New Zealand. A major void in the form of deficit in knowledge and understanding of construction logistics exists in New Zealand, therefore, the industry is unable to effectively address logistics issues, having limited skills for this (Ying et al. 2013, Ying and Robert, 2013, Ying and Tookey 2014, MBIE, 2020). Historically, the New Zealand construction sector has performed sub-optimally (Figure 5).

The New Zealand construction industry is primarily comprised of Micro, Small and Medium Enterprises (MSMEs) (Seadon & Tookey, 2018). 32.5% of the sector (approximately 60000 operating businesses) is comprised of small businesses (1 to 19 employees), and 65% of sole trading operators. Over 150 industry bodies and subsector groups, in addition to governmental, consenting, and regulatory bodies add to the milieu (Statistics New Zealand 2019, MBIE 2021). These figures demonstrate the ‘firm’ or ‘industry’ fragmentation outwardly, implying external as well as internal manifestation.

Sectoral reviews identify deep fragmentation in the New Zealand construction sector along a host of other dimensions, significant ones being leadership, pipeline of work, procurement,

policy, lack of integration and collaboration, supply chain issues, risk management, mistrust, and knowledge management (Duncan et al. 2018, MBIE 2019).

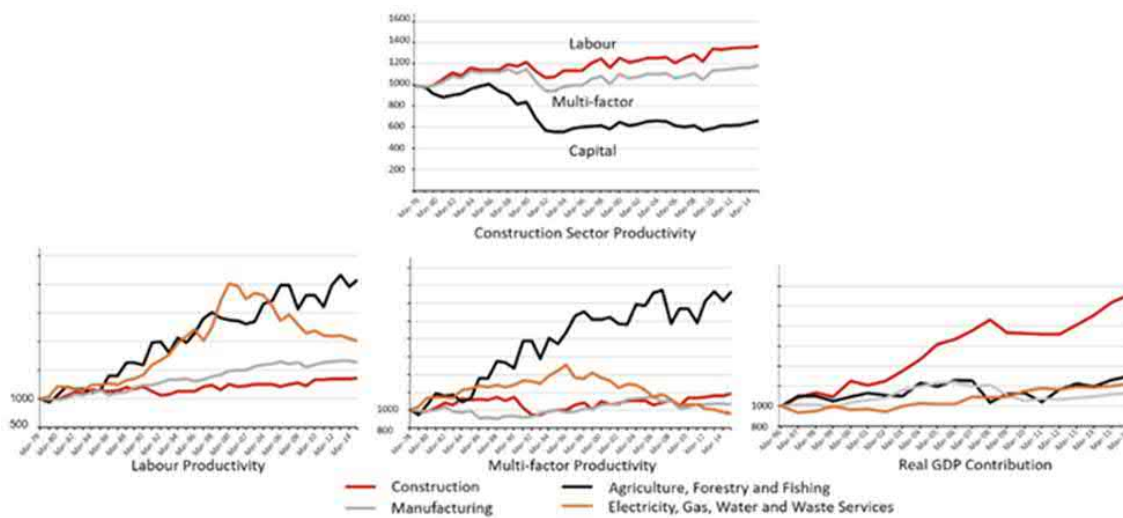


Figure 5. New Zealand construction sector productivity (Curtis 2018)

As far as sustainability of the sector is concerned, though the nation has a very clear objective of continuously improving sustainability, the deep fragmentation once again creates a barrier, making it operate in parts rather than as a whole. The Construction Sector Accord and the Transformation Plan (MBIE 2019, 2020) have a sustainability focus defining the ‘what’, however, leaving the ‘how’ to industry. Adoption of partnering and alliancing in a big way has made New Zealand a world leader in the domain. However, the sustainability impacts of these delivery paradigms are visible only in big projects, primarily infrastructure, and public procurement. BAU is yet to adopt sustainability enablers such as Lean, and BIM, extensively adopted in overseas markets, with the size of construction businesses being a major barrier. Factors affecting sustainable construction in New Zealand are presented at Figure 6.

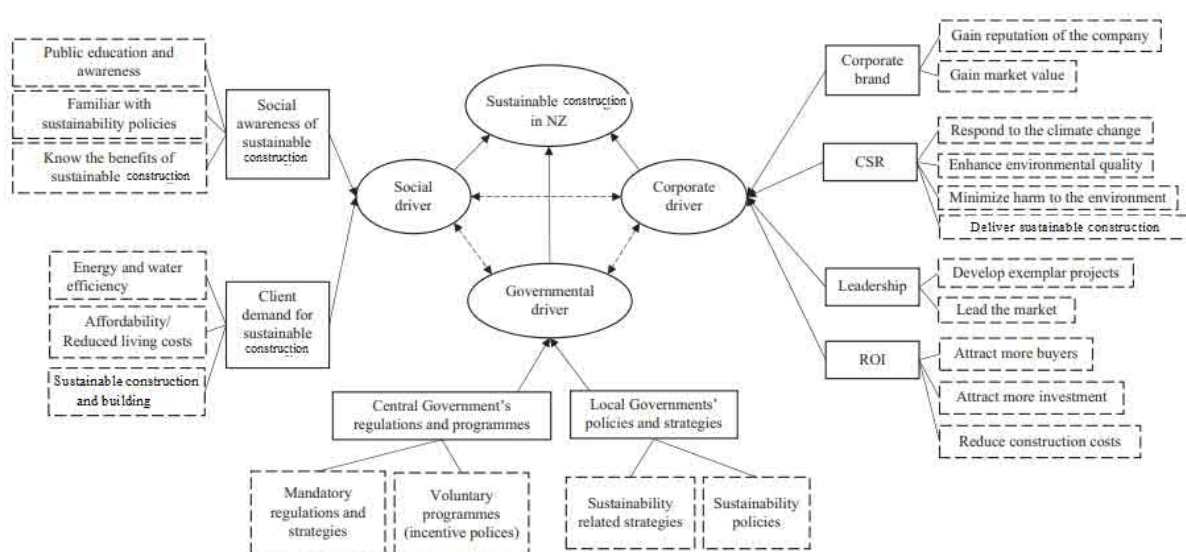


Figure 6. Drivers of Sustainable Construction in New Zealand (Li et al. 2019)

Logistics in Construction

Logistics, peculiar to the construction domain, may be defined as: *“The scope of construction logistics concerns all supply and disposal shipments of building materials, construction equipment and construction personnel to and from the construction site”* (Quak et al. 2011 cited Balm and Ploos van Amstel 2017); *“Construction logistics is the entire complex of measures aimed at getting the right equipment, the right materials and the right workers with the right level of quality to the right construction site at the right moment and at minimum cost to meet the customer’s requirements”* (Quak et al. 2011 cited Balm and Ploos van Amstel 2017); *“...a process of strategically managing the procurement, movement and storage of materials, parts and finished inventory (and the related information flows) through the organisation and its marketing channels in such a way that current and future profitability are maximised through the cost-effective fulfilment of orders”* (Wegelius-Lehtonen 2001).

Logistics are typically comprised of: Transport and movement; Storage and warehousing; Industrial packaging; Manipulation of materials; Stock control; Fixing of orders; Forecasting; Planning of production; Purchase; Appropriately pitched customer service; Plants and warehouse locations; and, Waste collection and disposal (Szymonik 2012).

Construction logistics involve the preparation, management, coordination, and control of product flow from raw material processing to final utilisation in the finished project and reverse logistics of waste removal and disposal (Agapiou et al. 1998, Ying and Tookey 2014). These are comprised of (Serra and Oliveira 2003, Sobotka et al. 2005, Ying et al. 2018):-

- **Whole-project Logistics** Sees the building site through the lens of a production system. It is a member of many logistics chains, executing complex processes within the constraints of budget, space, and time.
- **Supply Logistics** Delivery of products from sources external to the construction viz material and human resources for building activities. Supply logistics are comprised of supplier management, transportation, material resource procurement planning, processing, and maintenance of procured resources.
- **On-site Logistics** On-site material flow coordination internal to the construction site.

A generic construction logistics model groups together planning and organisation, transportation, and site activities (Figure 7).

Activities within the three domains of Planning/organisation, Site, and Transport typically perform the the following roles: **Role 1** - Establishing clear SC - construction site interfaces; **Role 2** - Increasing supply chain efficiency; **Role 3** - Increasing the efficiency of site processes and activities; **Role 4** - Value addition; **Role 5** - Possible integration of the construction site with the SC; **Role 6** - Local stakeholder coordination.

Construction characteristics distinctively influence logistics: Each site, being unique and temporary, needs a new logistics setup; Sites are material intensive and are typically supplied based on requirements (typically an irregular supply schedule); Construction activities are usually sequential, delays transmit through all activities, which demands timely deliveries in right quantities; and, Different operational and management philosophies, and inefficient resource (especially transport) utilisation as a result of fragmentation of the industry, where-in many construction companies, suppliers and LSPs work in different temporary construction consortia (CIVIC 2018).

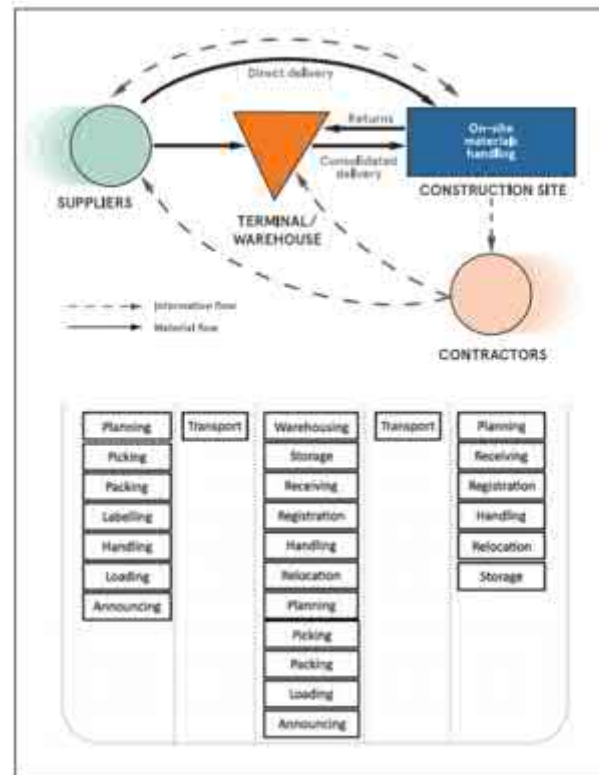


Figure 7. A generic construction logistics model (CIVIC 2018)

The processes comprising logistics are: material flow; information flow; decision-making; stocking; infrastructure for logistics flows; orders; procurement, warehousing and inventory management; provision of work-posts in materials, raw materials and components; packing/packaging; transport; waste management; service; and, collection, processing, and transmission of information (Ghiani et al. 2004, Szymonik 2012). These may be categorised into: Real processes (physical processes, that occur during the physical flows, or processes described by real variables pertaining to the real sphere e.g., selection, packaging, shipping, and warehousing); and, Regulatory processes (belonging to the domain of regulatory or management tools; reflecting the instant situation, these comprise non-physical processes, such as perception, information collection, processing, and transmission, and decision-making). Of the host construction logistics processes, transportation and physical inventory management are the primary real processes. These may be amplified as follows:-

- Inventory management forms a key issue for logistics planning and operations. It aims at determining stock levels for minimising total operating costs, while satisfying customer service requirements. It considers the relative importance of customers, transportation policies, economic significance of different products, production flexibility, and competition.
- Freight transportation permits production and consumption to be far away from each other, leading to wider markets, stimulating direct competition between widely dispersed suppliers. Freight transportation contributes to a substantial part of the cost of logistics and significantly impacts the customer service level. Transportation planning, therefore, has an important role in logistics system management.

Blending of freight transportation attributes (Channels – The path taken by a product from manufacturer to end user; Consolidation – Achieving economies of scale by combining smaller shipments into larger ones; Modes of transport and intermodality of transportation; and, transit

time) with inventory considerations leads to three distribution strategies (direct shipment, warehousing, and crossdocking) (Ghiani et al., 2004)

Discussion: Logistics Management and Sustainability of Construction

Unsustainability in Construction

Unsustainability creeps into construction from multiple perspectives, from an overarching industry perspective, to the individual business/construction site perspective, primarily from sub-optimal utilisation of resources, whatever these may be. The organising of the construction industry is characterised by fragmentation, project focus and separation of design and production phases. Construction supply chain problems such as adversarial relationships, lack of communication and information exchange, lethargy in adopting technology, and the cost of logistics subsumed in the material cost, exacerbate the problem. Multiplicity of stakeholders, the design-technical-social triad of project complexity is yet another contributor to the overall inefficiency of the industry.

Some of the problem areas affecting efficiencies on-site are: poor management of materials, equipment and tools, lack of storage space for materials, damage from ingress of elements of nature and the movement of people, materials not meeting specification, late procurement-late deliveries, ad-hocism in movement of materials to the point of application, a fragmented supply market with no standardised procedures for ordering and delivery, and waste management. While supply logistics are primarily affected by coordination of transportation issues and sub-optimal utilisation of transport in terms of capacity utilisation which continues to be abysmally low, and fragmented in terms of forward and reverse logistics of construction (Alarcon and Mardones 1999, McKinnon and Ge 2006, Tombesi and Whyte 2013, Sundquist et al. 2018, Jones et al. 2021).

Instances of inefficiencies from the literature are: 15% of workers' time spent on moving materials and equipment (Strandberg and Josephson 2005); Waste in construction amounting to 30-35% of production cost; Equipment utilisation being just for about half the potential working time (Josephson and Saukkoriipi 2005 cited Sundquist et al. 2018); Manual work on sites for moving materials representing approximately 43% of on-site logistics costs (Wegelius-Lehtonen 2001); and, 'Traditional trading', based on lowest price, resulting in extra costs varying between 40-250% of the purchase price (Vrijhoef and Koskela 2000).

Logistics, as the inventory-transportation aggregate, is activity based. An activity configuration consists of the activities that are involved in the creation of a particular product or service. These may have different interdependencies *viz* Complementary or closely complementary (representing different phases of a production process requiring some manner of co-ordination; those requiring *ex ante* matching of plans are closely complimentary, while those not requiring this matching are complimentary); and, similar or dissimilar (similar activities require the same capability for their undertaking). In the construction context, activities may have pooled, sequential, and reciprocal interdependencies, with reciprocal interdependencies representing the highest level of complexity. These dominate construction. (Knotten et al. 2014, Dubois et al. 2018). An activity being the fundamental elemental component of a process, fragmented activities aggregate into process inefficiencies, be they in the wider industry, or at the supply-logistics-site interface.

Logistics Management as a Sustainability Enabler

A look at the definition of logistics management viz “*Logistics management activities typically include inbound and outbound transportation management, fleet management, warehousing, materials handling, order fulfilment, logistics network design, inventory management, supply/demand planning, and management of third-party logistics services providers. To varying degrees, the logistics function also includes sourcing and procurement, production planning and scheduling, packaging and assembly, and customer service. It is involved in all levels of planning and execution--strategic, operational, and tactical. Logistics management is an integrating function, which coordinates and optimises all logistics activities, as well as integrates logistics activities with other functions including marketing, sales manufacturing, finance, and information technology*” (CSCMP n.d.), illustrates the possibilities the management function can bring to the construction domain in terms of coordination. The literature indicates linking supply logistics (including activities such as specifications, acquisition, transport and delivery of materials to the construction site) and site logistics (including physical flow planning and logistics organising on the construction site) being the key to accomplish integration in construction supply chains (Vrijhoef and Koskela 2000, Ying et al., 2014). Four perspectives of logistics management will be discussed, the overall industry, the supply-logistics-site interface, the site, and transport technology.

Logistics Management from the Industry Viewpoint

Three fundamental aspects viz re-configuring activities, re-combining resources, repositioning actors form the basis of logistics management from the industry perspective (Sundquist et al. 2018).

Reconfiguration of activities maybe through: An actor taking over activities from, or delegation to others (changes in the division of labour) usually driven by economies of scale; Changes in activity configuration (addition, withdrawal or new methodologies); Change in scope and scale (capacity and capability changes); and, Changes in coordination (impacting interdependence).

Re-combining resources can be done through: Changes in resource exploitation (improvements in economies of scale; increased similarity in activities); Changes in the logic of combining resources (physical resources such as vehicles and materials; non-physical resources such as planning and skills); Improving the joint effect of a set of resources, which may lead to a change in the interfaces between resources; and, Control of resources (through direct ownership or access).

Re-positioning of actors may take place through; Replacement of actors (reliance on internal capabilities; interaction with others); Changing involvement with partners (extent of interaction and collaboration); Changes in the connections between relationships (cooperation and joint actions); Interaction patterns and the relationship atmosphere (frequency and depth of interaction; conflict, power, trust, commitment).

Logistics Management from the Supply Logistics-Site Interface Viewpoint

While the industry perspective drew primarily on overarching logistics management principles, the Supply-Logistics-Site interface is primarily concerned with optimisation of resources involved in the inventory-transport aggregate (Browne et al. 2005, WRAP 2011, Allen et al. 2012, DG MOVE European Commission 2012, Dubois et al. 2018).

The de-centralised coordinated configuration: Contractors and subcontractors coordinate their own materials supply- and site logistics activities. Each contractor is responsible for its respective site logistics activities. The supply-chain-site interface is not organised for joint

planning and each delivery is more or less stand-alone. Attempt by suppliers to provide customised deliveries results in sub-optimal transport utilisation and long queuing, while optimal utilisation of vehicle capacity may lead to large quantities of materials lying on site, leading to avoidable wastages. The on-site efficiency is low in production and materials handling owing to a low degree of specialisation and lack of possibilities to capture similarity amongst activities. Both materials handling and production activities are dependent on the same resources, and construction workers alter between these activities. The waiting time for using resources, the need of excessive capacity for moving around materials at the site, and time for tracing out materials hamper efficient resource utilisation. The need for joint coordination of activities is low since each actor takes care of the interdependencies between materials handling and production activities by themselves. The coordination costs are thus low in this configuration.

On-site coordinated configuration: This involves joint coordination of on-site logistics activities and the supply-chain-site interface. Transportation interfacing with the site is coordinated jointly while the up-stream supply chains are not subject to joint coordination. Enabling a just-in-time approach, this configuration typically requires a logistics co-ordinator, undertaking site layout planning, coordination of physical deliveries, and handling of materials. Construction workers are not involved in materials handling. This approach is usually applied on complex projects and lack of space. Improved efficiency on site in terms of materials handling and production activities is achieved. Reduction in waste of materials from storage and moving around is also accrued. Efficiencies of individual supply chains due to the requirement of extensive off-site adjustments to cope with on-site prerequisites.

Supply network coordinated configuration: The scope of joint coordination extends beyond the site to include supply chains. It reduces the number of transports arriving at construction sites. Material supplies are typically directed to a consolidation facility outside the area for storage, consolidation and kitting. Deliveries to the construction site from the consolidation facility are carried out on demand. A logistics specialist with physical resources and skills regarding the material supply chains is responsible for the on-site logistics activities; the interface to the site; and for logistics coordination of parts of the supply chains and typically operating the consolidation facility. This approach is characterised by a potentially higher degree of efficiency in the supply chains as coordination to achieve co-loading enables the exploitation of similarities amongst transport activities across supply chains. Figure 8 illustrates the three configurations.

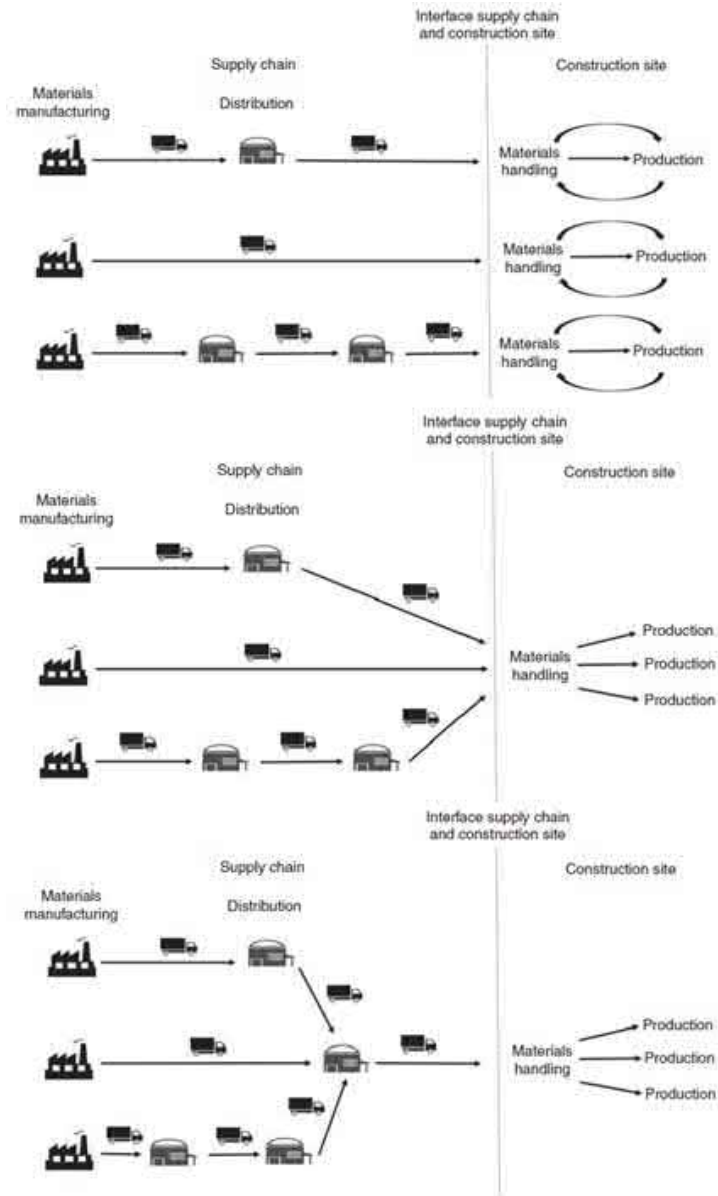


Figure 8. The three supply-logistics-site interface models (Dubois et al. 2019)

Logistics Management on Site

A host of problems exist on site with regards to coordination, scheduling, communication, material handling, equipment utilisation and worker productivity. These are illustrated at Figure 9.

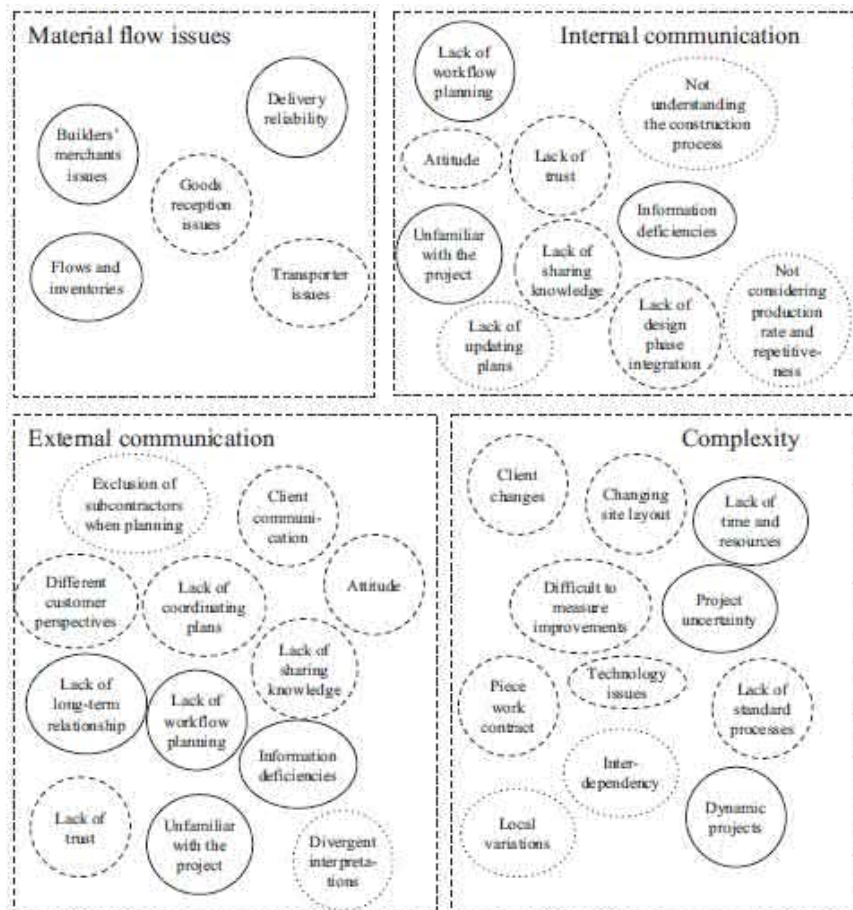


Figure 9. On-site logistics issues in construction (Thunberg et al., 2017)

Logistics Management from the Transport Viewpoint

Urban Freight Transport (UFT) can be characterised by a systemic framework consisting of three components i.e., **Demand** (for goods produced at places other than at the demand location, and requiring transportation), **Supply** (for meeting the demand by supplying logistics viz facilities and transport) and **Context** (logistics operations in facilities and actual vehicle movements resulting from the interaction between demand and supply). The physical environment, in which demand and supply take place, defines the contexts and domains in which different SCs operate. Each of these components can be linked to one or more UFT stakeholders viz Receivers, Shippers, Logistics Service Providers (LSPs), Local Authorities and Citizens. *Receivers* generate demand for goods and, therefore for transport (demand side), *Shippers* send goods to fulfil this demand, logistics operations and actual deliveries by *LSPs* being the direct result of the interaction between *Receivers* and *Shippers*. Contextual movements are regulated by *Local Authorities* and the physical environment where all this takes place, is inhabited by *Citizens* (Kin et al. 2017). The following attributes of transport are relevant to sustainability of construction:-

- **Externalities** “Transport externalities refer to a situation in which a transport user either does not pay for the full costs (e.g., including the environmental, congestion or accident costs) of his/her transport activity or does not receive the full benefits from it” (DG Transport EU 1995, p. 4); “The crucial importance of transport externalities arises from the fact that, in a market economy, (economic) decisions are heavily dependent on market prices. However, when market prices fail to reflect existing scarcities (clean air, absorptive capacity of the environment, infrastructure etc.), the

individual decisions of consumers and producers no longer add up to an outcome that provides maximum benefits to society as a whole. Thus, pricing on the basis of full social costs is a key element of an efficient and sustainable transport system” (DG Transport EU 1995, p. 5). Figure 10 illustrates the externalities of freight transport.

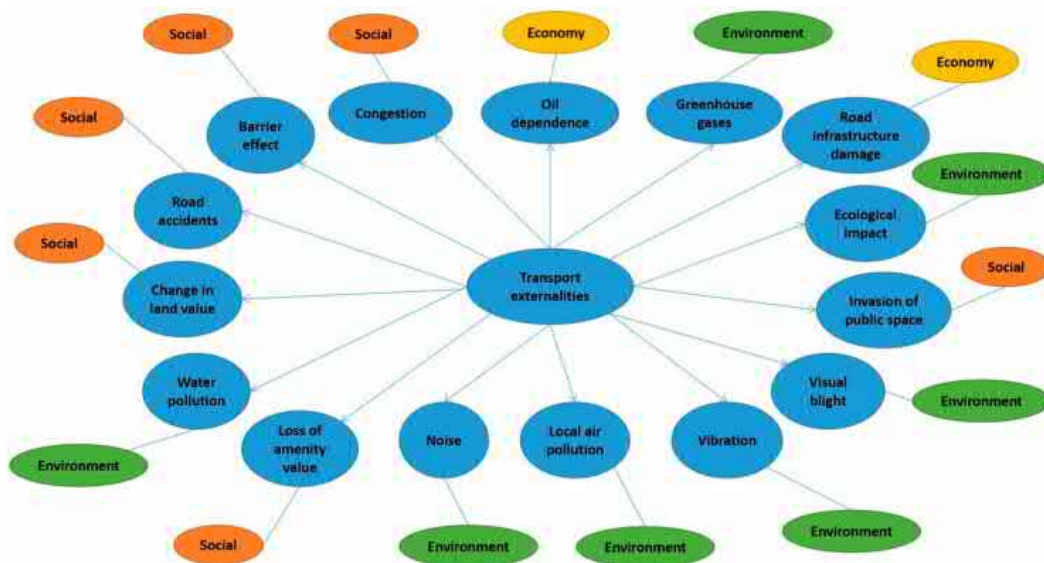


Figure 10. Externalities of freight transport (Chatziioannou et al. 2020)

- **Costs** Transportation costs are approximately half the logistics costs, though this does not directly imply that transport contributes as much to the negative impacts. However, considering that construction materials are generally of low cost and high volume as compared to other industries (Shakantu et al. 2003, Ying and Roberti 2013, Balm and Ploos van Amstel 2017), and that the other processes involved in construction logistics are business processes (except warehousing) and not physical processes like transportation, it may be concluded that transportation may actually be responsible for more than half the costs of construction logistics as a whole. With materials usually accounting for approximately 30%-50% of a building project cost (Agaipiou et al. 1998, Vidalakis and Tookey, 2005, Ying et al. 2014), transportation costs constitute circa 39%-58% of the total logistics costs and between 4%-10% of the selling price of the building (Shakantu et al. 2003). As per another estimate, transportation costs can vary between 10%-20% of construction costs. (BRE, 2003).
- **Infrastructure** In addition to being a cost component of construction logistics, the requirement of transport for the construction industry creates additional transport flows and a competition with other traffic users for existing infrastructure, creating an infrastructural deficit, or overloading of the road network in most urbanised areas. Establishment of infrastructure invariably lags the demand, leading to difficult accessibility and congestion in most cases (DG MOVE European Commission 2012, Kin et al., 2017). All forms of transport also have a detrimental (damaging) effect on infrastructure.
- **Management** Construction materials delivery and waste removal are usually different businesses having different SCs with different orientations with no integration. These are uncoordinated activities since most construction material suppliers operate with a dedicated vehicle fleet for material deliveries (McKinnon and Ge 2006, Shakantu et al. 2008, Balm and Ploos van Amstel 2017). Distribution of construction material in urban

areas, therefore, consists of a very high level of empty trips between in-bound and out-bound traffic flows (Crainic et al. 2004, DG MOVE European Commission 2012).

- Activities of adjacent construction sites are also not synchronised, as a norm, causing congestion in the road transport network and potential underutilisation of transport. Vehicles being employed for removal of waste from construction sites, over and above vehicles delivering construction materials, leads to increased vehicular traffic. Construction material delivery vehicles move full to construction sites, and empty in the opposite direction; the opposite being true for vehicles that remove C&DW from construction sites (Berden 2017, Shakantu and Emuze 2012).
- Transport efficiency critically depends on vehicle capacity utilisation measured across the onward and return trips, finding backloads for returning vehicles being a major logistical challenge (McKinnon and Ge 2006). Non-optimal capacity utilisation causes increased per unit carbon emissions and externalities vis-à-vis tonnage handled (WRAP, 2011). Empty running, earlier identified as a wasted resource, is now considered an environmental liability. Most sustainable distribution strategies, at both the government and individual business levels, therefore, focus acutely on reducing empty running of vehicles (McKinnon and Ge 2006).

The New Zealand Context

New Zealand produces mixed signals insofar as sustainability of the construction sector resulting from logistics management is concerned.

A pioneer in Relational Project Delivery, New Zealand has adopted alliancing and given it a 'Kiwi' blend. Evolving from project alliances, the New Zealand construction sector today boasts of alliances from long-term association in construction, ranging from schools and their maintenance, to heavy construction and infrastructure development. Integrated/collaborative delivery has resulted in optimisation of logistics and resources amongst other benefits, contributing to sustainability. Noteworthy examples are: The Stronger Christchurch Infrastructure Rebuild Team (SCIRT), The Hamilton City Council Infrastructure Alliance, The North Canterbury Transport Infrastructure Recovery Alliance, and the Watercare Enterprise Alliance (New Zealand Infrastructure Commission 2020). Relational delivery progresses through functional awareness, addresses resource flows, manages information, and unifies intra/inter-organisational capabilities, converging into a seamless pipeline with upstream and downstream visibility. Quite clearly, it has a very high defragmentation potential.

Consolidation has been researched and implemented as a freight logistics optimisation mechanism (including for construction) in Europe. It is, however, a maiden endeavour for New Zealand. It can potentially provide sustainability benefits, especially in view of extended logistics and transit routes, near total road transport dependency, a clear demarcation between long-haul and urban distribution, and sprawl driven logistics, through fewer movements, lesser handling, shorter transportation distances, better vehicle utilisation, and energy efficiency (Kohn and Brodin, 2008; IEA, 2018; Ying and Tookey, 2014). Loading efficiency and operational frequency, though, require balancing. Representing embodiment of the elements of A-S-I-F (Avoid-Shift-Improve-Fuel framework) for freight transport (Schipper *et al.*, 2009), CCCs are a powerful tool for strategic and operational switch towards improved operational sustainability.

So far as transport optimisation for sustainable logistics is concerned, New Zealand presents a substantial opportunity, with 93% freight transportation being road based having 99% fossil fuels dependency. A quarter of the transport sector emissions may be attributed to construction transport. Reduction in kilometres travelled by large trucks, raising the average loads of trucks

and distribution practices have been mentioned as governmental focus areas in the New Zealand Energy Strategy to 2050 (Ministry of Economic Development, 2007). A host of other government directives/strategies point in the direction of transport initiatives for emissions reduction (25% freight transport emissions reduction by 2035). These are MfE's *Emissions Reduction Plan* discussion document; MoT's *2020 Green Freight Strategic Working Paper*], *Government Policy Statement on Land Transport 2021-22/2030-31*, and *Transport Emissions: Pathways to Net Zero by 2050*; NZTA's *Arataki Version 2*; and the Climate Change Commission's, *A low emissions future for Aotearoa*. They, however fall short of actual implementation actions, seeking more research. Some of the possible solutions are Consolidation Schemes, Logistics/Freight Hubs, 'First'/'Last' mile delivery schemes, Modal shift, Integration of Forwards/Reverse Logistics, Transition to cleaner transport technology and its management, and Possible public intervention in transport procurement.

New Zealand's unique attributes *viz* geographical isolation, import dependency due to lack of manufacturing capability, extended internal distances within a small regional extent, primacy of road transport, small and fragmented market, size of economy, and regulatory voids, however, present substantial barriers. The high fragmentation due to a majority of players being small businesses also creates barriers for such initiatives or schemes. A balance needs to be achieved between the sustainability requirements and business needs of the sector on the one hand, and public funding/support on the other.

The Research Opportunity

Water services in Auckland include development, planning, and construction of infrastructure for efficient and cost-effective delivery, and future proofing capabilities. Each project has traditionally been treated standalone, and tendering trends show circa 11% construction costs attributable to transport (Turner, 2019). While the former indicates short term Construction Supply Chain Management (CSCM) thinking, the latter suggests existence of significant optimisation potential in the logistics domain.

A recent decade long NZ\$2.4bn waterworks delivery programme (Ruth, 2019) employs a CCC (operational delivery vehicle) as a logistics solution under the 'Enterprise' programme alliance (strategic instrument), both aligning substantially with the Construction Sector Accord. Peak execution will see 14 projects being managed concurrently (Turner, 2019). The strategic-operational combination aims 20% reduction in construction costs and 40% in construction carbon by 2024, and 20% health and safety (H&S) improvements year on year (Duncan, 2019).

Both approaches are 'firsts' in New Zealand for new infrastructure delivery. The programme alliance deviates from the New Zealand Transport Agency's (NZTA) project alliance model and has different process dynamics compared to the 'Stronger Christchurch Infrastructure Rebuild Team' (SCIRT) alliance for rebuild (Ibrahim *et al.*, 2015), while the CCC is a maiden implementation. This portfolio-based rethink of infrastructure procurement marks a step change in practice, with potentially far-reaching implications.

Application of the two approaches across North America and Europe is discussed extensively in literature. Implementation is based upon large contiguous tracts of area, connectivity, large sized markets/economies, and availability of technology (Allen *et al.*, 2012, 2014; Browne *et al.*, 2012; DG MOVE EC, 2012; ICE, 2018). The variance of New Zealand's attributes with these and endeavour being maiden (Duncan, 2019; Turner, 2019) underscores an existing contextual research gap. It, therefore, presents a uniquely posited research opportunity for assessing sustainability outcomes to prove the relevance of the model for New Zealand and create contextual implementation benchmarks.

Proposed Research Framework

Based on the preceding discussion, a research framework for construction logistics management as a sustainability enabler in the New Zealand construction sector from the strategic as well as the operational perspectives is shown at Figure 11.

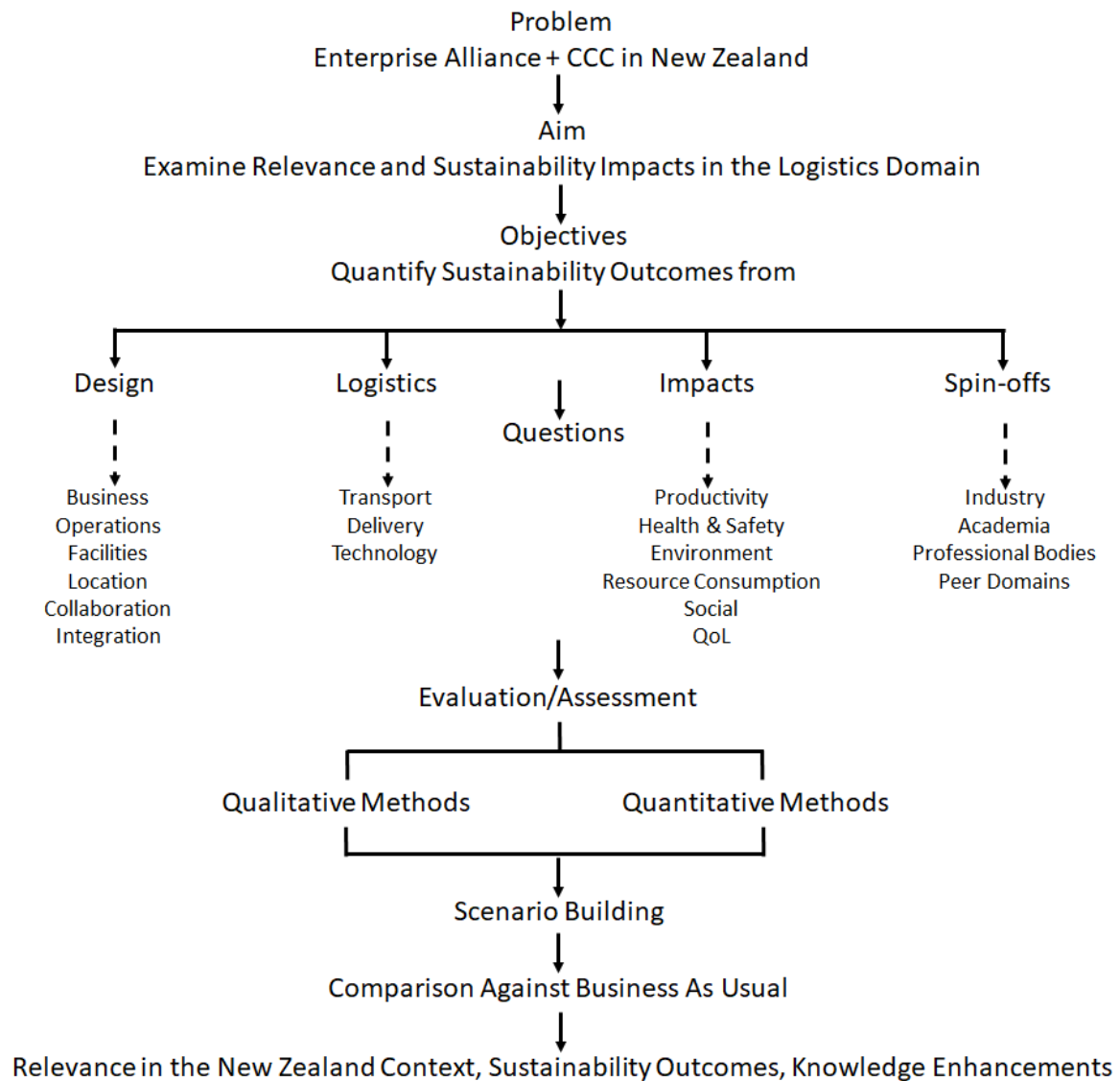


Figure 11. A research framework (Authors' conception).

Conclusion

The construction industry is, by nature, conservative and fragmented. Nowhere is this more acute than in a country like New Zealand, whose geographical isolation typically sees adoption of initiatives lagging the UK by as much as eight years. Comprised of approximately 96% small businesses, it is a typical manifestation of what fragmentation may be. Add increasing complexity of projects, insularity of professions, shorter timelines, and sustainability requirements to the milieu, and here is an almost unmanageable concoction of circumstance.

Most of the attributes of New Zealand as a nation, an economy, and as a market, though, present exactly the required opportunity for defragmentation, and improved sustainability of the sector.

The fact that construction requires substantial resources to be moved on to the site, underscores the importance of logistics, and more specifically that of transport. However, fragmentation makes the whole construction logistics exercise in New Zealand unsustainable. It also presents possibilities for defragmented, integrated and collaborative delivery. The New Zealand market presents mixed signals towards sustainability of the construction sector, on the one hand pioneering alliancing (implying integrated and collaborative delivery), while on the other, still grappling with the issues of fragmented operational delivery. Possibilities for defragmented logistics delivery abound, however, these will need to be adopted with a distinct ‘Kiwi’ flavour, and may require direct public intervention.

The Watercare endeavour adopting long-term infrastructure delivery under a programme alliance, with a CCC as the logistics vehicle presents a potent research opportunity for examining the impacts of the two initiatives, combined as well as individually, on reducing fragmentation through application of Supply Chain Management principles from strategy through operational delivery down to the construction site.

References

- Agapiou, A., Flanagan, R., Norman, G., and Notman, D., 1998. The Changing Role of Builders Merchants in the Construction Supply Chain. *Construction Management and Economics*, 16(3), 351–361. <https://doi.org/10.1080/014461998372376>
- Alarcon, L., and Mardones, D., 1998. Improving the Design-Construction Interface. *Paper presented at the 6th Annual Conference of the International Group for Lean Construction, Guarujá, Brazil*. Available at: https://www.researchgate.net/publication/228707074_Improving_the_design-construction_interface [Retrieved 01 November 2021]
- Alashwal, A.M., and Abdul-Rahman, n.d. Developing a Conceptual Framework of Fragmentation in Construction. Available at: <https://www.library.auckland.ac.nz/external/finalproceeding/Files/Papers/46530final00176.pdf> [Retrieved 28 October 2021]
- Alashwal, A.M., and Fong, P.S., 2015. Empirical Study to Determine Fragmentation of Construction Projects. *Journal of Construction Engineering and Management*, 141(7), 04015076. [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0000986](https://doi.org/10.1061/(ASCE)CO.1943-7862.0000986).
- Allen, J., Browne, M., Woodburn, A., and Leonardi, J., 2012. The Role of Urban Consolidation Centres in Sustainable Freight Transport. *Transport Reviews*, 32(4), 473–490. <https://doi.org/10.1080/01441647.2012.688074>
- Amsterdam University of Applied Sciences (AUAS), 2017. *Analysis of Construction Logistics Calculation Models and Factors that Obstruct their Development*. Available at: https://www.civic-project.eu › files › 2017_06_01_d.2.1_final_anoniem.pdf [Retrieved 21 October 2021]
- Anumba, C.J., Baron, G., and Evbuomwan, N.F.O., 1997. Communications Issues in Concurrent Life-cycle Design and Construction. *BT Technology Journal*, 15(1), 209–216. <https://doi.org/10.1023/A:1018660002374>
- Baiden, B.K., and Price, A.D.F., 2010. The Effect of Integration on Project Delivery Team Effectiveness. *International Journal of Project Management*, 29(2), 129–136. <https://doi.org/10.1016/j.ijproman.2010.01.016>
- Balm, S., and Ploos van Amstel, W., 2017. Exploring Criteria for Tendering for Sustainable Urban Construction Logistics. In: E. Taniguchi, and R. Thompson, R., eds. *City Logistics 1: New Opportunities and Challenges*. Hoboken, USA: John Wiley & Sons, 251–263. <https://doi.org/10.1002/9781119425519.ch13>
- Berden, M., 2017. *Analysis of Construction Logistics Calculation Models and Factors that obstruct their Development*. Available at: https://www.civic-project.eu › files › 2017_06_01_d.2.1_final_anoniem.pdf [Retrieved 22 October 2021]
- Browne, M., Sweet, M., Woodburn, A., and Allen, J., 2005. *Urban Freight Consolidation Centres: Final Report*. London, United Kingdom: Transport Studies Group, Ministry of Transport. Retrieved from https://ukerc.rl.ac.uk/pdf/RR3_Urban_Freight_Consolidation_Centre_Report.pdf
- Building Research Establishment (BRE), 2003. *Construction Site Transport: The Next Big Thing*. Watford, UK: BRE. Available at: <https://www.bre.co.uk/pdf/constructiontraffic.pdf> [Retrieved 02 November 2021]
- Chatziioannou, I., Alvarez-Icaza, L., Bakogiannis, E., Kyriakidis, C., and Chias-Becerril, L., 2020. A Structural Analysis for the Categorization of the Negative Externalities of Transport and the Hierarchical Organization of Sustainable Mobility’s Strategies. *Sustainability*, 2020(12), 6011. <https://doi.org/10.3390/su12156011>

- Commission of the European Communities (EC), 1997. *The Competitiveness of the Construction Industry*. Brussels, Belgium. Available from: <https://aei.pitt.edu/3497/1/3497.pdf> [Retrieved 23 October 2021]
- Construction in the Vicinities Innovative Co-creation (CIVIC), 2018. *Smart Construction Logistics*. Sweden: CIVIC. Available at: https://www.civic-project.eu/sites/default/files/content/bilder/civic-handbook_digital-2.pdf [Retrieved 26 October 2021]
- Council of Supply Chain Management Professionals (CSCMP), n.d. *Supply Chain Management Terms and Glossary*. Available at: https://cscmp.org/CSCMP/Educate/SCM_Definitions_and_Glossary_of_Terms.aspx [Retrieved 01 November 2021]
- Crainic, T., Ricciardi, N., and Storchi, G., 2004. Advanced Freight Transportation Systems for Congested Urban Areas. *Transportation Research Part C: Emerging Technologies*, 12(2), 119–137. <https://doi.org/10.1016/j.trc.2004.07.002>
- Curtis, M., 2018. *Study Report SR 388 (2018) Productivity in the Construction Industry 2017*. Porirua, New Zealand: Building Research Association New Zealand Ltd. (BRANZ). Available at: <https://www.branz.co.nz/pubs/research-reports/sr388/> [Retrieved 29 October 2021]
- Curwell, S., and Cooper, I., 1998. The Implications of Urban Sustainability. *Building Research & Information*, 26, 17–28. <https://doi.org/10.1080/096132198370074>
- DG MOVE European Commission, 2012. *Study on Urban Freight Transport*. Available at: https://civitas.eu/sites/default/files/2012_ec_study_on_urban_freight_transport_0.pdf [Retrieved 30 October 2021]
- Director General for Transport, European Union (DG Transport, EU), 1995. *Green Paper Towards Fair and Efficient Pricing in Transport*. Brussels, Belgium: European Commission. Available at: https://europa.eu/documents/comm/green_papers/pdf/com95_691_en.pdf [Retrieved 31 October 2021]
- Du-Plessis, C., 2002. *Agenda 21 for Sustainable Construction in Developing Countries – A Discussion Document*. Pretoria, South Africa: International Council for Research and Innovation in Building and Construction Technology, United Nations Environmental Programme International Environment Technology Centre. Available from: https://www.researchgate.net/publication/284193645_Agenda_21_for_Sustainable_Construction_in_Developing_Countries_published_for_CIB_and_UNEP_by_CSIR_Building_and_Construction_Technology_Pretoria [Retrieved 01 October 2021]
- Dubois, A., and Gadde, L., 2002. The Construction Industry as a Loosely Coupled System: Implications for Productivity and Innovation. *Construction Management and Economics*, 20, 621–631. <http://dx.doi.org/10.1080/01446190210163543>
- Dubois, A., Hulthén, K., and Sundquist, V., 2019. Organising logistics and transport activities in construction. *The International Journal Of Logistics Management*, 30(2), 620–640. <https://doi.org/10.1108/ijlm-12-2017-0325>
- Duncan, A., 2019. *Construction Lifelines* (Unpublished proposal). New Zealand: Building Research Association New Zealand Ltd. (BRANZ).
- Duncan, A., Kingi, V., and Brunsdon, N., 2018. *Adopting New Ways in Building and Construction Industry*. Porirua, New Zealand: Building Research Association New Zealand Ltd. (BRANZ). Available at: https://d39d3mj7qio96p.cloudfront.net/media/documents/SR406_Adopting_new_ways.pdf [Retrieved 31 October 2021]
- Egan, Sir J., 1998. *Rethinking Construction*. London: Department of Trade and Industry. Available at: http://constructingexcellence.org.uk/wp-content/uploads/2014/10/rethinking_construction_report.pdf [Retrieved 26 October 2021]
- Ekeskär, A., and Rudberg, M., 2016. Third-party Logistics in Construction: The Case of a Large Hospital Project. *Construction Management and Economics*, 34(3), 174–191. <https://doi.org/10.1080/01446193.2016.1186809>
- Enshassi, A., Kochendoerfer, B., and Rizq, E., 2014. An Evaluation of Environmental Impacts of Construction Projects. *Revista Ingeniería de Construcción (RIC)*, 29(3), 234–254. Available at: https://scielo.conicyt.cl/pdf/ric/v29n3/en_art02.pdf [Retrieved 22 October 2021]
- Fernandes, D., Costa, A., and Lahdenperä, P., 2017. Key Features of a Project Alliance and their Impact on the Success of an Apartment Renovation: A Case Study. *International Journal of Construction Management*, 18(6), 482–496. <https://doi.org/10.1080/15623599.2017.1344913>
- Fernández-Solís, J., 2008. The Systemic Nature of the Construction Industry. *Architectural Engineering and Design Management*, 4(1), 31–46. <https://doi.org/10.3763/aedm.2008.s807>
- Fong, P.S., 2003. Knowledge Creation in Multidisciplinary Project Teams: An Empirical Study of the Processes and their Dynamic Interrelationships. *International Journal of Project Management*, 21(2003), 479–486. [http://dx.doi.org/10.1016/S0263-7863\(03\)00047-4](http://dx.doi.org/10.1016/S0263-7863(03)00047-4)
- Ghiani, G., Laporte, G., and Musmanno, R., 2004. *Introduction to Logistics Systems*. Hoboken, NJ: J. Wiley. Available at: https://pc-freak.net/international_university_college_files/Introduction%20to%20Logistic%20Systems%20Planning%20&%20cont%20rol.pdf [Retrieved 04 October 2021]
- Hosseini, Z., Habib, F., and Mirsaedie, L., 2012. Sustainability in Building and Construction: Revising Definitions and Concepts. *International Journal of Emerging Sciences*, 2(4), 570–578. Available at:

- https://www.researchgate.net/publication/236033739_Sustainability_in_Building_and_Construction_Revising_Definitions_and_Concepts [Retrieved 25 October 2021]
- Ibrahim, A., & Price, A., 2005. Impact of Social and Environmental Factors in the Procurement of Healthcare Infrastructure. In: *Proceedings of the 2nd Scottish Conference for Postgraduate Researchers of the Built and Natural Environment (PRoBE) 16-17 November 2005, Glasgow Caledonian University* (pp. 217–227). Rotterdam, The Netherlands: International Council for Research and Innovation in Building and Construction (CIB).
- Institution of Civil Engineers (ICE), 2018. *P13 Blueprint*. London, UK.
- International Council for Research and Innovation in Building and Construction (CIB). (2004). *50 Years of International Cooperation to Build a Better World*. Rotterdam, The Netherlands: International Council for Research and Innovation in Building and Construction (CIB).
- International Energy Agency (IEA), (2018). *Global EV Outlook 2018 Towards Cross-Modal Electrification*. Paris, France. Available at: https://centrodeinnovacion.uc.cl/assets/uploads/2018/12/global_ev_outlook_2018.pdf [Retrieved 20 October 2021]
- Jones, K., Mosca, L., Whyte, J., Davies, A., and Glass, J., 2021. Addressing Specialisation and Fragmentation: Product Platform Development in Construction Consultancy Firms. *Construction Management and Economics* (Online). <https://doi.org/10.1080/01446193.2021.1983187>
- Kibert, C., 1994. Establishing Principles and a Model for Sustainable Construction. *Paper presented at CIB TG 16, Sustainable Construction, November 1994, Tampa, Florida, USA*. Available at: https://www.irbnet.de/daten/iconda/CIB_DC24773.pdf [Retrieved 27 October 2021]
- Kibert, C., 2005. *Sustainable Construction: Green Building Design and Delivery*. New Jersey, USA: John Wiley & Sons.
- Kibert, C., 2007. The Next Generation of Sustainable Construction. *Building Research & Information*, 35(6), 595–601. <https://doi.org/10.1080/09613210701467040>
- Kin, B., Verlinde, S., and Macharis, C., 2017. *Towards a Sustainable Urban Freight Transport System - Axes for Intervention*. Paper presented at the Logistics Research Network Annual Conference. Southampton, UK: The Chartered Institute of Logistics and Transport (CILT). Available at: https://www.researchgate.net/publication/325719493_Towards_a_sustainable_urban_freight_transport_system_-_Axes_for_intervention [Retrieved 02 November 2021]
- Klakegg, O., & Artto, K., (2008). Integrated Management Framework for the Governance of Multiple Projects. In: *Proceedings of the 22nd IPMA World Congress, 2008, Rome* (pp. 11–38).
- Knotten, V., Svalstuen, F., Aslesen, S., and Dammerud, H., 2014. Integrated Methodology for Design Management – A Research Project to Improve Design Management for the AEC Industry in Norway. *Proceedings of the 22nd Annual Conference of the International Group for Lean Construction, Oslo, Norway*. Available at: https://www.researchgate.net/publication/278410080_Integrated_methodology_for_design_management_-_a_research_project_to_improve_design_management_for_the_AEC_industry_in_Norway [Retrieved 29 October 2021]
- Kohn, C., and Brodin, M., 2008. Centralised Distribution Systems and the Environment: How Increased Transport Work Can Decrease the Environmental Impact of Logistics. *International Journal of Logistics Research and Applications*, 11(3), 229–245. <https://doi.org/10.1080/13675560701628919>
- Lanting, R., 1998. Sustainable Construction in the Netherlands (Report 9). In: *CIB Sustainable Development and the Future of Construction: A Comparison of Visions from Various Countries*. Rotterdam, The Netherlands: International Council for Research and Innovation in Building and Construction (CIB). Available at: <https://www.irbnet.de/daten/iconda/CIB13589.pdf> [Retrieved 26 October 2021]
- Li, X., Liu, Y., Wilkinson, S., and Liu, T., 2019. Driving Forces Influencing the Uptake of Sustainable Housing in New Zealand. *Engineering, Construction and Architectural Management*, 26(1), 46–65. <https://doi.org/10.1108/ecam-07-2017-0111>
- Lundesjo, G., 2011. *Using Construction Consolidation Centres to Reduce Construction Waste and Carbon Emission*. Waste and Resources Action Plan (WRAP), UK. Available at: <https://www.fitoutuk.com/storage/documents/CCC%20combined.pdf>
- McKinnon, A., and Ge, Y., 2006. The Potential for Reducing Empty Running by Trucks: A Retrospective Analysis. *International Journal of Physical Distribution & Logistics Management*, 36(5), 391–410. <https://doi.org/10.1108/09600030610676268>
- Ministry of Business, Innovation and Employment, New Zealand Government (MBIE), 2019. *Construction Sector Accord*. Wellington, New Zealand: MBIE. Available at: <https://www.constructionaccord.nz/assets/Construction-Accord/files/0930eac2bb/construction-sector-accord.pdf> [Retrieved 28 October 2021]
- Ministry of Business, Innovation and Employment, New Zealand Government (MBIE), 2020. *Construction Sector Transformation Plan*. Wellington, New Zealand: MBIE. Available at:

- <https://www.constructionaccord.nz/assets/Construction-Accord/files/construction-accord-transformation-plan.pdf> [Retrieved 27 October 2021]
- Ministry of Business, Innovation and Employment, New Zealand Government (MBIE), 2021. *Construction Sector Accord 2020 Progress and Next Steps*. Wellington, New Zealand: MBIE. Available at: <https://www.mbie.govt.nz/dmsdocument/14957-construction-sector-accord-2020-progress-and-next-steps-proactiverelease-pdf> [Retrieved 29 October 2021]
- Morana, J., Gonzales-Feliu, J., and Semet, F., 2014. Urban Consolidation and Logistics Pooling: Planning, Management and Scenario Assessment Issues. In: Morana, J., Gonzales-Feliu, J., and Semet, F. (Eds.), *Sustainable Urban Logistics: Concepts, Methods and Information Systems* (pp. 187–210). Berlin, Germany: Springer-Verlag. https://doi.org/10.1007/978-3-642-31788-0_10
- Naismith, N., Monaghan, B., Zhang, T., Doan, D., GhaffarianHoseini, A., and Tookey, J., 2016. Examining the Productivity in the NZ Construction Industry. *Paper presented at the 2nd NZAAR International Event Series on Natural and Built Environment, Cities, Sustainability and Advanced Engineering, Kuala Lumpur*. Available from: https://www.researchgate.net/publication/323358720_EXAMINING_THE_PRODUCTIVITY_IN_THE_NZ_CONSTRUCTION_INDUSTRY [Retrieved 21 October 2021]
- Navarro-Correcher, C., Cervera, C., Argent, J., and Prunonosa, S., 2018. Business Models Analysis of Construction Consolidation Centres. In: *Proceedings of 7th Road Transport Research Arena TRA, Vienna, Austria*. <https://doi.org/10.5281/zenodo.1254826>
- Nawi, M.N.M., Baluch, N., and Bahaiddin, A.Y., 2014. Impact of Fragmentation Issue in Construction Industry. *MATEC Web of Conferences*, 15. <http://dx.doi.org/10.1051/mateconf/20141501009>
- Nelms, C., Russell, A., and Lence, B., 2007. Assessing the Performance of Sustainable Technologies: A Framework and its Application. *Building Research & Information*, 35(3), 237–251. <https://doi.org/10.1080/09613210601058139>
- New Zealand Infrastructure Commission, 2020. *Rapid Mobilisation Models for the Construction Sector to Support Post COVID-19 Recovery*. Available at: <https://www.constructionaccord.nz/assets/Construction-Accord/files/accord-rapid-mobilisation-models.pdf> [Retrieved 25 October 2021]
- Ratcheva, V., 2009. Integrating Diverse Knowledge through Boundary Spanning Processes – The Case of Multidisciplinary Project Teams. *International Journal of Project Management*, 27(2009), 206–215. <https://doi.org/10.1016/j.ijproman.2008.02.008>
- Riazi, S.R.M., Zainuddin, M.F., Nawi, M.N.M., Musa, S., and Lee, A., 2020. A Critical Review of Fragmentation Issues in the Construction Industry. *Talent Development & Excellence*, 12(2s), 1510–1521. Available at: <https://usir.salford.ac.uk/id/eprint/57063/1/545-Article+Text-947-1-10-20200514.pdf> [Retrieved 21 October 2021]
- Ruth, J., 2019. Watercare Inks \$2.4b 10-year Contract with Fulton Hogan, Fletcher Construction, *The New Zealand Herald*, 27 September [online]. Available at: https://www.nzherald.co.nz/business/news/article.cfm?c_id=3&objectid=12271583
- Schipper, L., Fabian, H., and Leather, J., 2009. *Transport and Carbon Dioxide Emissions: Forecasts, Options Analysis, and Evaluation*. Manila, Philippines: Asian Development Bank. Available at: <http://www.indiaenvironmentportal.org.in/files/Transport-CO2-Emissions.pdf> [Retrieved 10 November 2021]
- Seadon, J., and Tookey, J., 2018. Drivers for Construction Productivity. *Engineering, Construction and Architectural Management*, 26(6), 945–961. <https://doi.org/10.1108/ECAM-05-2016-0127>
- Serra, S., and Oliveira, O., 2003. Development of the Logistics Plans in Building Construction. In: *Proceedings of the Second International Conference on Structural and Construction Engineering: System-Based Vision for Strategic and Creative Design, Rome, Italy*. Available at: https://www.researchgate.net/publication/275345704_Development_of_the_logistics_plans_in_building_construction [Retrieved 16 October 2021]
- Shakantu, W., Tookey, J., and Bowen, P., 2003. The Hidden Cost of Transportation of Construction Materials: An Overview. *Journal of Engineering, Design and Technology*, 1(1), 103–118. <https://doi.org/10.1108/eb060892>
- Shakantu, W., Bowen, P., Muya, M., and Tookey, J., 2008. Flow Modelling of Construction Site Materials and Waste Logistics: A Case Study from Cape Town, South Africa. *Engineering, Construction and Architectural Management*, 15(5), 423–439. <https://doi.org/10.1108/09699980810902721>
- Shakantu, W., and Emuze, F., 2012. Improving H&S by Limiting Transport Externalities in South Africa. In: *Proceedings for the 20th Annual Conference of the International Group for Lean Construction (IGLC)*. San Diego, USA: IGLC. Available at: <https://iglcstorage.blob.core.windows.net/papers/attachment-83f0dbc8-8f9a-40b1-a05f-2cefb2561598.pdf> [Retrieved 26 October 2021]
- Sheffer, D., and Levitt, R., 2012. Fragmentation Inhibits Innovation: Overcoming Professional and Trade Lock-in. *Building Research and Information*, 2012 Special Issue on New Professionalism. Available at: https://gpc.stanford.edu/sites/g/files/sbiybj8226/f/wp069_0.pdf [Retrieved 22 October 2021]

- Singer, L., 2018. *Creating Value Through Procurement: A Report into Public Sector Procurement of Major Infrastructure Projects*. New Zealand: Entwine. Available at: <https://infrastructure.org.nz/resources/Documents/Reports/Infrastructure%20NZ%20Procurement%20Study%20Report%20FINAL.pdf> [Retrieved 23 October 2021]
- Smith, J., O’Keeffe, N., Georgiou, J., and Love, P., 2004. Procurement of Construction Facilities: A Case Study of Design Management within a Design and Construct Organisation. *Facilities*, 22(1/2), 26–34. <https://doi.org/10.1108/02632770410517924>
- Sobotka, A., Czarnigowska, A., and Stefaniak, K., 2005. Logistics of Construction Projects. *Foundations of Civil and Environmental Engineering*, 6, 203–216. Available at: <https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.124.6468&rep=rep1&type=pdf> [Retrieved 22 October 2021]
- Statistics New Zealand, 2019. *Business Operations Survey: 2018*. Available at: <https://www.stats.govt.nz/information-releases/business-operations-survey-2018> [Retrieved 29 October 2021]
- Strandberg, J. and Josephson, P-E., 2005. What do construction workers do? Observations in housing projects. In: *Proceedings of the 11th joint CIB international symposium combining forces, 13–16 June Helsinki*, 184–193.
- Sundquist, V., Gadde, L., and Hulthén, K., 2018. Reorganizing Construction Logistics for Improved Performance. *Construction Management and Economics*, 36(1), 49–65. <https://doi.org/10.1080/01446193.2017.1356931>
- Szymonik, A., 2012. *Logistics and Supply Chain Management*. Available at: https://www.researchgate.net/publication/297369572_Logistics_and_Supply_Chain_Management [Retrieved 28 October 2021]
- Thunberg, M., Rudberg, M., and Karrbom Gustavsson, T., 2017. Categorising on-site problems. *Construction Innovation*, 17(1), 90–111. <https://doi.org/10.1108/ci-10-2015-0059>
- Tombesi, P., and Whyte, J., 2013. Challenges of Design Management in Construction. In: *The Handbook of Design Management*. London, UK: Bloomsbury. Available at: https://www.researchgate.net/publication/327273268_Challenges_of_Design_Management_in_Construction [Retrieved 27 October 2021]
- Transport for London, 2008. *London Construction Consolidation Centre Final Report*. Westminster, UK: University of Westminster, Transport Studies Department. Available at: https://www.ndslogistik.se/files/reports/1425975813_9.pdf
- Turner, C., 2019. *Draft Proposal for Whangaparaoa Peninsula Watercare Projects (Unpublished)*. Watercare, Auckland, New Zealand.
- United Nations Economic Commission for Europe (UNECE), n.d. *Share of Construction in GDP*. Available from: <https://w3.unece.org/PXWeb/en/Charts?IndicatorCode=8> [Retrieved 01 October 2021]
- United Nations Environment Programme, 2015. *Global Waste Management Outlook*. Available at: <https://www.uncclearn.org/wp-content/uploads/library/unep23092015.pdf> [Retrieved 29 October 2021]
- United Nations Environment Programme, 2020. *2020 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector*. Nairobi.
- Vidalakis, C., and Tookey, J., 2005. The Involvement of Builders’ Merchants in the Development of Improved Construction Logistics. In: *Proceedings of the 2nd Scottish Conference for Postgraduate Researchers of the Built and Natural Environment (PProBE)*. Glasgow, Scotland: Glasgow Caledonian University, 337–350. Available at: <http://www.irbnet.de/daten/iconda/CIB10642.pdf> [Retrieved 24 October 2021]
- Vrijhoef, R., and Koskela, L., 2000. The Four Roles of Supply Chain Management in Construction. *European Journal of Purchasing & Supply Management*, 6(3–4), 169–178. [https://doi.org/10.1016/S0969-7012\(00\)00013-7](https://doi.org/10.1016/S0969-7012(00)00013-7)
- Waste and Resources Action Programme (WRAP), 2011. *Using Construction Consolidation Centres to Reduce Construction Waste and Carbon Emissions*. Available at: <http://www.wrap.org.uk/sites/files/wrap/CCC%20combined.pdf> [Retrieved 28 October 2021]
- Wegelius-Lehtonen, T., 2001. Performance Measurement in Construction Logistics. *International Journal of Production Economics*, 69(1), 107–116. [https://doi.org/10.1016/S0925-5273\(00\)00034-7](https://doi.org/10.1016/S0925-5273(00)00034-7)
- Xiao, Y. and Watson, M., 2017. Guidance on Conducting a Systematic Literature Review. *Journal of Planning Education and Research*, 39(1), 93–112. <https://doi.org/10.1177/0739456x17723971>
- Ying, F., and Roberti, H., 2013. Improving Construction Logistics. *BUILD 134*(February/March 2013). Available at: <https://www.buildmagazine.org.nz/assets/PDF/Build-134-80-Research-Improving-Construction-Logistics.pdf> [Retrieved 25 October 2021]
- Ying, F., Tookey, J., and Roberti, J., 2013. SCM Competencies in Construction: Issues and Challenges in New Zealand. *Journal of Engineering, Design and Technology*, 13(4), 522–538. <https://doi.org/10.1108/JEDT-01-2013-0002>
- Ying, F., and Tookey, J., 2014. *Managing Logistics Cost – A Missing Piece in Total Cost Management*. International Cost Engineering Council IX World Congress, Milano, Italy. Retrieved from <https://openrepository.aut.ac.nz/handle/10292/11850>

Ying, F., Tookey, J., and Seadon, J., 2018. Measuring the Invisible: A Key Performance Indicator for Measuring Construction Logistics Performance. *Benchmarking: An International Journal*, 25(6), 1921–1934. <https://doi.org/10.1108/bij-11-2016-0176>

Creating Capacity and Capability for the Future of the Built Environment Through a New Sustainability Maturity Assessment Model

Ross Reed^{1*} and Nkeiruka N. Ndubuka-McCallum²

¹*Britcon (UK) Ltd.*

²*Aberdeen Business School, Robert Gordon University, UK.*

*Corresponding author: ross.reed@britcon.co.uk

Abstract

The unsustainable practices of the current generation have put the future of everything else in question, including that of the built environment, never mind the very future of future generations. The world increasingly is struggling to cope with the resultant effects of these practices for many reasons, including limited capacity and lack of capability in terms of required skills and knowledge.

As a key stakeholder of the built environment or perhaps its cornerstone, the construction industry is facing increasing urgency to reform its practices by embracing and embedding sustainability at the core of daily dealings and operations. Despite efforts on this front by some organisations within this sector, there are still challenges. A key one in the UK construction industry seems to revolve around how Small Medium Enterprises (SMEs) can effectively manage and improve their sustainability performance, given their lack of involvement during high-level decision making for development projects.

Against this background, the consultancy project that informs this paper attempted to explore how a UK-based SME construction contractor could manage and improve its sustainability practices and, therefore, performance against the triple bottom line. The study primarily produced a new sustainability maturity assessment model based on indicators across the triple bottom line – environmental, social, and financial dimensions, with an added dimension that explored leadership indicators such as supply chain collaboration. The integrity and reliability of the model were tested on the case company by applying the model to live projects and following this up by interviewing participants from the case company.

The model encourages sustainable thinking and collaboration, with the aim to increase upstream influence and, in turn, lead to more sustainable project outcomes.

Keywords

Construction; Performance-Measurement; Sustainability; Triple-Bottom-Line; UK

Introduction

In recent years, governments worldwide increasingly recognise the importance of improving sustainability, leading to global frameworks such as the United Nations Sustainable Development Goals – SDGs (United Nations 2015). Some nations have developed tailored approaches; for instance, in New Zealand, the Climate Change Response Amendment Act 2019 set budgets to help achieve a target of net-zero by 2050 and the Building for Climate Change Programme was then set up in 2020. For them, the importance of improving sustainability in construction is hinged on the fact that the industry is responsible for around 20% of the nation's carbon emissions (Bui *et al.* 2021). In the UK, a Committee on Climate Change (CCC) was set up, which resulted in the government setting a target of achieving net-zero greenhouse gas emissions by 2050 (The Lancet 2019; Department for Business, Energy and Industrial Strategy 2019).

Previous studies identified issues with construction firms achieving good sustainability performance or targets such as meeting UN SDGs and moving towards net-zero. Industry experts in countries such as the US and UK have cited a lack of a standard approach and not knowing what to measure as barriers (De Wolf, Pomponi and Moncaster 2017). Additional barriers include economic issues such as the cost of changing, uncertainty about return on investment and a lack of knowledge around how to change (Heffernan *et al.* 2015). Whilst there is a consensus that something must be done, the issue remains around what to measure and how to act on those measurements. This is echoed in the New Zealand context, drawing on Abdelaal and Guo's (2021) study, which identified a clear gap between attitudes towards sustainability and backing this up in practice.

When looking at sustainability in the construction industry, studies have focused heavily on developing carbon-neutral buildings (Cohen *et al.* 2021; De Wolf, Pomponi and Moncaster 2017; Heffernan *et al.* 2015; Berry, Davidson and Saman 2013). Whilst this is an important part of achieving sustainability, it fails to address the sustainability performance of the construction companies themselves, such as during construction or on construction projects that do not involve a traditional building, including civil projects (e.g., car parks, drainage) or industrial buildings such as warehouse units (Brinks, Kornadt and Oly 2016). For organisations such as the case company, customer requirements and specifications are an uncontrollable factor; if customers request that more sustainable materials or methods be used on a building, these will be paid for and adhered. However, there is currently less financial incentive to change areas directly controlled by contractors, such as material deliveries or on-site fuel consumption (Karlsson *et al.* 2020). For instance, UK government subsidies such as the "Green Homes Grant" and "Public Sector Decarbonisation Fund" have been aimed predominantly at improving the energy output of homes and public buildings (Department for Business, Energy, and Industrial Strategy 2020), meaning there is a focus on construction outputs rather than the processes that organisations such as the case company can influence. This was recognised in a progress report by the UK CCC (2020), which acknowledged progress in the energy output of buildings but identified embedded emissions, including emissions from the construction process, as still requiring attention and lacking strategic guidance.

Consequently, this study addresses these issues by developing a model for measuring sustainability performance for a case company (a UK-based SME Construction Contractor).

Literature Review

As well as moral obligations to improve, the desire to achieve competitive advantage for dealing with future legislative changes is a crucial driver for improving sustainability performance (Kücükbay and Sürücü 2019; Hristov, Chirico and Appolloni 2019). Thus,

Mansell, Philbin and Konstantinou (2020) found that 88% of employees from larger organisations in the UK construction sector would like to measure their performance against the UN SDGs. However, they acknowledged that development projects tend to have their success defined purely on outputs such as cost and time, but not outcomes such as social or environmental impacts, which suggests a conflict between a desire to measure and improve sustainability performance and a feeling of being restricted by how success is judged. Whilst client requirements around sustainability remain sparse, this will likely change in the future due to factors such as increased end-user pressure or tighter legislation (Upstill-Goddard *et al.* 2016), hence the need for organisations to be prepared by understanding their current sustainability performance and how to improve it.

Knowing what to measure and understanding how different decisions affect sustainability performance necessitates that organisations understand their areas of influence. Construction SMEs have their biggest impact during transport and construction-installation processes, and most other aspects are client-driven, such as materials selection (De Wolf, Pomponi and Moncaster 2017). However, production/manufacturing and ongoing maintenance are the biggest contributing phases, meaning there will continue to be a lack of focus on the stages that construction SMEs can directly affect, as global research has primarily focused on technical measurement approaches looking at building designs. These are outside the contractors' sphere of influence (Hashemi, Ghoddousi and Nasirzadeh 2021). Conversely, researchers in Sweden identified that whilst emissions from operational phases may be the highest, the construction and transport phases still account for a significant enough portion of total carbon emissions to be worthy of greater attention (Karlsson *et al.* 2020).

Existing literature around sustainability in construction has focused on building lifecycle assessments and/or purely environmental aspects. Despite being a widely adopted approach, it fails to appropriately account for social or economic impacts (Onat *et al.* 2017). This study, therefore, encompassed a more rounded view of sustainability, based on the triple bottom line approach, which encourages organisations to balance their social, environmental, and economic performance (Elkington 1997; Parkin, Sommer and Uren 2003; Mansell, Philbin and Konstantinou 2020; Hashemi, Ghoddousi and Nasirzadeh 2021).

Barriers to Improving Sustainability Performance in Construction

A key issue is that development projects are judged purely on outputs such as cost and time, but not outcomes, such as social or environmental impacts (Mansell, Philbin and Konstantinou 2020), with clients making their decisions based on the quickest or cheapest options, not the best sustainability performance (Abuzeinab, Arif and Qadri 2017; Darko and Chan 2017; Agbesi, Fugar and Adjei-Kumi 2018; Abdebaal and Guo 2021). This aligns with a consensus that the private sector is unlikely to choose to fully aim for sustainable development of its own free will (Jones and Comfort 2020). This choice sits at the top of the supply chain, which some consider an issue. Giesekam, Barrett and Taylor (2016) noted that many decisions in the UK construction industry are made too early, meaning those further down the supply chain that may have useful knowledge have no opportunity to influence key decisions. This may be stifling innovation, which itself could be vital in achieving improved all-round sustainability performance (Ndubuka and Rey-Marmonier 2019). This was recognised ahead of COP26, with improved collaboration being one of the key goals of the conference to encourage governments and businesses to work together (UK Government 2021). Albeit one that has been rather tricky from observing the conference and related proceedings.

A lack of knowledge around what and how to measure are barriers for measuring sustainability performance, possibly due to difficulties with understanding or interpreting the requirements set out in current sustainability standards and frameworks (Mansell, Philbin and Konstantinou 2020; Darko and Chan 2017), with there also being a general lack of understanding on what

terms such as zero carbon, net zero, or green building mean (Heffernan et al. 2015; Gibbs and O'Neill 2015). The UK Green Building Council (2015) recognised the need to distinguish operational carbon (i.e., the operational energy efficiency of buildings) from non-operational carbon (i.e., embodied carbon) relating to greenhouse gas emissions from other phases such as construction. De Wolf, Pomponi and Moncaster (2017) highlighted that efforts to trigger reductions in embodied impacts are behind expected progress of reducing operational impacts, meaning there is still a lack of benchmarking data available for embodied carbon. Other authors agreed with this and cited a lack of a standard measurement approach as a reason for unreliable results and thus a lack of meaningful benchmarking (Karlsson et al. 2020; Nuñez-Cacho et al. 2018).

Potential Solutions

Despite the need for clear government policy, there have been other attempts to improve sustainability performance in UK construction. Rating systems such as Leadership in Energy and Environmental Design (LEED) and the Building Research Establishment Environmental Assessment Method (BREEAM), the most widely adopted scheme, effectively assess the sustainability impact associated with a given building (Bernardi et al. 2017; De Wolf, Pomponi and Moncaster 2017). However, related questions aim to assess the building/project rather than an individual organisation (Bernardi et al. 2017). Construction companies only influence around 7-8.5% of final BREEAM ratings and even less on LEED results (Apanavičienė, Maliejus and Fokaides 2020). Thus, contractors who desire to measure and improve their sustainability performance may need to find alternative methods. By contrast, New Zealand-based studies have cited the sheer number of different rating systems available as a problem, resulting in different organisations using different standards to inform their sustainability decision-making (Bui et al. 2021). This suggests a similar overall problem across both countries, in that organisations are unsure of the best measurement method to implement, leading to inconsistent approaches within the same sector.

Some more mature organisations in terms of measuring sustainability believe that organisational leaders need to provide a clearly defined strategy so that their workforce understand what the measurements are trying to achieve, which should involve setting tangible, relevant and simple targets to progressively improve and maintain motivation through achievement (Opoku, Cruickshank and Ahmed 2015). In one study, senior executives in the construction industry agreed that adopting an approach to measure the triple bottom line could be beneficial (Mansell, Philbin and Konstantinou 2020), with there being a consensus that a balanced scorecard could be the most suitable approach (Kücükbay and Sürücü 2019; Hristov, Chirico and Appolloni 2019; Malesios, Dey and Abdelaziz 2018), especially for measuring qualitative sustainability performance indicators (Dudic et al. 2020). Johnson (2015), however, proposed that businesses should not replicate an existing method but instead take a tool, such as a balanced scorecard, and adapt it to suit their specific needs.

Existing Literature

There is a lack of studies with participants from construction contractors, with interviews often undertaken with architects, clients, or researchers (Agbesi, Fumar and Adjei-Kumi 2018; Abuzeinab, Arif and Qadri 2017; De Wolf, Pomponi and Moncaster 2017). Where contractors have been included in studies, they have tended to be larger companies or those identified as having already made a significant effort to improve their sustainability practices, with almost no representation for organisations that have not yet tried (Nunez-Cacho et al. 2018). Abdebaal and Guo (2021) aimed to consider a variety of stakeholders, including contractors in New Zealand. However, only 6.9% of participants were from contractor organisations. Consequently, the current study addresses the general gap identified in extant literature around

exploring the perspectives of smaller UK contractors', with one organisation (the case company) as its central focus.

When considering the triple bottom line approach, societal impacts should be given fair consideration alongside economic and environmental performance. Previous studies around sustainability in construction have focused on environmental factors such as carbon impact or energy efficiency, with a majority of these then only considering operational emissions, which has left a lack of research into embodied carbon and an even greater gap regarding the social aspects of sustainability (Hashemi, Ghoddousi and Nasirzadeh 2021). These gaps are consistent with those identified by Giesekam, Barrett and Taylor (2016) five years ago, suggesting a lack of progress in plugging those gaps in contemporary studies. Zhang, Oo and Lim (2019) focused on the social aspects of sustainability in construction, but only on barriers to implementation with no regard given to measuring and improving performance. Studies that tried to encompass the whole triple bottom line approach in implementing sustainability performance measurement tended to focus on larger organisations, non-construction organisations, or organisations selected specifically because the authors were already aware of their success with improving sustainability performance (Hristov, Chrigo and Appolloni 2019; Mansell, Philbin and Broyd 2020; Jones and Comfort 2020). The studies that focused on sustainability management tools explored only the reasons for implementation and the current level of implementation, as opposed to offering recommendations on the best tools to implement (Johnson 2015; Johnson and Schaltegger 2016). Others ranked the most important factors to measure for sustainability performance but did not unpack how they can be measured (Hashemi, Ghoddousi and Nasirzadeh 2021).

Literature Summary

Many decisions within construction projects are controlled by clients, who tend to cite a lack of government action in terms of either financial incentives or clear legislative requirements as a reason not to alter their decision-making. As it is likely that the government will at some stage try and force this change, contractors will need to find a balance between altering their approach to sustainability management to be as prepared as possible for increased legislative requirements and remaining competitive in the short-term by not taking on additional costs that clients will not fund. Therefore, contractors wishing to improve their sustainability performance should focus on finding cost-effective solutions within their control. Additionally, given the lack of measurement tools, contractors will need to find a way to measure their current position in terms of sustainability performance to identify how they need to improve. To do this, they could assess the maturity of their approach to managing sustainability. The remainder of this paper attempts to provide a method for achieving this, as literature searches for existing studies around sustainability maturity assessment in UK construction and derivatives thereof provided no relevant results.

Research Methodology

The project that underpins this paper required a mix of quantitative research questions that can help develop a new framework or action plan (Doody and Bailey 2016) and qualitative research questions, which add value to research projects on sustainability (Doğan, Turhan and Bakirlioğlu 2016). As qualitative methods are suitable for capturing experiences and interpretations (Graebner, Martin and Roundy 2012) and quantitative research questions improve research validity, both helped put the research into context for the case company.

The first qualitative element was the review of secondary data, which was used to develop the sustainability assessment model shown in Appendix 1. A survey was then conducted to review the suitability of the proposed model, using a mix of qualitative and quantitative questions. The

model was then tested before qualitative research was undertaken through semi-structured interviews to follow up on the test. This sequential multi-phase approach was suitable to progress through the different stages of research required for the study (Schoonenboom and Johnson 2017).

Data Collection

Archival research of existing articles was used for the initial development of the model to gather secondary qualitative data. This was suitable as it allowed for gathering the greatest amount of data in the short timeframe available (Saunders, Lewis and Thornhill 2019) and enabled analysis of the strengths and weaknesses of existing approaches to develop and refine the new process. A mixed-method survey was selected as a time-effective way to gather primary data (Gómez and Mouselli 2018); it allowed multiple methods to be combined, increasing the confidence level placed on the model's suitability before testing. Although the generalisability of the data gathered is limited because the testing of the model was specific to the case company context, it does not imply that other firms cannot adapt the model with similar characteristics as the case company.

The main advantage of secondary data, which was used to produce a new model based on the findings of previous studies in the form of journal articles, was a quick collation of detailed qualitative information so that more time could be spent analysing data (Saunders, Lewis and Thornhill 2019; Adams, Khan and Raeside 2014). The drawback was that because of the wide-ranging scope of the topic, many articles were not written considering the same context as the case company. Thus, care was taken to identify key terms to help refine the literature search, which is vital for gathering relevant data (Gómez and Mouselli 2018). The main criteria considered to ensure articles were relevant included; related studies were the UK-based (or similar) construction industry; relating to construction contractor SMEs; considering the sustainability impacts influenced by contractors' decisions (as opposed to developers and designers); covering all three pillars of sustainability; published within the last five years and peer-reviewed.

An abundance of secondary data was available due to the high importance of sustainability in recent times, which enabled the development of a new sustainability assessment model. Key trends were analysed, and conclusions were found in the selected journal articles to add weight to the arguments for including different indicators in the proposed model and designing the model in a certain way. However, there was insufficient secondary data to assess the complete suitability of the new model for the case company, meaning primary data was also required to answer the study's research questions. A questionnaire was suitable due to its efficiency in gathering responses; it supported the refinement of the new model. Whilst a researcher-completed questionnaire would have had the advantage of clarifying or following up on responses, a self-completed survey was selected to maximise the number of responses that could be received in the limited time available.

The questionnaire was designed to consist mainly of closed, quantitative questions to provide simplicity for the respondents (Gómez and Mouselli 2018), but also included some open, qualitative questions for respondents to elaborate on their responses where their individual experience was relevant. Questions were written succinctly as ideally, questions should not be longer than 20 words to enhance comprehension for participants (Sekaran and Bougie 2016). The survey was kept as short as possible to cover the data gathering needs of the study, which yielded higher response rates (Adams, Khan and Raeside 2014).

A semi-structured interview approach was utilised to review the testing of the new model. Qualitative interviews are preferred when there are only a small number of potential participants (Gómez and Mouselli 2018), as was the case for the case company where

participants were selected. For time-management purposes, these interviews were conducted as group interviews, which also meant they could be conducted as soon as possible after the model testing, facilitating better recall from the participants in line with the Ebbinghaus curve for memory recall (Fisher and Radvansky 2019). The approach adopted allowed for key themes to be explored and for responsive exploration of different views put forward by the participants (Saunders, Lewis and Thornhill 2019).

Sampling & Participants

To keep data relevant, the secondary research for this study looked at sustainability in UK construction, focusing on SME sized contractors and issues within their sphere of influence. As the model was developed for a specific company, the target population for the primary research was broken down to include just individuals working for the case company in roles that might be required to implement the proposed model or make decisions that might affect the organisation's performance against the indicators selected. Due to time constraints, non-probability sampling methods were used. Convenience sampling allowed for selecting participants from within the case company, particularly those involved in projects accessible to the researcher. Whilst not being the most credible sampling approach, it allowed for quick and easy data collection (Adams, Khan and Raeside 2014).

The survey was shared with 54 potential participants, with 33 full responses received, meeting the minimum sample size (30) required for meaningful analysis. Of the 33 respondents, 17 were willing to trial the new model. As this number of participants was below the minimum threshold level of 30, all 17 were requested to engage with the semi-structured group interviews that followed the test. Saunders, Lewis and Thornhill (2019) recommend that interviews are conducted in groups of 4-12 and are split horizontally across the organisation's structure so that participants are not hindered or subject to bias that might occur when being interviewed in the presence of senior figures. Therefore, the participants were split into three groups, with two groups each involving six project-delivery level participants and the third group consisting of five senior management level participants.

Data Analysis

To take meaning from the qualitative data gathered during the literature review, thematic analysis was selected as it allows researchers to understand and communicate key conclusions from detailed data (King and Brooks 2018) by identifying themes to find trends and highlight gaps in the information (Adams, Khan and Raeside 2014), and is considered a flexible approach suitable to a variety of situations (Braun and Clarke 2016). Firstly, data coding was used, whereby data was summarised and organised into categories (Saunders, Lewis and Thornhill 2019). This enabled the identification of themes, based on codes relating to the overall aim and objectives of the study (Braun and Clarke 2016). For this study, journal findings were organised based on the relevant aspects of sustainability in construction that they covered, including research country; UN SDGs; social /environmental/economic aspects; measuring sustainability; and imparting change.

Limitations

Time constraint was the main limitation of this study. Whilst a longitudinal study would have been preferred to test the model and monitor the longer-term effects of its use, time constraints meant that only a cross-sectional study was possible. Given the evolving nature of sustainability as a topic and how likely there will be further changes and developments, it is unclear how long the results will remain valid. To test the suitability of the model in a wider context, it would have been beneficial to involve more organisations in the study, making the

proposed model and associated recommendations more relevant to the wider industry. However, time constraints again made this impractical.

Findings and Discussion

Identifying Suitable Indicators

Previous literature has focused on environmental performance, particularly in terms of carbon. Nuñez-Cacho *et al.* (2018) suggested 44 sustainability indicators for construction contractors be split into categories of energy management, water management, waste management, waste reduction, materials, emissions, and culture. Whilst a good starting point, these measures were not all directly controlled by contractors and included no social or economic aspects of sustainability, nor environmental aspects such as ecological impact. Küçükbay and Sürücü (2019) took this into account when developing their performance criteria and identified that using a balanced scorecard approach would be ideal for measuring performance across the three pillars of sustainability. Johnson and Schaltegger (2016) found that larger organisations best utilise most sustainability management tools than smaller businesses; they are likely to benefit from using modified, simpler versions tailored to suit the specific organisation and users. This echoes Mansell, Philbin and Konstantinou's (2020) assertion that the development of simple KPIs is required for construction projects. However, the proposed criteria put forward were all quantitative (Küçükbay and Sürücü 2019). Additionally, as some measures may not be tangible facts, a way of capturing potentially subjective qualitative data must be considered (Opoku, Cruickshank and Ahmed 2015), with qualitative indicators being beneficial for measuring sustainability when assessing social aspects (Scerri and James 2010; Hristov, Chirico and Appolloni 2019). Subjective measures may also be required for environmental measures, including whether an organisation is taking the right approach towards improving sustainability, meaning a qualitative self-evaluation tool could be the best approach (Yu *et al.* 2018). Nuñez-Cacho *et al.* (2018) suggested using a set of questions as indicators to all be answered with a scaled level of implementation (*i.e.*, 1-7 scoring scale).

Agbesi, Fugar and Adjei-Kumi (2018) used subjective questions to measure sustainability and included economic, social, and environmental factors. However, their measures focused solely on sustainable procurement and not project delivery for contractors. Merging these measures with those put forward by Nuñez-Cacho *et al.* (2018) provides a set of measurements taking the triple bottom line into account. So these were used as a starting point for producing the set of measures shown in Appendix 1, with further measures added to build a well-rounded set of measures for sustainability performance. Another previous study ranked and tested indicators on highways construction projects, which resulted in a similar set of indicators being created (Hashemi, Ghoddousi and Nasirzadeh 2021), adding further weight to the argument for using the questions in Appendix 1.

Given the role that leadership can play in both organisational and industry change for sustainability in construction (Opoku, Cruickshank and Ahmed 2015), indicators have been added to monitor information sharing up and down the supply chain by both making sustainability suggestions to clients and seeking suggestions from suppliers, which, as seen in other industries, could facilitate innovation (Li 2021). Others agreed that additional categories such as leadership are required in addition to economic, social, and environmental indicators, but also suggested that the complexity of a traditional balanced scorecard can hinder its implementation (Hristov, Chirico and Appolloni 2019; Malesios, Dey and Abdelaziz 2018), which is why the set of indicators in Appendix 1 was kept to a simple set of questions.

To further refine the model in Appendix 1, relevant UN Sustainable Development Goals were considered. Jones and Comfort (2020) identified the SDGs most relevant to UK contractors, so the targets associated with these were reviewed to ensure a complete view of sustainability in

construction was considered. This led to the inclusion of additional questions covering innovation, new employment opportunities, modern slavery, pollution, education, and ecology. This aligns with a previous study, which found that the best approach to measuring against the UN SDGs is to first prioritise them and then set targets and goals across the triple bottom line, which can be reported on (Mansell, Philbin and Broyd 2020).

As identified by Giesekam, Barrett and Taylor (2016), many key sustainability decisions are made early in the project timeline. This was also acknowledged by Yu *et al.* (2018), who developed a qualitative method for measuring sustainability approach during project planning. The questions developed in Appendix 1 have therefore also been designed to be used at the earliest possible stage, but also be revisited during project delivery to ensure relevant sustainability factors are considered throughout construction.

Weighting and Scoring the Indicators

An issue with measuring sustainability performance is that economic measures tend to be given more weighting than social and environmental factors, which dilutes the aim of measuring success across the triple bottom line (Hristov, Chirico and Appolloni 2019). To address this, the indicators in Appendix 1 were given an equal weighting of 25% each across the Economic, Environmental, Social and Leadership sections, with individual indicators then weighted evenly within their section. For example, the six economic factors are weighted at 4.17% each ($25 / 6 = 4.17$).

As it was identified that successful implementation of a new sustainability performance management tool in a smaller organisation requires it to be simple and tailored to that specific organisation, performance against the questions in Appendix 1 was measured using a colour-coded system, known as RAG (Red Amber Green) scoring:

- Green = A positive response, whereby the indicator has been addressed in line with company policy. Given a score of 1.
- Amber = A neutral response, whereby an attempt has been made to address the issue but has fallen short. Given a score of 0.5.
- Red = A negative response, whereby there has been no attempt or a complete failure to achieve the requirements of company policy. Given a score of 0.

This approach fits with current practices at the case company. Furthermore, Abbasnejad *et al.* (2017) demonstrated that using RAG scoring can drive improvement through different stages of maturity by gradually increasing the requirements or performance thresholds that result in a "green" score. Moreover, the system enables the visual representation of performance indicators, which can enable quick communication and interpretation of data (Manville *et al.* 2016). Glasson *et al.* (2021) used a similar system for measuring performance on a UK construction project. They found that it was effective and easy for various stakeholders to understand.

Summary of Indicators

The final set of indicators shown in Appendix 1 consists of 31 questions split across Economic, Social, Environmental and Leadership factors. They were designed to allow their use at various stages throughout a project, looking at early decision-making and collaboration through to practical implementation of decisions. The tool was designed to be simple, cost-effective, and not time-consuming to avoid some of the key barriers to implementation that have been identified. By asking the right questions at different phases of a project, contractors can understand how their decisions affect key sustainability issues so they can balance outcomes across the triple bottom line, understand the level of maturity of their current approach, and

identify areas for improvement. The tool in Appendix 1 aligns with the shared basic components of successful evaluation tools, which include a set of categories, a simple scoring system, a weighting system, and a final output that is easily understood (Bernardi et al. 2017).

It was considered that too many measures on a project could create resistance, thus leading to ineffective implementation (Scerri and James 2010; Hristov, Chrigo and Appolloni 2019). However, as it had not been previously defined how many measures are too many, part of the further research conducted on this project was to determine whether the proposed model is considered suitable by potential users.

Testing

Thirty-three complete survey responses were received. Respondents came from various roles covering all project functions within the case company. Generally, they had a high amount of experience in the construction industry but a mixed amount of experience working for the case company. Seventeen of the respondents engaged in six of the case company's live projects at the time agreed to take part in testing the model. Following the testing of the model, group interviews were used to obtain participants' views on its suitability. The groups were split into Group 1 - senior management, and Groups 2 and 3 - project delivery staff.

All seventeen participants said they found the assessment tool easy to use. The majority of the comments across the three groups interviewed revolved around the simplicity of the RAG (Red, Amber, Green) scoring system and the ease to interpret visual elements. There was also a consensus that the questions were easy to understand. Participants from Group 2 discussed how the questions posed may be a source of education for some of the organisation staff members. of the organisation's staff. In contrast, the other two groups focused on the model being simple and not overly time-consuming.

All but one of the participants felt that the tool provided a good assessment of how key sustainability issues are being managed. Group 1 participants discussed how well the indicators related to typical tender questions, commenting that using the tool may lead to having more suitable evidence to provide to clients. The participant who answered "No" felt the tool shows not how the issues are being managed but whether they are being managed. Other participants again referenced the simplicity of the tool. The Managing Director summed up the importance of collaboration both up and down the supply chain, as identified in the literature review (Zhang et al. 2018):

"If we're going to become a truly sustainable business, we will need to sometimes convince our clients that we can offer a more sustainable solution and that sometimes that solution will be worth paying extra for. And on the other side of it, we need to rely on the expertise that our subcontractors have in their given areas and make sure we're consulting them and taking advantage of that expertise."

All participants agreed that the model covers all relevant sustainability issues and is suitable for use within the organisation. The tool's simplicity was again referenced in response to these questions, with some participants mentioning how the RAG system aligns with some existing practices within the organisation. This alignment may be beneficial for reducing friction relating to the introduction of new processes, as it will feel familiar for the staff (Johnson, Whittington and Scholes 2011). Time was a common topic for the project delivery staff, with a consensus that avoiding any new processes being overly time-consuming would be important for their uptake within the organisation (Appelbaum et al. 2017)

Conclusion

The construction industry focuses on the environmental aspects of sustainability, with most attention on the operational carbon footprints of buildings (Giesekam, Barrett and Taylor 2016; Hashemi, Ghoddousi and Nasirzadeh 2021). The key drivers for improving sustainability performance appear to be moral obligations and a desire to get ahead of the curve before any anticipated legislative change, with both identified during the literature review and backed up during the primary research (De Wolf, Pomponi and Moncaster 2017; Kücükbay and Sürücü 2019; Hristov, Chirico and Appolloni 2019). The key barrier is a client focus on cost above other performance measures. This was highlighted during the literature review and was also a common theme during the primary research phase (Mansell, Philbin and Konstantinou 2020; Abuzeinab, Arif and Qadri 2017; Darko and Chan 2017; Gibbs and O'Neill 2015; Agbesi, Fugar and Adjei-Kumi 2018). Close collaboration with clients will be crucial for overcoming this problem since many key sustainability decisions in construction sit with clients/developers. This was identified in the literature, and primary research participants strongly agreed (De Wolf, Pomponi and Moncaster 2017; Yu *et al.* 2018).

The secondary research did not identify an existing model that was suitable for the case company, as existing models tended to cover areas outside of contractors' control. Therefore, a new model was developed as presented in Appendix 1, taking key themes from existing research to build a suitable set of sustainability performance indicators (Nuñez-Cacho *et al.* 2018; Kücükbay and Sürücü 2019; Johnson and Schaltegger 2016; Mansell, Philbin and Konstantinou 2020; Opoku, Cruickshank and Ahmed 2015; Yu *et al.* 2018; Agbesi, Fugar and Adjei-Kumi 2018; Hashemi, Ghoddousi and Nasirzadeh 2021; Jones and Comfort 2020).

The model was tested with positive feedback from participants. Collaboration with clients and suppliers was identified as an important issue, along with management of the relevant environmental, economic, and social issues under the control of the company. However, one criticism raised was that the model shows whether sustainability is being managed well but does not cover how it is managed. Therefore, the case company may benefit from updating their management systems or creating sustainability management plans for projects, which should be communicated to ensure staff are aware of what is expected.

Real improvement in construction sustainability will require legislative change (De Wolf, Pomponi and Moncaster 2017; Berry, Davidson and Saman 2013; Karlsson *et al.* 2020; Agbesi, Fugar and Adjei-Kumi 2018; Jones and Comfort 2020), which in turn can force changes in decision-making processes from the developers/clients that make decisions on critical items such as building designs (Hashemi, Ghoddousi and Nasirzadeh 2021). Participants at the case company agreed that client decision-making has the biggest influence on sustainability performance for construction projects.

However, contractors such as the case company can still influence various sustainability factors across environmental, economic, and social areas during the construction phase, included in the new model presented in Appendix 1. However, to recognise the significant influence from clients, additional measures such as client collaboration and supply chain collaboration have been included to both try and increase downstream influence and garner learning from upstream partners (Zhang *et al.* 2018).

This study has addressed gaps in existing literature, including a previous lack of participants from SME, sized construction contractors such as the case company. Furthermore, this study has included wider sustainability issues, as many previous studies have focused solely on operational carbon emissions. A suitable model for the case company to measure sustainability performance has been provided.

Whilst the findings of this study are specific to the case company; they could provide a good starting point for similar studies across similar organisations. Future research could extend the findings of this study by applying the new sustainability performance measurement tool across various organisations to test its suitability on a wider scale. If successful, this could help provide an industry performance benchmark for the sustainability indicators influenced directly by construction contractors, which could help inform policymakers and industry leaders on appropriate steps to improve the construction industry's overall sustainability performance. Furthermore, a longitudinal study of the use of the model could provide insight into its long-term implications, such as whether applying the model leads to improved sustainability performance, enhanced knowledge amongst users, or greater collaboration and knowledge sharing between organisations. Additionally, the findings and new model could be applied outside of the UK where suitable, such as in New Zealand, where the construction industry is still in the early stages of transitioning to better sustainability practices (Bui et al. 2021), meaning a model aimed at promoting more sustainable decision-making could prove very beneficial, mainly to help address the gap between a desire to improve but lack of any practical shift in approach (Abdebaal and Guo 2021).

References

- ABBASNEJAD, T., BEHBOUDI, M.R., SAHELIZADEGAN, F. and MAHMOODI, J., 2017. Strategic performance measurement of employees based on project efficiency and effectiveness. *Iranian Journal of Management Studies*, 10(1), pp.207-236.
- ABDELAAL, F. and GUO, B.H.W., 2021. Knowledge, attitude and practice of green building design and assessment: New Zealand case. *Building and Environment*, 201 (2021), p. 107960.
- ABUZEINAB, A., ARIF, M. and QADRI, M.A., 2017. Barriers to MNEs green business models in the UK construction sector: An ISM analysis. *Journal of Cleaner Production*, 160(September 2017), pp. 27-37.
- ADAMS, J., KHAN, H.T.A. and RAESIDE, R., 2014. *Research Methods for Business and Social Science Students*. 2nd ed. London: SAGE Publications Ltd.
- AGBESI, K., FUGAR, F.D. and ADJEI-KUMI, T., 2018. Modelling the adoption of sustainable procurement in construction organisations. *Built environment project and asset management*, 8(5), pp. 461-476.
- APANAČIČIENĖ, R., MALIEJUS, K. and FOKAIDES, P., 2020. Sustainability Assessment of the Building Construction Stage Using Building Sustainability Assessment Schemes (BSAS). *Earth and environmental science*. [online]. Available from: <https://iopscience.iop.org/article/10.1088/1755-1315/410/1/012064> [Accessed 1 June 2021].
- APPELBAUM, S.H., CAMERON, A., ENSINK, F., HAZARIKA, J., ATTIR, R., EZZEDINE, R. and SHEKHAR, V., 2017. Factors that impact the success of an organizational change: a case study analysis. *Industrial and Commercial Training*, 49(5), pp. 213-230.
- BERNARDI, E., CARLUCCI, S., CORNARO, C. and BOHNE, R.A., 2017. An analysis of the most adopted rating systems for assessing the environmental impact of buildings. *Sustainability*, 9(7), p.1226.
- BERRY, S., DAVIDSON, K. and SAMAN, W., 2013. The impact of niche green developments in transforming the building sector: The case study of Lochiel Park. *Energy Policy*, 62(November 2013), pp. 646-655.
- BRAUN, C. and CLARKE, V., 2016. Thematic analysis. *The Journal of Positive Psychology*, 12(3), pp. 297-298.
- BRINKS, P., KORNADT, O. and OLY, R., 2016. Development of concepts for cost-optimal nearly zero-energy buildings for the industrial steel building sector. *Applied Energy*, 173 (July 2016), pp. 343-354.
- BUI, T.T.P., WILKINSON, S., DOMINGO, N. and MACGREGOR, C., 2021. Zero Carbon Building Practices in Aotearoa New Zealand. *Energies*, 14(15), p.4455.
- COHEN, R., DESAI, K., ELIAS, J. and TWINN, R., 2021. Net zero carbon: Energy performance targets for offices. *Building Services Engineering Research and Technology*, 42(3), pp.349-369.
- DARKO, A. and CHAN, A.P.C., 2017. Review of Barriers to Green Building Adoption. *Sustainable Development*, 25(3), pp. 167-179.
- DE WOLF, C., POMPONI, F. and MONCASTER, A., 2017. Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice. *Energy and Buildings*, 140 (April 2017), pp. 68-80.
- DEPARTMENT FOR BUSINESS, ENERGY AND INDUSTRIAL STRATEGY, 2019. *UK becomes first major economy to pass net zero emissions law*. [online]. London: Department for Business, Energy and Industrial Energy. Available from: <https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law> [Accessed 01 May 2021].

- DEPARTMENT FOR BUSINESS, ENERGY AND INDUSTRIAL STRATEGY, 2020. *Greener homes, jobs and cheaper bills on the way as government launches biggest upgrade of nation's buildings in a generation*. [online]. London: Department for Business, Energy and Industrial Energy. Available from: <https://www.gov.uk/government/news/greener-homes-jobs-and-cheaper-bills-on-the-way-as-government-launches-biggest-upgrade-of-nations-buildings-in-a-generation> [Accessed 27 June 2021].
- DOĞAN, Ç., TURHAN, S. and BAKIRLIOĞLU, Y., 2016. Evolving Paths: Undergraduate Design Education through Graduate and Generative Research with a Particular Focus on Sustainability. *The Design Journal*, 19(4), pp. 585-604.
- DOODY, O. and BAILEY, M.E., 2016. Setting a research question, aim and objective. *Nurse Researcher*, 23(4), pp. 19-23.
- DUDIC, Z., DUDIC, B., GREGUS, M., NOVACKOVA, D. and DJAKOVIC, I., 2020. The innovativeness and usage of the balanced scorecard model in SMEs. *Sustainability*, 12(8), p.3221.
- ELKINGTON, J., 1997. *Cannibals with Forks: The Triple Bottom Line of 21st Century Business*. Oxford: Capstone.
- FISHER, J.S. and RADVANKSY, G.A., 2019. Linear Forgetting. *Journal of Memory and Language*, 108, p. 104035.
- GIBBS, D. and O'NEILL, K., 2015. Building a green economy? Sustainability transitions in the UK building sector. *Geoforum*, 59 (February 2015), pp. 133-141.
- GIESEKAM, J., BARRETT, J.R. and TAYLOR, P., 2016. Construction sector views on low carbon building materials. *Building Research and Information*, 44(4), pp. 423-444.
- GLASSON, J., DURNING, B., BRODERICK, M. and WELCH, K., 2021. Monitoring and auditing the local socio-economic and environmental impacts of the early stage construction of Hinkley Point C Nuclear Power Station, UK. *Impact Assessment and Project Appraisal*, 39(2), pp.84-95.
- GÓMEZ, J.M. and MOUSELLI, S., eds., 2018. *Modernizing the Academic Teaching and Research Environment*. Cham, Switzerland: Springer.
- GRAEBNER, M.E., MARTIN, J.A. and ROUNDY, P.T., 2012. Qualitative Data: Cooking without a recipe. *Strategic Organization*, 10(3), pp. 276-284.
- HASHEMI, H., GHODDOUSI, P. and NASIRZADEH, F., 2021. Sustainability Indicator Selection by a Novel Triangular Intuitionistic Fuzzy Decision-Making Approach in Highway Construction Projects. *Sustainability*, 13(1477) p. 1477.
- HEFFERNAN, E., PAN, W., LIANG, X. and DE WILDE, P., 2015. Zero carbon homes: Perceptions from the UK construction industry. *Energy policy*, 79, pp.23-36.
- HRISTOV, I., CHIRICO, A. and APPOLLONI, A., 2019. Sustainability Value Creation, Survival, and Growth of the Company: A Critical Perspective in the Sustainability Balanced Scorecard (SBSC). *Sustainability*, 11(7), p. 2119.
- JOHNSON, G., WHITTINGTON, R. and SCHOLLES, K., 2011. *Exploring Strategy*. 9th Ed. Harlow: Pearson Education Limited.
- JOHNSON, M.P., 2015. Sustainability Management and Small and Medium-Sized Enterprises: Managers' Awareness and Implementation of Innovative Tools. *Corporate social-responsibility and environmental management*, 22(5), pp. 271-285.
- JOHNSON, M.P. and SCHALTEGGER, S., 2016. Two Decades of Sustainability Management Tools for SMEs: How Far Have We Come? *Journal of small business management*, 54(2), pp. 481-505.
- JONES, P. and COMFORT, D., 2020. The UK's largest volume housebuilders and the sustainable development goals. *Property management*, 39(1), pp. 139-152.
- KARLSSON, I., ROOTZÉN, J., TOKTAROVA, A., ODENBERGER, M., JOHNSON, F. and GÖRANSSON, L., 2020. Roadmap for decarbonization of the building and construction industry—a supply chain analysis including primary production of steel and cement. *Energies*, 13(16), p.4136.
- KING, N. and BROOKS, J., 2018. Thematic Analysis in Organisational Research. In: C. CASSELL, A. CUNLIFFE and G. GRADY eds. *The SAGE Handbook of Qualitative Business and Management Research Methods*. London: Sage Publications Ltd. Pp. 219-236.
- KÜÇÜKBAY, F. and SÜRÜCÜ, E., 2019. Corporate sustainability performance measurement based on a new multicriteria sorting method. *Corporate social-responsibility and environmental management*, 26(3), pp. 664-680.
- LI, G., 2021. The impact of supply chain relationship quality on knowledge sharing and innovation performance: evidence from Chinese manufacturing industry. *The Journal of Business & Innovation Marketing*, 36(5), pp. 824-848.
- MALESIOS, C., DEY, P.K. and ABDELAZIZ, F.B., 2018. Supply chain sustainability performance measurement of small and medium sized enterprises using structural equation modelling. *Annals of Operations Research*, 294(1), p. 623-653.
- MANSELL, P., PHILBIN, S.P. and BROYD, T., 2020. Development of a New Business Model to Measure Organizational and Project-Level SDG Impact—Case Study of a Water Utility Company. *Sustainability*, 12(16), p. 6413.

- MANSELL, P., PHILBIN, S.P. and KONSTANTINOOU, E., 2020. Delivering UN Sustainable Development Goals' Impact on Infrastructure Projects: An Empirical Study of Senior Executives in the UK Construction Sector. *Sustainability*, 12(7998), pp. 7998-8026.
- MANSELL, P., PHILBIN, S.P. and KONSTANTINOOU, E., 2020. Redefining the Use of Sustainable Development Goals at the Organisation and Project Levels—A Survey of Engineers. *Administrative Sciences*, 10(55), pp. 1-39.
- MANVILLE, G., GREATBANKS, R., WAINWRIGHT, T. and BROAD, M., 2016. Visual performance management in housing associations: a crisis of legitimation or the shape of things to come?. *Public Money & Management*, 36(2), pp.105-112.
- NDUBUKA, N.N. and REY-MARMONIER, E., 2019. Capability approach for realising the Sustainable Development Goals through Responsible Management Education: The case of UK business school academics. *The International Journal of Management Education*, 17(3), p.100319.
- NUÑEZ-CACHO, P., GÓRECKI, J., MOLINA-MORENO, V. and CORPAS-IGLESIAS, F.A., 2018. What gets measured, gets done: Development of a circular economy measurement scale for building industry. *Sustainability*, 10(7), p.2340.
- ONAT, N.C., KUCUKVAR, M., HALOG, A. and CLOUTIER, S., 2017. Systems thinking for life cycle sustainability assessment: A review of recent developments, applications, and future perspectives. *Sustainability*, 9(5), p.706.
- OPOKU, A., CRUICKSHANK, H. and AHMED, V., 2015. Organizational leadership role in the delivery of sustainable construction projects in UK. *Built environment project and asset management*, 5(2), pp. 154-169.
- PARKIN, S., SOMMER F. and UREN, S., 2003. Sustainable development: understanding the concept and practical challenge. *Proceedings of the ICE – Engineering Sustainability*, 156(1), pp. 19–26.
- SAUNDERS, M.N.K., LEWIS, P. and THORNHILL, A., 2019. *Research Methods for Business Students*. 8th ed. Harlow: Pearson Education Limited.
- SCERRI, A. and JAMES, P., 2010. Accounting for sustainability: combining qualitative and quantitative research in developing 'indicators' of sustainability. *International Journal of Social Research Methodology*, 13(1), pp. 41-53.
- SCHOONENBOOM, J. and JOHNSON, R.B., 2017. How to Construct a Mixed Methods Research Design. *Kölner Zeitschrift für Soziologie und Sozialpsychologie*, 69(2), pp. 107-131.
- SEKARAN, U. and BOUGIE, R., 2016. *Research Methods for Business*. 7th ed. Chichester: Wiley.
- THE LANCET, 2019. Net zero by 2050 in the UK. *The Lancet*, 393(10184), p. 1911.
- UK GOVERNMENT, 2021. Collaboration. [online]. London: UK Government. Available from: <https://ukcop26.org/cop26-goals/collaboration/> [Accessed 27 June 2021].
- UK GREEN BUILDING COUNCIL, 2015. *Tackling embodied carbon in buildings*. London: UK Green Building Council.
- UNITED NATIONS, 2015. *THE 17 GOALS*. [online]. New York, NY: United Nations. Available from: <https://sdgs.un.org/goals> [Accessed 30/04/2021].
- UPSTILL-GODDARD, J., GLASS, J., DAINTY, A. and NICHOLSON, I., 2016. Implementing sustainability in small and medium-sized construction firms: the role of absorptive capacity. *Engineering, Construction and Architectural Management*, 23(4), pp. 407-427.
- YU, M., ZHU, F., YANG, X., WANG, L. and SUN, X., 2018. Integrating sustainability into construction engineering projects: Perspective of sustainable project planning. *Sustainability*, 10(3), p.784.
- ZHANG, D., SUN, X., LIU, Y., ZHOU, S. and ZHANG, H., 2018. The effects of integrative leadership on the enterprise synergy innovation performance in a supply chain cooperative network. *Sustainability*, 10(7), p.2342.
- ZHANG, Q., OO, B.L. and LIM, B.T.H., 2019. Drivers, motivations, and barriers to the implementation of corporate social responsibility practices by construction enterprises: A review. *Journal of Cleaner Production*, 210(February 2019), pp. 563-584.

7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM

Creating Capacity and Capability for the Future of the Built Environment

Appendix 1: Measures / Indicators for Measuring Sustainability in a Construction Contractor SME

Category	Sub-Category	Question	Weighting per Category	Weighting per Sub-Category	RAG Score
Economic	Local Economy	Has labour been sourced locally where possible?	25%	4.17%	
Economic	Local Economy	Have materials been sourced locally where possible?		4.17%	
Economic	Client	Does the project represent good value for money?		4.17%	
Economic	Profit	Have acceptable profit margins been achieved?		4.17%	
Economic	Efficiency	Has efficiency been maximised (time and use of resources)?		4.17%	
Economic	Innovation	Have any new or innovative solutions been trialled or implemented?		4.17%	
Environment	Energy	Has energy consumption been kept as low as reasonably practicable?	25%	1.92%	
Environment	Energy	Have renewable / clean energy sources been utilised wherever possible?		1.92%	
Environment	Water	Has water consumption been minimised?		1.92%	
Environment	Water	Have methods for water recycling been utilised wherever possible?		1.92%	
Environment	Materials	Has material usage been reduced wherever possible?		1.92%	
Environment	Materials	Have materials been re-used wherever possible?		1.92%	
Environment	Materials	Has sourcing of reduced carbon / sustainable alternatives been maximised?		1.92%	
Environment	Waste	Has waste been minimised?		1.92%	
Environment	Waste	Has hazardous waste been correctly managed?		1.92%	
Environment	Emissions	Have transport emissions of personnel been minimised?		1.92%	
Environment	Emissions	Have delivery emissions been minimised through careful planning?		1.92%	
Environment	Pollution	Has sufficient effort been made to prevent pollution to land, air and water?		1.92%	
Environment	Ecology	Have impacts on flora and fauna been assessed and managed?		1.92%	
Social	Safety	Has the project been delivered safely (workers and local community)?	25%	4.17%	
Social	Community	Has noise nuisance been minimised?		4.17%	
Social	Community	Has traffic disruption been minimised?		4.17%	
Social	Employment	Have new employment opportunities been created for locals?		4.17%	
Social	Employment	Have new employment opportunities been created for young persons / apprenticeships?		4.17%	
Social	Employment	Have efforts been made to ensure no forced labour or modern slavery has occurred throughout the supply chain?		4.17%	
Leadership	Clients	Have more sustainable solutions been suggested to the client wherever possible?	25%	4.17%	
Leadership	Clients	Have more sustainable solutions been agreed to by the client?		4.17%	
Leadership	Suppliers	Have sustainability issues been considered during supplier / subcontractor selection?		4.17%	
Leadership	Suppliers	Have suggestions for more sustainable solutions been sought from suppliers / subcontractors wherever possible?		4.17%	
Leadership	Suppliers	Have more sustainable suggestions from suppliers / subcontractors been implemented?		4.17%	
Leadership	Education	Have efforts been made to ensure staff and organisations have awareness of relevant sustainability issues?		4.17%	

The applications of building information modelling for the lifecycle performance of green buildings: a systematic literature review

Peng Wang* and Zhenan Feng

School of Built Environment, Massey University, Auckland, New Zealand.

**Corresponding author: 714143938@qq.com*

Abstract

Buildings and construction are one of the major contributors to global warming and climate change. The development and operation of green buildings are of critical importance to achieve sustainability. Although a series of assessment criteria has been proposed to evaluate green buildings, such as Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM), as well as Green Star New Zealand, it is challenging to track and analyse the lifecycle performance of green buildings.

Building Information Modelling (BIM) has emerged as a digital technology which has the potential to address this issue. BIM integrates the lifecycle data of buildings, such as geometries, materials, facilities, systems, physical properties, and thermal properties. With these types of data and information, the environmental performance and impact of green buildings can be assessed properly. However, most of current studies mainly concentrate on the applications of BIM for green buildings in one or two of lifecycle phases (e.g., construction phase or operation phase). The integration of BIM and green buildings for whole lifecycle performance is lacking.

This research aims to explore the current applications of BIM implemented in the lifecycle of green buildings and the sustainable factors addressed by BIM applications. This research applied a systematic literature review to achieve the research aim.

The results indicate that 1) BIM can be applied to evaluate energy consumption and carbon emission in the design, construction, and operation processes of green buildings. 2) BIM provides a platform to integrate with LEED green rating systems). The findings indicate various advantages of BIM in terms of assessing the energy consumption, CO₂ emissions, and the features of green buildings.

Keywords

BIM, carbon emissions, energy analysis, green buildings, life cycle assessment.

Introduction

The development and operation of buildings contribute to a substantial consumption of energy and emission of carbon (Gao *et al.* 2019). For instance, the government of New Zealand has reported that carbon emissions from the construction industry have increased by 66% in the

decade from 2007 to 2017. Hence, if there are proper ways to deliver the design, construction, and operation works throughout the entire life cycles of buildings, the energy-savings can be approached significantly. In response to this trend, the new concept of green buildings has been developed and practiced by the global construction industry.

Although the practitioners have established comprehensive measures to assess the green buildings through their life cycle, they are still confronted with a major challenge when collecting the relevant data to achieve the criteria of Green Building Assessment Schemes (GBAS). This is because the lack of sufficient tools to evaluate green buildings, and using the traditional assessments are relatively inconsistent and inaccurate with respect to time and costs (Ansah *et al.* 2019).

To assist the assessments of the green buildings, Building Information Modelling (BIM) has been emerging as an intelligent information-based process to create an innovative working platform improving the productivity and sustainability in the construction industry. (Elmualim and Gilder 2014, Lu *et al.* 2017, Rodrigues *et al.* 2020). The BIM technology has contributed to facilitating the management and integration of information through the entire life cycle of buildings. Therefore, BIM has the potential to be one of the most efficient methods to cope with this issue. However, the current literature has rare information about the life cycle assessment (LCA) for green buildings using BIM. To fill this gap, this research adopts a systematic literature review approach to give insights into the applications of BIM for green buildings from design to operation phases.

Literature Review

The construction industry has caused serious environmental issues, such as climate change and energy shortage, as using traditional methods for buildings generate 33% of greenhouse gases and consume over 40% of global energy (United Nations Environment Programme, 2009). To resolve resource constraints and achieve sustainability, the top priority is to develop green buildings.

At present, a series of assessment standards have been proposed to evaluate green buildings. For instance, the United States Green Building Council has proposed an Energy and Environmental Design Building (LEED) rating system. The British Building Research Establishment has introduced a method to assess green buildings called Building Research Establishment Environmental Assessment Method (BREEAM). The New Zealand Green Building Council (NZGBC) has introduced Green Star New Zealand, which is an adapted version of Green Star Australia, established in 2007. The Building and Construction Authority (BCA) in Singapore promoted Green Mark Assessment Criteria. These approaches all revolve around energy savings and emission reductions (Espinoza *et al.* 2012, Zhang *et al.* 2017). However, the majority of current studies mainly concentrate on the assessment of design, and construction stages, but rarely assess the operation and maintenance stages. In this situation, when the high carbon emission and energy consumption caused by the building users in the operation and maintenance stages, the overall environmental performance will be influenced (Cheng *et al.* 2020). Hence, it is important to assess the entire LCA for green buildings.

LCA is a methodology for analysing environmental impacts related to all the stages of products throughout their whole life cycles. Cheng *et al.* (2020) stated that the traditional method of LCA normally has four steps, including scope definition, inventory analysis, impact assessment, and result interpretation. Each step needs to collect used materials and data about building performance, but it is difficult to create a database and obtain accurate quantities to complete the analysis work.

In the past decades, although BIM has become a wide application in the construction industry, the current studies still lack comprehensive reviews to establish a link between green buildings and BIM applications (Lu *et al.* 2017). Whether the applications of BIM can be utilised to assess green buildings through the life cycle should have in-depth research. Therefore, the motivation of this study is to evaluate the applications of BIM for green buildings over the life cycle.

Research Methodology

Khan *et al.* (2003) demonstrate a workflow to conduct systematic literature review. The first step of this research is to formulate questions, as problem formation with the determination of the questions will guide the literature review. Therefore, two main research questions have been formulated to investigate these two research objectives: 1. How have BIM applications been applied in the lifecycle of green buildings? 2. What factors have been addressed by BIM for green buildings?

The next step is to search and select the relevant literature papers. The majority of journal articles and conference proceedings have been collected from Scopus, which is the largest abstract and citation database of peer-reviewed literature. Apart from that, retrieving relevant articles from the reference lists of selected papers were also adopted by using 'Google Scholar' to cover any missing papers. This searching engine provides a simple way to broadly search for scholarly literature.

The keywords for searching articles in Scopus are 'BIM' and 'Green buildings'. The search work was carried out on 10 May 2021. The total number of papers obtained from Scopus is 561.

After that, the filtering process was conducted following a framework named Preferred Reporting Items for systematic Literature Review and Meta-Analyses (PRISMA) (Moher *et al.* 2009), including inclusion and exclusion criteria. If the articles do not include BIM applications implemented in the life cycle phases of green buildings (e.g., design phase or construction phase) in the title or abstracts, these papers were excluded. The rest of the articles were assessed for eligibility. The target articles should fulfil the following criteria:

1. The BIM-based assessment for green buildings through the lifecycle has been proposed and analysed,
2. An experiment has been conducted to collect the learning outcome,
3. Data analysis has been conducted to evaluate,
4. The publication time span is limited from 2000 to 2021.

The articles that cannot fulfil the above criteria were excluded. The selection process is demonstrated in Figure 1.

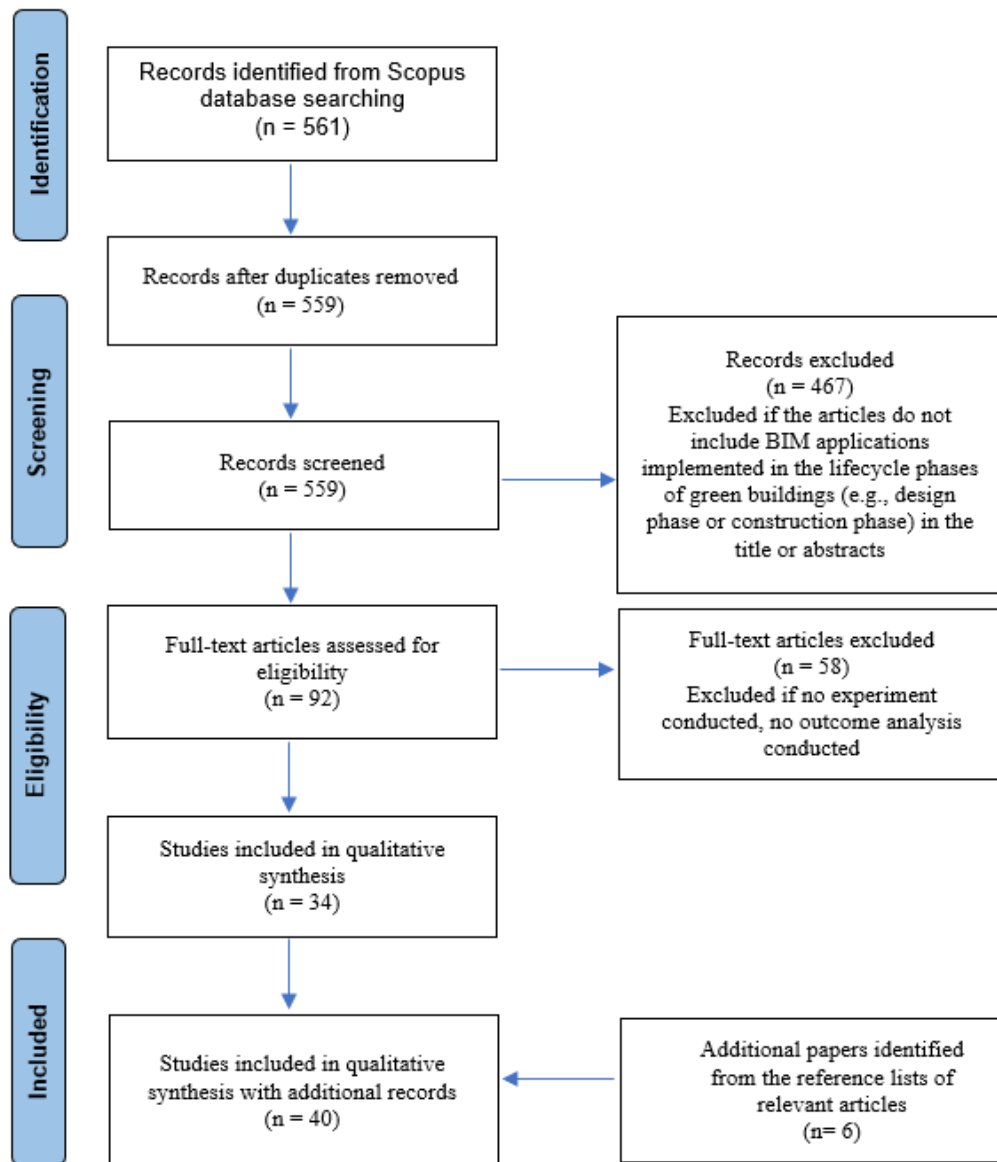


Figure 1. The process of research article selection

Consequently, 40 papers were identified as the target articles for this systematic literature review (Abanda and Byers 2016, Ajayi *et al.* 2015, Alothman *et al.* 2021, Azhar and Brown 2009, Azhar *et al.* 2010, Azhar *et al.* 2011, Bonenberg and Wei 2015, Chen and Hsieh 2013, Chen and Nguyen 2015, Cheng *et al.* 2020, Doan *et al.* 2018, Doan *et al.* 2019, Ebrahim and Wayal 2019, El Sayary and Omar 2021, Gandhi and Jupp 2014, Gardezi and Shafiq 2019, Ghaffarianhoseini *et al.* 2017, Jalaei *et al.* 2020, Jalaei and Jrade 2014, Jalaei and Jrade 2015, Khahro *et al.* 2021, Krisel and Nies 2008, Lee *et al.* 2015, Lee *et al.* 2015, Li *et al.* 2012, Lin *et al.* 2019, Lu *et al.* 2019, Maltese *et al.* 2017, Najjar *et al.* 2017, Nguyen *et al.* 2010, Rathnasiri *et al.* 2021, Rodrigues *et al.* 2020, Ryu and Park 2016, Singh and Sadhu 2019, Solla *et al.* 2016, Uddin *et al.* 2021, Wen *et al.* 2020, Wu and Issa 2014, Yang *et al.* 2018, Zhang and Xing 2015). Among these papers, 38 were published in the journal articles, with the remaining two published as conference proceedings. Most of the papers were published after 2010, with only two were published in 2008 and 2009.

Findings and Discussion

This research implements qualitative data analysis. The focus of this review is the previous research outcomes, which is to extract data from each paper and integrate these outcomes. To support this stage, a matrix will be established by using Microsoft excel to list all the analyses and outcomes that the previous studies identified. When the previous researchers obtain the same outcome, the evidence will be integrated and listed in the matrix.

BIM-supported design phase

In the review papers, the applications of BIM were developed to deal with sustainability issues in the design phase. This process contained building performance analyses and simulations, such as energy consumption analyses and carbon emission simulations. Apart from that, a few papers were carried out the further development of BIM energy simulation tools to improve the efficiency of the design stage. Table 1 shows BIM-based simulation items recognised by this review.

Table 1. The aspects of energy simulation based on BIM

Simulation aspects	Articles	Description
Orientation	Alothman <i>et al.</i> 2021, Azhar <i>et al.</i> 2011, Ebrahim and Wayal 2019, Khahro <i>et al.</i> 2021, Singh and Sadhu 2019	Minimise the energy consumption and maximise the ventilation and solar radiation
Heating and cooling loads	Alothman <i>et al.</i> 2021, Ajayi <i>et al.</i> 2015, Azhar <i>et al.</i> 2010, Ebrahim and Wayal 2019, Khahro <i>et al.</i> , 2021, Lee <i>et al.</i> 2015, Lin <i>et al.</i> 2019, Rodrigues <i>et al.</i> 2020, Singh and Sadhu 2019, Zhang and Xing 2015	Select the favourable WWR, exterior materials and HVAC systems to improve the capability of HCL
Daylighting	Azhar <i>et al.</i> 2011, Bonenberg and Wei 2015, Lee <i>et al.</i> 2015, Lin <i>et al.</i> 2019	Achieve indoor environmental quality and energy efficiency

BIM-based energy performance analyses in the design process

In the review papers, BIM was adopted to assess the energy consumption of green buildings, including orientation simulations, heating and cooling loads (HCL) analyses, daylighting analyses. In terms of the orientation simulations, BIM technology was identified the function to visually simulate the building's orientation, which is a critical feature to achieve green buildings. The proper building orientation has a valuable contribution to minimise the energy consumption and maximise the ventilation and solar radiation throughout the building operation phase (Alothman *et al.* 2021, Khahro *et al.* 2021), which can directly reduce the load on lighting and HVAC systems (Singh and Sadhu 2019). BIM-based simulation analysis has the function to select the favourable building orientation that contributes to the minimum energy consumption of buildings (Azhar *et al.* 2011). Abanda and Byers (2016) examined the influence of building orientation on energy consumption and explored how BIM could be utilised to facilitate this process. Alothman *et al.* (2021), Azhar *et al.* (2011) and Singh and Sadhu (2019) made a comparison with various building's orientation directions to optimise the

sustainable design. Based on the comparison of the energy consumption in accordance with the different building orientation directions, results indicated that a well-orientated building could decrease a huge amount of energy usage over its entire lifecycle. Ebrahim and Wayal (2019) and Khahro *et al.* (2021) changed the building's orientation up to 15°, this option allowed the building with better airflow and energy saving.

To improve energy efficiency, HCL is the second aspect to assess green buildings in the design stage. The assessment process can be divided into two aspects, including building material analysis and HVAC system analysis. With regard to the former, BIM applications can support the designers to analyse each part of the building's components and calculate the energy use of the buildings. BIM embodied database has a library that allows the designer to add and modify various alternative materials for energy analysis. It provided a platform for the designers to change the characters of the building envelope and seek solutions to evaluate HCL of buildings. Lee *et al.* (2015) proposed a BIM-based energy modelling to analyse the relationship between window to wall ratio (WWR) and HCL of a high-rise building. Ajayi *et al.* (2015), Ebrahim and Wayal (2019), Khahro *et al.* (2021), Lin *et al.* (2019), Singh and Sadhu (2019), and Zhang and Xing (2015) compared the effect of different WWR, wall materials, and roof materials implemented in residential buildings to promote the capability of HCL based on the applications of BIM. Alothman *et al.* (2021) and Rodrigues *et al.* (2020) utilised BIM tools to calculate the life cycle energy consumption of alternative window, wall, and roof materials. Results indicated that the improvement of the conductions and insulations of windows, walls, and roofs developed the HCL of buildings to achieve energy efficiency.

In addition, HVAC systems have a significant influence on the energy use of the building life cycle. The core purpose of implementing HVAC systems is to improve the quality of indoor air and control HCL for buildings. BIM-based energy analysis can estimate the life cycle electricity usage and the life cycle fuel usage of various types of HVAC systems. These parameters enable the designers to analyse the energy efficiency of HVAC systems. For example, Alothman *et al.* (2021) and Singh and Sadhu (2019) evaluated different types of HVAC systems in BIM software and simulated the annual electricity and fuel usage of this equipment, which provided effective data to improve energy efficiency of HVAC systems. Azhar *et al.* (2010) evaluated the feasibility of BIM for HVAC analysis via a case study. Results showed that BIM could significantly facilitate to developing complex building performance analyses and achieve an optimised building design.

Daylighting analysis is also a significant factor for promoting a green building design, as it assists the green buildings to achieve energy efficiency and indoor environmental quality. The reviewed papers introduced that the applications of green BIM tools could be used to analyse daylighting of buildings. Azhar *et al.* (2011), Bonenberg and Wei (2015), and Lee *et al.* (2015) used BIM to perform a series of daylighting studies for positioning on a selected construction site during the design phase. Lin *et al.* (2019) created a BIM-model and simulated sunlight changes, solar radiation, and natural daylighting to examine the energy efficiency performance of a retail market, which provided the optimisation plans to consider as a reference for subsequent re-construction design.

Apart from the above energy analyses for green buildings, a few papers focused on the further development of BIM energy simulation tools to support the design stage. El Sayary and Omar (2021) investigated a decision-making tool for architects in the design phases, which was the energy consumption template plug-in embodied in BIM applications to enhance the design performance. Results showed that this added tool could assist users to evaluate their designs and achieved a zero-energy building. Rodrigues *et al.* (2020) used BIM-modelling software to perform the potential of BIM in energy management and analysis of an existing two-story

public building. Results showed that BIM contained all energy-related information and designers could select the most appropriate solution in the database of BIM to save the energy consumption, which was proved the potential of BIM in the AEC sector. Wen *et al.* (2020) proposed an empirical analysis to develop the effectiveness of BIM for green buildings. Results indicated that the application value of BIM was fully achieved in the design process but decreased in the construction and operation phases. Maltese *et al.* (2017) confirmed that the use of BIM applications to provide data for energy consumption assessment and sustainability evaluation could integrate design, construction, and operation guiding towards a Net Zero Energy building.

BIM-based carbon emission analysis in the design process

In eight papers, BIM was implemented as a simulation tool to perform the carbon footprint analysis and to support the design process of green buildings. Ajayi *et al.* (2015) and Khahro *et al.* (2021) utilised BIM for quantity take-off and evaluated the environmental impacts of commonly used building materials, including brick, timber, concrete, and steel, on the lifecycle performance of buildings. Uddin *et al.* (2021) also used BIM for quantity take-off for residential buildings to calculate the embodied carbon dioxide (CO₂) content for construction materials by considering the standard database in India and the inventory of Carbon and Energy (ICE). Lu *et al.* (2019) used BIM to propose an analytical framework quantifying the carbon emissions of a hospital through its entire life cycle, which provided a solution that minimised the carbon emissions of buildings and improved the performance of buildings. Cheng *et al.* (2020) presented the LCA-BIM method for green building assessment to calculate CO₂ emissions of a public building in different construction activities (e.g., construction and operation stage).

In addition to the above functions of BIM in the design stage, other papers concentrated on the further development of BIM applications in evaluating carbon emissions. For instance, Lee *et al.* (2015) proposed a green-BIM template to estimate CO₂ emissions of the common construction materials through the entire life cycle, which enabled the designers to compare the environmental impacts of different building components (e.g., wall, floor, beam, column, and window). This situation provided an efficient decision-making to select low-carbon construction materials. Gardezi and Shafiq (2019) proposed a prediction BIM-based model for the operational carbon emissions at the design phase. Chen and Hsieh (2013) and Li *et al.* (2012) investigated a plug-in that used BIM and the database of a carbon calculation software to calculate the real-time CO₂ emissions of buildings.

BIM-supported construction phase

In a few papers, BIM was implemented to explore CO₂ emissions that generated in the construction process. Based on the BIM applications, the amount of carbon emission that generate from the productions of building materials, the process of material transportation, and on-site construction activities can be analysed. The multiple data effectively assist the manager to control CO₂ emissions in the construction stage. For instance, Lu *et al.* (2019) applied BIM to analyse carbon emissions of 10 building materials and different work types in the construction stage. Yang *et al.* (2018) used BIM to assess carbon emissions generated during the process of building material transportation and the use of construction equipment.

BIM-supported operation phase

The main energy consumption and carbon emissions in the operation stage is the use of HVAC systems, water supplying, lighting systems, and other operational equipment. In a few review

papers, BIM technology was identified as a management tool to monitor the performance of green buildings. Rathnasiri *et al.* (2021) compared the applicability of green BIM energy simulation for an existing green building that has been accredited LEED rating systems. Results indicated that BIM-based building performance analyses were accurate and realistic compared with actual results, which could be effectively implemented to manage the existing buildings of energy consumption. Lu *et al.* (2019) evaluated the carbon emissions generated in the operation stage of a hospital in China, including HVAC systems, daylighting, water supplying, and equipment use.

BIM and green building rating systems

BIM and LEED

In nine papers, the applications of BIM were applied to integrate with the LEED rating system. Azhar *et al.* (2011) investigated a conceptual framework to explore the relationship between BIM and the LEED rating system. Results indicated that BIM tools could evaluate up to 17 LEED credits. Solla *et al.* (2016) identified 38 LEED credits could be achievable by using BIM applications. Krisel and Nies (2008) utilised BIM to analyse the credits of water efficiency, energy and atmosphere, as well as indoor environmental quality in LEED. Chen and Nguyen (2015) integrated geographic information with BIM to improve the efficiency of building's location and transportation analysis for the credit of suitable site in LEED. Jalaei and Jade (2014) recognised that BIM tools could evaluate the credits of material and resources, coupled with energy and atmosphere in LEED.

Apart from that, some papers focused on the further development of BIM tools in assisting LEED rating system analysis. Wu and Issa (2014) investigated a BIM execution plan for a LEED project. Nguyen *et al.* (2010) proposed a framework to extract data from the BIM-based building model for supporting the sustainability assessment, which was based on the LEED green building rating system. Jalaei *et al.* (2020) and Jalaei and Jade (2015) created a plugin for automatic calculate the required number of points based on the LEED green building rating system to facilitate project teams in making sustainability-related decisions. Ryu and Park (2016) proposed an improved method to fulfil LEED certification for an existing building.

BIM and Green Star (New Zealand)

A few papers investigated the applications of BIM for green buildings in New Zealand. Gandhi and Jupp (2014) stated that BIM applications could be implemented to perform the criteria of Green Star, but not all criteria could be addressed by BIM applications. This is because the awareness of considering the benefits between BIM and Green Star has still received insufficient attention (BRANZ, 2015). To facilitate the development of integrating BIM and Green Star in New Zealand, Ghaffarianhoseini *et al.* (2017) explored the relationship between BIM and Green Star. Results showed that the applications of BIM could support practitioners to achieve the majority of Green Star criteria. However, Doan *et al.* (2018) and Doan *et al.* (2019) examined whether BIM and Green Star could be created a link and be adopted in the construction industry. Results indicated that a relationship between them did not exist currently, but there was a potential to integrate BIM and Green Star. The lack of integration was due to the lack of client demand, the low level of BIM development, and the lack of both Green Star and BIM understanding.

BIM and LCA

In the review papers, the researchers combined BIM and LCA to analyse the overall environmental impacts of green buildings, such as energy consumption and carbon emission. Azhar and Brown (2009) examined whether BIM simulation software had the capacity to integrate with LCA. Cheng *et al.* (2020) proposed the LCA-BIM method to analyse the carbon emissions of common building materials through the entire life cycle. Najjar *et al.* (2017) analysed the methodology of LCA from a building perspective and proposed the role of BIM and LCA integration in evaluating the environmental impacts of building materials, which enabled both the decision-making process and sustainable design procedure in the construction sector. Ajayi *et al.* (2015) and Lu *et al.* (2019) introduced a framework for integrating BIM and LCA, which could be implemented in the early design stage to assist the designers and engineers to acquire reliable outcomes related to the environmental impacts of buildings. Jade and Jalaei (2014) utilised BIM with the LCA tool (Impact Estimator) to create a model for evaluating the environmental impacts in the design phase. Lee *et al.* (2015) also investigated a BIM-based model with Korean life cycle inventory (LCI) databases to evaluate the environmental performance of buildings.

Based on the data analysed above, the applications of BIM utilised to develop the lifecycle performance of green buildings have been identified. In the design stage, the applications of BIM provide a platform to evaluate the performance of buildings through the entire life cycle in the early design process. This is because BIM technology enables the designers to simulate design features of green buildings, which contains energy performance analyses and carbon emission simulations. In terms of the energy consumption analyses, BIM tools can assist the designers to simulate three main aspects of green buildings (orientation, HCL, and daylighting). The orientation simulation can significantly minimise the energy consumption and maximise the ventilation and solar radiation of green buildings. HCL analyses can assist the designers to select the favourable WWR, exterior building materials and HVAC systems. Daylighting analyses enable the green buildings to achieve indoor environmental quality and energy efficiency. The designers can implement these identified functions of BIM to analyse the energy performance of green buildings and make decisions in the design stage. In addition, BIM allows the designers to evaluate CO₂ emission in the design stage, as BIM can calculate the embodied carbon contents in different building materials. By comparing the data, the designers can select low-carbon emission materials to promote the criteria of green buildings. Apart from that, the applications of BIM have the function to integrate with the LCA method in the design stage, which allows the designers to analyse the overall environmental impacts of green buildings in the early design phase. This situation can predict CO₂ emission and energy consumption in the construction and operation stage, providing a series of data for the management in these phases.

In the construction stage, BIM is only used to monitor and reduce the carbon emission that generates from three construction activities, including building material production, material transportation, and on-site construction activities. Yet, the analysis of energy consumption in this stage is not identified. In the operation stage, both energy consumption and carbon emission of green buildings can be evaluated by BIM tools. The use of HVAC systems, lighting, water supplying, and building equipment is the main sources of energy consumption and carbon emission. By simulating these factors, BIM is adopted as a management tool to monitor the performance of existing green buildings.

Integrating BIM with rating systems provides a simple and effective method for designers to evaluate the energy consumption and carbon emissions of green buildings. This is in line with the researchers who use BIM to investigate the credits in the LEED rating system. Although

most of the current papers only introduce the integration of BIM and the LEED rating system, not all the credits in LEED can be assessed by BIM. In seven categories of LEED, BIM can implement to analyse sustainable sites, water efficiency, energy and atmosphere, material and resources, and indoor environmental quality, but BIM cannot be used to evaluate the credits of innovation in design and regional priority. Additionally, the current situation of integrating BIM with Green Star is limited. This is because the lack of client demand, the low level of BIM development, and the lack of both Green Star and BIM understanding lead to the failure of creating a link between BIM and Green Star in the construction industry. Whether BIM and Green Star could be integrated requires further research in the future.

Conclusion

To conclude, this systematic literature review was carried out on the integration of BIM applications and green buildings for overall lifecycle performance. Two research objectives, including the current BIM applications implemented in the lifecycle of green buildings and the sustainable aspects addressed by BIM applications, were extensively explored. The findings indicate various advantages of BIM in terms of assessing the energy consumption, CO₂ emissions, and the features of green buildings. However, this research has a few limitations. Only a few papers introduce BIM to assess the performance of green buildings in the construction and operation phases. There may be other aspects that are important to developing and implementing BIM for the construction and operation stage. Whether BIM applications can be used to monitor energy consumption (e.g., the mechanical plants using for earthworks, transportation, compacting, lifting requires a significant portion of energy) in the construction stage. As a result, there is still in need to investigate the applications of BIM in the construction and operation stages in future research. Furthermore, most of the existing research focus on integrating BIM and the LEED rating system. There is still in need to investigate further research on integrating BIM and other green building rating systems.

Acknowledgement

This research was supported by Building Research Association of New Zealand (BRANZ) as part of ‘Creating capacity to transition to zero-carbon programme’.

References

- Abanda, F.H. and Byers, L, 2016. An investigation of the impact of building orientation on energy consumption in a domestic building using emerging BIM (Building Information Modelling). *Energy*, 97, 517-527.
- Alothman, A. Ashour, S. and Krishnaraj, L, 2021. Energy performance analysis of building for sustainable design using BIM: A case study on institute building. *International Journal of Renewable Energy Research*, 11 (2), 556-565.
- Ajayi, S.O. Oyedele, L.O. Ceranic, B. Gallanagh, M. and Kadiri, K.O, 2015. Life cycle environmental performance of material specification: A BIM-enhanced comparative assessment. *International Journal of Sustainable Building Technology and Urban Development*, 6 (1), 14-24.
- Ansah, M.K. Chen, X. Yang, H. Lu, L. and Lam, P.T.I., 2019. A review and outlook for integrated BIM application in green building assessment. *Sustainable Cities and Society*, 48.
- Azhar, S., 2010. Building information modelling (BIM): trends, benefits, risks, and challenges for the AEC industry. *Leadership and Management in Engineering*, 11 (3), 241-252.
- Azhar, S. Brown, J.W. and Sattineni, A., 2010. A case study of building performance analyses using building information modelling. *2010-27th International Symposium on Automation and Robotics in Construction*, 213-222.
- Azhar, S. and Brown, J., 2009. BIM for sustainability analyses. *International Journal of Construction Education and Research*, 5 (4), 276-292.

- Azhar, S. Carlton, W.A. Olsen, D. and Ahmad, I., 2011. Building information modeling for sustainable design and LEED ® rating analysis. *Automation in Construction*, 20 (2), 217–224.
- Bonenberg, W. and Wei, X., 2015. Green BIM in Sustainable Infrastructure. *Procedia Manufacturing*, 3, 1654–1659.
- BRANZ, 2015. *Government as client: using building information modelling on NZ construction projects*. Available from: <http://www.building.govt.nz/UserFiles/File/Sector%20info/report-govt-asclient>.
- Chen, P. H. and Nguyen, T. C., 2015. Integration of Building Information Modelling (BIM) and LEED's Location and Transportation Category. In *Proceedings of the 32nd International Symposium on Automation and Robotics in Construction*, 1–3.
- Chen, Y.W. and Hsieh, S. H., 2013. A BIM assisted rule based approach for checking of green building design. In *Proceedings of the 13th International Conference on Construction Applications of Virtual Reality*, 47–55.
- Cheng, B. Li, J. Tam, V.W.Y. Yang, M. and Chen, D., 2020. A BIM-LCA approach for estimating the greenhouse gas emissions of large-scale public buildings: A case study. *Sustainability (Switzerland)*, 12 (2), 685.
- Chong, H.Y. Lee, C.Y. and Wang, X.Y., 2017. A mixed review of the adoption of Building Information Modelling (BIM) for sustainability. *Journal of Cleaner Production*, 142, 4114–4126.
- Chong, H.Y. and Wang, X., 2016. The outlook of building information modelling for sustainable development. *Clean Technologies and Environmental Policy*, 18 (6), 1877–1887.
- Doan, D.T. Ghaffarianhoseini, A. Naismith, N. Ghaffarianhoseini, A. Zhang, T. and Tookey, J., 2019. Examining Green Star certification uptake and its relationship with Building Information Modelling (BIM) adoption in New Zealand. *Journal of Environmental Management*, 250.
- Doan, D.T. Ghaffarianhoseini, A. Naismith, N. Zhang, T. Tookey, J. and Ghaffarianhoseini, A., 2018. Examining the relationship between building information modelling (BIM) and Green Star. *International Journal of Technology*, 9 (7), 1299–1307.
- Ebrahim, A. and Wayal, A.S., 2019. BIM based building performance analysis of a green office building. *International Journal of Scientific and Technology Research*, 8 (8), 566–573.
- Elmualim, A. and Gilder, J., 2014. BIM: Innovation in design management, influence and challenges of implementation. *Architectural Engineering and Design Management*, 10 (3–4), 183–199.
- El Sayary, S. and Omar, O., 2021. Designing a BIM energy-consumption template to calculate and achieve a net-zero-energy house. *Solar Energy*, 216, 315–320.
- Espinoza, O. Buehlmann, U. and Smith, B. (2012). Forest certification and green building standards: Overview and use in the U.S. hardwood industry. *Journal of Cleaner Production*, 33, 30–41.
- Gandhi, S. and Jupp, J., 2014. BIM and Australian green star building certification. *Proceedings of the 2014 International Conference on Computing in Civil and Building Engineering, Florida*, 275–282.
- Gao, H. Koch, C. and Wu, Y., 2019. Building information modelling based building energy modelling: A review. *Applied Energy*, 238, 320–343.
- Gardezi, S.S.S. and Shafiq, N., 2019. Operational carbon footprint prediction model for conventional tropical housing: a Malaysian prospective. *International Journal of Environmental Science and Technology*, 16 (12), 7817–7826.
- GhaffarianHoseini, A. Doan, D.T. Naismith, N. Tookey, J. and GhaffarianHoseini, A., 2017. Amplifying the practicality of contemporary building information modelling (BIM) implementations for New Zealand green building certification (Green Star). *Engineering, Construction and Architectural Management*, 24 (4), 696–714.
- Jalaei, F. Jalaei, F. and Mohammadi, S., 2020. An integrated BIM-LEED application to automate sustainable design assessment framework at the conceptual stage of building projects. *Sustainable Cities and Society*, 53, 101979.
- Jalaei, F. and Jade, A., 2015. Integrating building information modeling (BIM) and LEED system at the conceptual design stage of sustainable buildings. *Sustainable Cities and Society*, 18, 95–107.
- Jalaei, F. and Jade, A., 2014. Integrating Building Information Modeling (BIM) and energy analysis tools with green building certification system to conceptually design sustainable buildings. *Journal of Information Technology in Construction*, 19, 494–519.
- Jiao, Y. Wang, Y.H. Zhang, S.H. Li, Y. Yang, B.M. and Yuan, L., 2013. A cloud approach to unified lifecycle data management in architecture, engineering, construction and facilities management: integrating BIMs and SNS. *Advanced Engineering Informatics*, 27 (2), 173–188.
- Khahro, S.H. Kumar, D. Siddiqui, F.H. Ali, T.H. Raza, M.S. and Khoso, A.R., 2021. Optimizing energy use, cost and carbon emission through building information modelling and a sustainability approach: A case-study of a hospital building. *Sustainability (Switzerland)*, 13 (7), 3675.
- Khan, K. S. Kunz, R. Kleijnen, J. and Antes, G., 2003. Five steps to conducting a systematic review. *Journal of the Royal Society of Medicine*, 96 (3), 118–121.
- Lee, K.H. Kim, I.H. and Choo, S.Y., 2015. Model study of design components for energy-performance-based architectural design using BIM LOD 100. *Journal of Green Building*, 10 (2), 179–197.

- Lee, S. Tae, S. Roh, S. and Kim, T., 2015. Green template for life cycle assessment of buildings based on building information modeling: Focus on embodied environmental impact. *Sustainability (Switzerland)*, 7 (12), 16498-16512.
- Li, B. Fu, F. F. Zhong, H. and Luo, H. B., 2012. Research on the computational model for carbon emissions in building construction stage based on BIM. *Structural Survey*, 30 (5), 411-425.
- Lin, P.H. Chang, C.C. Lin, Y.H. and Lin, W.L., 2019. Green BIM assessment applying for energy consumption and comfort in the traditional public market: A case study. *Sustainability (Switzerland)*, 11 (17),4636.
- Lu, K. Jiang, X. Tam, V.W.Y. Li, M. W, H. Xia, B. and Chen, Q.,2019. Development of a carbon emissions analysis framework using building information modeling and life cycle assessment for the construction of hospital projects. *Sustainability (Switzerland)*, 11 (22),6274.
- Lu, Y. Wu, Z. Chang, R. and Li, Y., 2017. Building Information Modelling (BIM) for green buildings: A critical review and future directions. *Automation in Construction*, 83, 134-148.
- Maltese, S. Tagliabue, L.C. Cecconi, F.R. Cecconi, F.R. Pasini, D. Manfren, M. and Ciribini, A.L.C., 2017. Sustainability assessment through green BIM for environmental, social and economic efficiency. *Procedia Engineering*, 180, 520-530.
- Moher, D. Liberati, A. Tetzlaff, J. and Altman, D. G., 2009. Preferred reporting items for systematic reviews and meta-analyses: *The PRISMA statement*. *PLoS Medicine*, 6 (7).
- Najjar, M. Figueiredo, K. Palumbo, M. and Haddad, A., 2017. Integration of BIM and LCA: Evaluating the environmental impacts of building materials at an early stage of designing a typical office building. *Journal of Building Engineering*, 14, 115-126.
- Nguyen, T.H. Shehab, T. and Gao, Z., 2010. Evaluating sustainability of architectural designs using building information modelling. *Open Construction and Building Technology Journal*, 4, 1-8.
- Rathnasiri, P. Jayasena, S. and Siriwardena, M., 2021. Assessing the applicability of green building information modelling for existing green buildings. *International Journal of Design and Nature and Ecodynamics*, 15 (6), 763-776.
- Rodrigues, F. Isayeva, A. Rodrigues, H. and Pinto, A., 2020. Energy efficiency assessment of a public building resourcing a BIM model. *Innovative Infrastructure Solutions*, 5(2), 41.
- Ryu, H.S. and Park, K.S., 2016. A study on the LEED energy simulation process using BIM. *Sustainability (Switzerland)*, 8 (2), 138.
- Singh, P. and Sadhu, A., 2019. Multicomponent energy assessment of buildings using building information modelling. *Sustainable Cities and Society*, 49, 101603.
- Uddin, M.N. Wei, H.H. Chi, H.L. Ni, M. and Elumalai, P., 2021. Building information modeling (BIM) incorporated green building analysis: an application of local construction materials and sustainable practice in the built environment. *Journal of Building Pathology and Rehabilitation*, 6 (1),13.
- United Nations Environment Programme, 2009. Buildings and climate change: Summary for decision-makers. Available from: <http://hdl.handle.net/20.500.11822/32152>
- Wen, Q. Li, Z. Peng, Y. and Guo, B., 2020. Assessing the effectiveness of building information modeling in developing green buildings from a lifecycle perspective. *Sustainability (Switzerland)*,12 (23), 1-20.
- Wu, W. and Issa, R.R.A., 2014. BIM execution planning in green building projects: LEED as a use case. *Journal of Management in Engineering*, 31 (1), A4014007.
- Wong, J.K.W. Li, H. Wang, H. Huang, T. Luo, E. and Li, V., 2013. Toward low-carbon construction processes: the visualization of predicted emission via virtual prototyping technology. *Automation in Construction*, 33, 72-78.
- Wong, J.K.W. and Zhou, J., 2015. Enhancing environmental sustainability over building life cycles through green BIM: A review. *Automation in Construction*, 57, 156-165.
- Yang, X. Hu, M. Wu, J. and Zhao, B., 2018. Building-information-modelling enabled life cycle assessment, a case study on carbon footprint accounting for a residential building in China. *Journal of Cleaner Production*, 183, 729-743.
- Zhang, K. and Xing, Y., 2015. Application research on energy saving of small high rise office building based on BIM model. *International Journal of Simulation: Systems, Science and Technology*, 16 (4A), 12.1-12.46.
- Zhang, Y. Wang, J. Hu, F. and Wang, Y., 2017. Comparison of evaluation standards for green building in China, Britain, United States. *Renewable and Sustainable Energy Reviews*, 68, 262-271.

Investigating the motivation and barriers for microgrids in New Zealand

Zuo Zhang¹, Brian H.W. Guo¹, Johannes Dimyadi^{2,3}

¹Department of Civil and Natural Resources Engineering, University of Canterbury

²School of Computer Science, University of Auckland

³Codify Asset Solutions Limited (CAS)

*Corresponding author: zuo.zhang@pg.canterbury.ac.nz

Abstract

From the development of microgrids in the 1990s to recent years, microgrids have been deployed in many countries. There are various studies on the deployment of microgrids for multiple purposes in several countries. For the past two decades, Microgrids have been gaining momentum internationally as an effective method for delivering renewable energy to the power distribution network in the built environment alongside the conventional grid. Research has generally shown favourable tangible and intangible benefits of microgrids worldwide. However, the adoption of microgrids in New Zealand, to date, is still in its infancy, and there is a limited study investigating its current status, costs and benefits, and the potential impact on the New Zealand environment.

To fill the research gap, this paper aims to (1) investigate the current status of microgrids in New Zealand in terms of market demand, incentives, technology readiness, regulations, policies, and any barriers to implementation and deployment, (2) provide recommendations for the development and adoption of microgrids for the New Zealand built environment.

Based on data collected through interviews, the primary resistance to adopting Microgrids in New Zealand is the local networks. Microgrids' buy-back electricity rate is also a barrier to Microgrids' deployment. Future research needs to be done on virtual grids, including how the local network controls the devices within the microgrids, charging and even discharging the devices and regulating the electricity supply of critical demand.

Keywords: microgrids, renewable energy, energy efficiency, New Zealand built environment

Introduction

Buildings are responsible for 35% of global energy consumption and 38% of total direct and indirect energy-related CO₂ emissions (Wang et al., 2017). The New Zealand building sector contributes 20% of the country's GHG emissions (Vickers et al., 2018). To contribute to the global effort under the Paris Agreement, the New Zealand government established the Climate Change Commission in 2019 to advise the government on climate change within the framework of the Climate Change Response (Zero-Carbon) Amendment Act 2019 to reduce net emissions of greenhouse gases (except methane from plants and animals) to zero by 2050 (Climate Change Response Act, 2020).

There has been a transition towards a low carbon community globally in recent years with exemplars in Australia (Moloney *et al.*, 2010), the UK (Hobson *et al.*, 2016), and New Zealand (Landscape Architecture Aotearoa, 2020). Developing low carbon communities is key to meeting national-level carbon emission reduction targets. Auckland Council has established an Action Plan to develop an energy-resilient and low-carbon city (Auckland Council, 2018). The importance of low or zero-carbon home energy is highlighted among the seven action areas. The Action Plan calls for opportunities to improve energy efficiencies through community initiatives.

Ample evidence of the past decades has proven that the hierarchical and centrally-controlled grid is ill-suited to meet the energy demands of the 21st Century (Kolokotsa, 2016). As a self-sufficient energy supply system, microgrids are one solution to improve energy efficiency and reduce carbon emission at the community level (Hirsch *et al.*, 2018a; Zia *et al.*, 2018). The microgrid has a flexible architecture for deploying distributed energy resources (DERs) (Hirsch *et al.*, 2018a). It is a form of decentralised energy production that can operate on or off-grid. For the past two decades, microgrids have been gaining momentum internationally as an effective method for delivering renewable energy to the power distribution network alongside the conventional grid. The deployment of microgrids in New Zealand has been relatively slow compared with that of other developed countries. There is a gap in research that identifies drivers and barriers to the adoption of microgrids in New Zealand.

There is not any nationwide specific requirements or standard guideline as to the connection from Microgrids to the power grid. There are 29 local electricity distribution business (EDB) networks that deliver power to end users across New Zealand (Anton Trixl, 2021) (see Figure 1). Each EDB has its own regulations and policies for microgrid systems to connect to their grids.

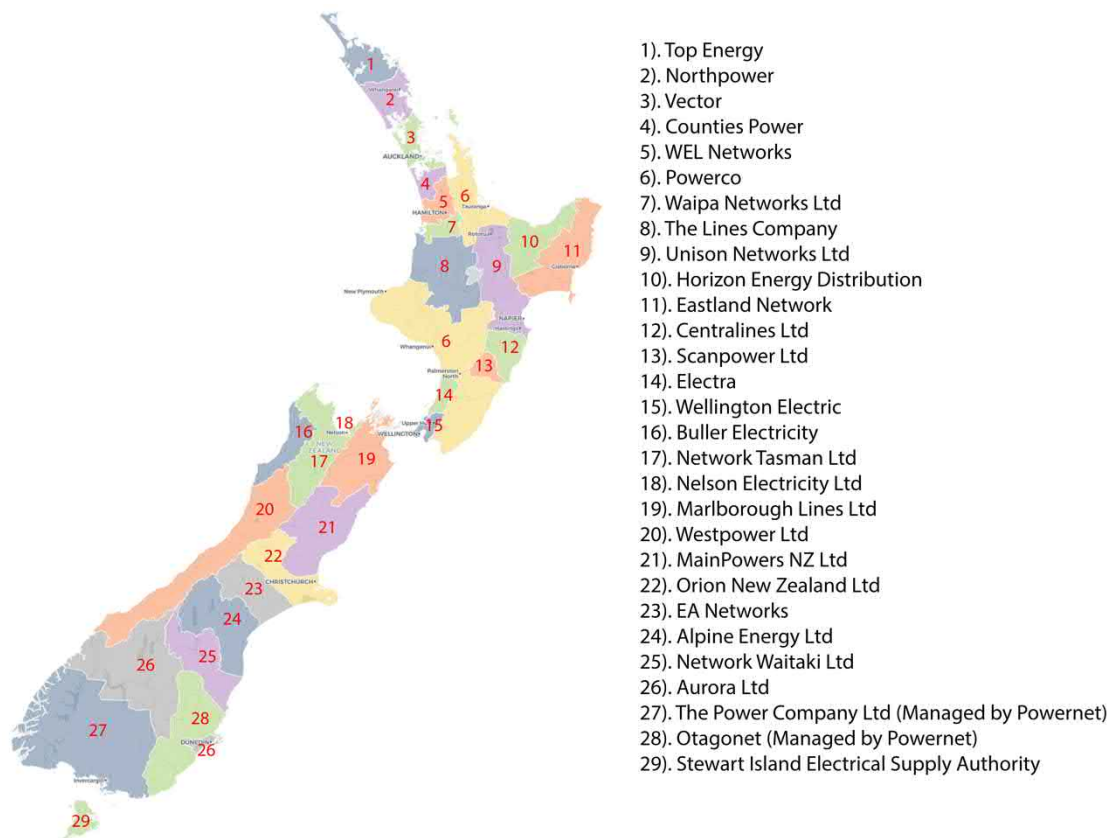


Figure 1. (ena Lines Company Map) Local electricity distribution business (EDB) networks

To address the research gap, this paper aims to (1) investigate and explore the market demand, incentives, technology readiness, regulations, policies, and any barriers to the implementation and deployment of microgrids in New Zealand, (2) provide recommendations for the development and adoption of microgrids for the New Zealand built environment.

Literature Review

According to Soshinskaya *et al.*, a microgrid is defined as a small-scale network for supplying electricity (Soshinskaya *et al.*, 2014). Microgrid systems can generate their electricity or be connected to the grid (Soshinskaya *et al.*, 2014). It can help manage and maximise the benefits of distributed generations (Morris *et al.*, 2011), while enabling the integration of renewable energy resources into the distribution system and improving the reliability of the in-situ networks (Morris *et al.*, 2011). The Microgrids can be connected to the grid or operate independently as an island model (Hirsch *et al.*, 2018). As a provider of distributed energy, microgrids play an essential part in improving building energy efficiency. It integrates distributed energy sources, energy storage devices and smart energy management systems (Hirsch *et al.*, 2018). In terms of power supply, there are three types of microgrids: AC, DC, and hybrid AC/DC (Angrisani *et al.*, 2020). Several studies on microgrids have focused on economic aspects and social benefits and the policy implications on microgrid deployment. Parhizi *et al.*, and their studies have included the economic factors, social benefits and policy implications on the microgrid deployment. According to Parhizi *et al.*, The cost of distributing renewable energy from microgrids is cheaper than buying electricity from the utility market. Furthermore, microgrids can generate electricity when market prices are high, and the reduction in electricity purchases means lower transmission and distribution costs (Parhizi *et al.*, 2015).

Since the conventional electricity distribution network is not designed for a large number of microgrids to be connected to the grid, the connection of a large number of smaller microgrids to the grid can cause many issues. Ustun *et al.* indicate that the challenge for microgrids is how these systems can be safely, consistently, reliably and efficiently connected to the grid (Ustun *et al.*, 2011).

The cost is probably the most significant challenge for deploying microgrids. Cost is possibly the primary constraint for installing a microgrid system, often microgrids are equipped with solar power systems, and the price of the solar system affects the affordability of the microgrid. However, according to Miller's report, while solar generation may not be economical in New Zealand at the moment, forecasts indicate that we are very close to the point where we will shortly experience rapid growth in renewable energy in New Zealand as the price of solar systems drops (Miller Allan, 2020) Therefore, the cost of a microgrid system can be reduced.

Besides the Microgrids' deployment, there are also researches on the environmental and technical aspects. The environmental aspect focuses on saving energy, reducing carbon emissions, and selecting or combining energy generation resources and energy storage systems to balance cost minimisation and carbon emission reduction (Anastasiadis *et al.*, 2018).

A critical function of the microgrid is to reduce carbon emissions. The increasing need for microgrids is that the government or our community is becoming more aware of the importance of reducing carbon emissions. Introducing microgrids with renewable energy will save energy and reduce carbon emissions. However, the question of how to accurately estimate energy use and how much carbon emissions are reduced before installing a microgrid remains a problem that needs to be solved (Li *et al.*, 2016).

Calculating carbon emissions requires taking into account various factors, such as electricity consumption and fuel consumption, and then calculating the carbon savings from renewable electricity generation based on the carbon emissions per kWh (Parhizi et al., 2015; Roslan et al., 2021).

Some studies have also mentioned carbon tax when investigating the relationship between carbon emission and microgrids. Anastasiadis et al. found that even in the presence of a carbon tax, owners of microgrids with renewable energy generation are still better off both in environmental terms and monetary terms (Anastasiadis et al., 2018).

The technical research focuses on microgrid devices, control systems, algorithm design and system optimisation. Inappropriate microgrid energy management systems can increase operating costs (Roslan et al., 2021). Parhizi et al. have pointed out that the microgrid system has two modes, islanded and grid-connected mode. It is also challenging to effectively switch between the two modes and control the Microgrid system. (Parhizi et al., 2015). For small microgrids, the seamless transition between grid and off-grid mode is challenging to achieve in a very short period (Soshinskaya et al., 2014).

However, a smart energy monitoring system integrated with an energy storage system can help to reduce energy consumption from the grid during peak demand (AlFaris et al., 2017). A complete energy management system for managing the devices in a microgrid should include the management of energy storage devices. The system should make its own decisions about whether to buy or sell electricity from the Grid (Zhang et al., 2013).

Smart monitoring systems are used to learn the energy consumption patterns or simulate energy consumption at the design phase and design a correct sized solar system and standby microgeneration systems (if needed). The system will automatically decide whether to sell the electricity back to the grid or store it in the battery during the operation. In addition, the smart system should determine if it should buy more energy and store it with the forecast of weather and households' daily routine. A suitable algorithm needs to be developed to make an optimal choice.

More than 80% of the electricity used in New Zealand is generated through renewable sources. And the problem with renewable energy generation is that they cannot guarantee a consistent supply throughout the year. The Ministry of Business, Innovation and Employment of New Zealand has indicated that it is worth noting that some renewable energy generation such as wind and solar, are intermittent and control the intermittent nature of renewable resources as part of New Zealand's power generation portfolio (Ministry of Business, Innovation and Employment 2020).

However, energy storage integrated microgrid systems can solve the conventional electricity distribution problem during the critical demand.

In addition to solving the problem of critical demand in electricity supply, microgrids are also vital to improve the resilience of the grid system in the event of extreme conditions. The microgrid is likely to still generate power when a natural disaster hits and the main power supply is interrupted. With climate change, the frequency of usually low-probability events is increasing, and microgrids are a potential solution to increase the resilience of the electricity supply system (Hussain et al., 2019).

Figure 2. (Department of Energy, 2015) shows the future grid systems; the aim is to make the Buildings as energy infrastructure, not passive consumers. Together with V2G (Vehicles to Grid) and VPP (virtual power plant structure), the overall system efficiency and reliability will be improved (Concept Consulting Group Ltd, 2016). The battery of an electric vehicle can be used as part of an energy storage device. In some cases, they can be fed back into the grid.

Musio *et al.*, also mention the concept of Vehicles to Grid (V2G) and Virtual power plant structure. According to Musio *et al.*, the virtual power plant structure(VPP) include distributed generators, energy storage and control systems (Musio *et al.*, 2010).

But on the other hand, if we look at the growth of electric cars, encouraged by government subsidies, it won't be long before most of us own them, and if they are connected to the grid at the same time, they will have a severe impact on the grid. That's why smart microgrids systems, controlled by the national grid, are the systems we need for the future.

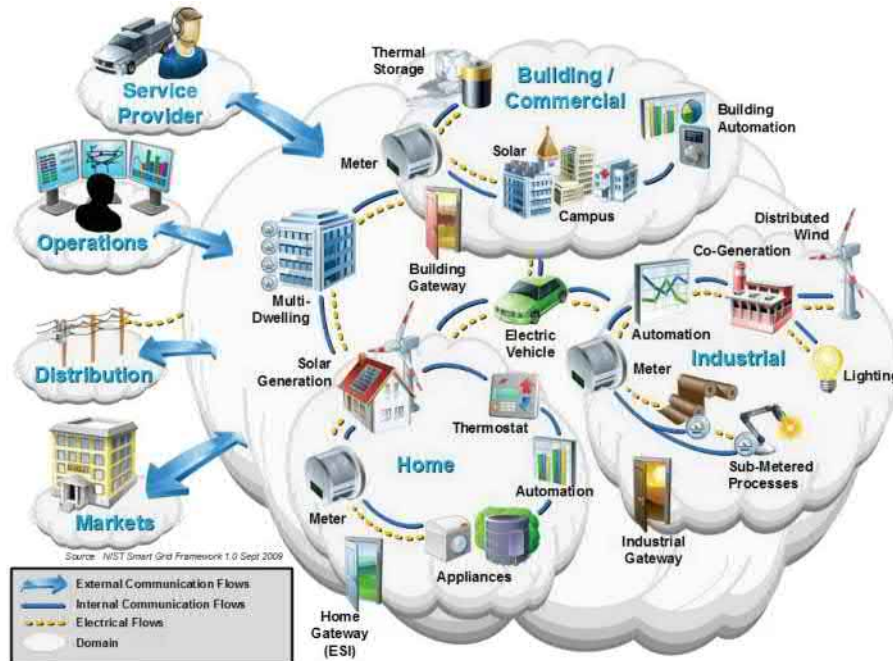


Figure 2. Future grid systems and smart building controls can communicate to improve overall system efficiency and reliability.

Research Methodology

A case study involving twelve different projects has been undertaken as part of this research. Four key parameters have been chosen for analysis, namely barriers, motivations, advantageous, and disadvantages. Common reasons for each type have been identified and categorised accordingly for further analysis.

The twelve projects used in the research are listed below:

1. Ports of Auckland-DC Microgrid Research Project
2. WEL Network will cost around NZ\$25 million to build a 35MW project in the Waikato District of New Zealand's upper North Island.
3. Solar micro-grids on the roofs of the Nelson workshops
4. First community microgrid in Auckland
5. The Renewable Energy Law Review: New Zealand
6. Solar Energy Future by Transpower
7. Vector PowerSmart projects, Watercare NZ's first 1 MW floating solar project

8. Research group: Smart Power and Renewable Energy Systems Group: Tackling renewable energy infrastructure challenges
9. University of Otago: Smart Grid, Green Power
10. University of Canterbury: Green grid
11. UOA project: Peer-to-Peer Transactive Energy Model for New Zealand Electricity Consumers
12. Community Resilience-Oriented Optimal Micro-Grid Capacity Expansion Planning: The Case of Totarabank Eco-Village, New Zealand

Motivation

- Zero Emissions and promote DC Microgrid.
- Improve resilience and support renewable generation uptake
- Reduce the power bills; Target for 100% renewable.
- To help strengthen the electricity supply in Kawakawa bay; Provide more reliable power for the Watercare wastewater system.
- The key drivers of policy reform in New Zealand are the government's commitments to 100% renewable generated electricity by 2030 and reduce all greenhouse gases (except biogenic methane) to 'net zero' by 2050
- The world is facing the prospect of global climate change while still hoping for advances in technology to slow this progression
- Land in Auckland at a premium, Watercare is constructing a floating 1 MWp PV array
- Implement new initiatives to reduce the effects of climate change drastically; Develop new electrical grid technologies so renewable energy methods can work more efficiently with current power grids
- Study the domestic power usage and future technologies; more energy generation methods are available
- To provide New Zealanders with access to reliable, safe, and affordable renewable energy
- Increasingly homes and businesses are equipped with PV, energy storage systems and EV's
- Increase energy resilience in the community against unplanned outage induced by equipment failure or extreme weather events

Findings and Discussions

Europe was an early leader in the development of microgrids. In Asia, Japan was an initial pioneer. South Korea, Singapore, and China have also developed microgrids in the last few years. The United States has become the leader in microgrids in recent years (Romankiewicz et al., 2014).

In New Zealand, the Auckland's largest grid company, Vector, also suggests that privately-owned microgrids can support communities on a small scale in emergencies. Investing in

microgrids is a cost-effective option to increase resilience (Vector, 2018). An exemplar effort by Vector is an installation of a 1MW/1.7MWh microgrid in Kawakawa Bay, a remote coastal location near Auckland, to improve the network's resilience in this area (Vector, 2018).

Based on data collected through interviews, the primary resistance to adopting Microgrids in New Zealand is the local networks. Although the electricity system follows the same regulation across New Zealand, the 29 local electricity distribution networks have different policies for microgrids connected to their electricity distribution network.

Microgrids' buy-back electricity rate is also a barrier to Microgrids' deployment. The New Zealand government does not provide subsidies for renewable energy generation. If the microgrid does not connect to the grid (island mode), the electricity buy-back rate is less critical. However, it is often the case that microgrids are connected to the grid because it does not require a big battery, thus reducing the setup cost. If a microgrid is entirely off-grid, more batteries, diesel generators or other means of backup will need to be installed.

Barriers

Based on the analysis, the barriers parameter can be classified into the following categories.

Technical Barrier

- DC appliances are not popular
- The current electrical grid uses alternating current (AC) technology, whereas many modern renewable energy technologies like solar and wind power, as well as other sustainable technology like electric vehicles, use direct current (DC).
- There are no long-term studies on floating solar farms, and the costs are relatively higher than the land-based solar farms. Also, the possible risks for the floating solar farm under extreme weather conditions is unclear.
- Increased variability in energy generation; potential power quality and congestion issues; low consumer engagement demand response

Financial Barrier

- The project's cost is relatively expensive; the life span of the batteries is only 20 years.
- The community needs to pay the initial capital investment

Policy Barrier

- The role of lines companies around the country is the critical barrier.
- The microgrid cannot supply power outside Kawakawa Bay
- Changing the energy policy to address the growing renewable energy sector is challenging. As in New Zealand, the energy policy framework has been relatively stable for 25 years.
- The barriers of using the blockchain architecture technology to develop the peer-to-peer transactive energy model are not only from the technology part. The energy retailers and line companies, as well as other existing stakeholders, are the primary resistance.

Others

- There are many myths and misconceptions about solar technology; for example, New Zealand isn't sunny enough for solar; Solar will make the power system unmanageable, etc.
- The domestic demand and how it may change in the future is not clearly understood.

Pros and Cons

Like all of other new technologies, Microgrids also has its own advantage and disadvantages. Although it helps to increase the power distribution efficiency and resilience, it does have some technical and political challenges.

Pros

- Reduce energy loss in the conversion process
- New Zealand's first utility-scale battery energy storage system (BESS); Improve network resilience
- Generate solar power becomes cheaper than buying it from the grid.
- The microgrid system is capable of providing additional support to the Watercare's wastewater vacuum pump station at Kawakawa Bay
- Energy policy reform will help with promoting more renewable generation.
- Falling costs and improving technology lead to global adoption of both distributed and utility solar.
- Avoid using valuable land; power approximately 200 homes or achieve a quarter of the Rosedale wastewater treatment plant's energy needs
- A partial transition of our electrical grid to DC would solve several issues with electricity generation more broadly and make it easier to use renewable energy technology.
- More control and much more subtlety in controlling power usage at peak times
- Market insights for current demands and trends; Industry Standard recommendations; various calculation model making
- Transactive energy is the emerging area of Power systems economics
- The microgrid is economically feasible over a 25-year life cycle; increased energy resilience.

Cons

- DC Appliances are not mainstream. Change to DC appliances will incur costs.
- Expensive, 25Million for 35MW BESS, Life span only 20 years
- There are no government subsidies for installing solar systems; The energy industry push-back towards renewables.
- The Battery Energy storage system is not very reliable.
- How the energy policy should change is not answered.
- The cost of solar generation is not as low as wind generation, especially in winter.
- The cost and durability of the floating solar farm might be a problem. The running cost of the floating solar farm is higher than the general solar farm.
- Creating a partial AC and partial DC electrical grid is pretty challenging. The outcome is unknown.
- The simulations developed by researchers might not present the correct future scenarios
- Modelling and in-depth knowledge of electricity networks and power management won't ensure new Zealander's access to reliable, safe, and affordable renewable energy.

- The research didn't consider the line companies, energy retailers, and other existing players.
- High wind, low solar regions is not cost-optimal

Results

By analysing the twelve projects, the barriers fall into four categories. The most significant barriers are the cost. Other barriers include the role of line companies, the energy policy, and technologies.

The motivations of the twelve projects are in three categories as well. They are: reduce carbon emission, increase renewable energy uptake and improve the resilience of the power supply.

Regarding the pros, improving the network resilience is the main benefit, the second advantage is the reduction in the electricity cost, and the third one is control over the grid and electricity usage.

Concerning the disadvantages, the major one is the cost issue. Cost is the main reason preventing the deployment of microgrid systems. Another downside is that the new systems and technologies may not be reliable, and the system's life span may not be long enough to make the system economically viable.

Conclusion

Future research needs to be done on virtual grids, including how the local network controls the devices within the microgrids, charging and even discharging the devices and regulating the electricity supply of critical demand.

Although many issues and challenges need to be addressed with the Microgrid system, microgrids also have opportunities. Promoting microgrid systems will help New Zealand to achieve its emission reduction goal. Also, if the reduction in the carbon footprint of each microgrid system can be quantified, it will help the New Zealand government or power companies to trade carbon credit more conveniently.

References

- AlFaris, F., Juaidi, A., & Manzano-Agugliaro, F. (2017) Intelligent homes' technologies to optimise the energy performance for the net-zero energy home, *In Energy and Buildings*, 153, p 262–274.
- Anastasiadis, A., Konstantinopoulos, S., Kondylis, G., Vokas, G. A., & Salame, M. J. (2018) Carbon tax, system marginal price and environmental policies on Smart Microgrid operation. *Management of Environmental Quality: An International Journal*, 29(1), p76–88.
- Angrisani, L., Arteaga, M., Bijaya Ketan Panigrahi, M., Kay Chen, T., Khamis, A., University in Egypt El Tagamo El Khames, G., Cairo City, N., Torsten Kroeger, E., Liang, Q., Martin, F., Cher Ming, T., Möller, S., Lab, U., Berlin, T., Subhas Mukhopadhyay, G., Ning, C.-Z., Nishida, T., Pascucci, F., & Woon Seng, G. (2020) *Microgrid: Operation, Control, Monitoring and Protection*. <http://www.springer.com/series/7818>
- Anton Trixl. (2021) *The Renewable Energy Law Review: New Zealand*. Available at: <https://thelawreviews.co.uk/title/the-renewable-energy-law-review/new-zealand>
- Auckland Council. (2018) *Becoming a Low Carbon Community An Action Plan*. Available at: <https://www.aucklandcouncil.govt.nz/about-auckland-council/how-auckland-council-works/local-boards/all-local-boards/whau-local-board/Documents/whau-becoming-low-carbon-community.pdf>
- Concept Consulting Group Ltd. (2016) *Electric cars, solar panels, and batteries in New Zealand Vol 2: The benefits and costs to consumers and society*. Available at: www.concept.co.nz

- Department of Energy, U. (2015) *AN ASSESSMENT OF ENERGY TECHNOLOGIES AND RESEARCH OPPORTUNITIES Chapter 5: Increasing Efficiency of Building Systems and Technologies*. Available at: [Chapter 5 — Increasing Efficiency of Buildings Systems and Technologies | Department of Energy](#)
- Fu, Y., Liu, X., & Yuan, Z. (2015) Lifecycle assessment of multi-crystalline photovoltaic (PV) systems in China. *Journal of Cleaner Production*, 86, p180–190. <https://doi.org/10.1016/j.jclepro.2014.07.057>
- Hirsch, A., Parag, Y., & Guerrero, J. (2018) Microgrids: A review of technologies, key drivers, and outstanding issues. In *Renewable and Sustainable Energy Reviews*, 90, p402–411. Elsevier Ltd. <https://doi.org/10.1016/j.rser.2018.03.040>
- Hobson, K., Hamilton, J., & Mayne, R. (2016) Monitoring and evaluation in UK low-carbon community groups: benefits, barriers and the politics of the local. *Local Environment*, 21(1), p124–136. Available at: <https://doi.org/10.1080/13549839.2014.928814>
- Hussain, A., Bui, V. H., & Kim, H. M. (2019) Microgrids as a resilience resource and strategies used by microgrids for enhancing resilience. In *Applied Energy*, 240, p56–72. Available at: <https://doi.org/10.1016/j.apenergy.2019.02.055>
- Khan, F. I., Hawboldt, K., & Iqbal, M. T. (2005) Life Cycle Analysis of wind-fuel cell integrated system. *Renewable Energy*, 30(2), p157–177. Available at: <https://doi.org/10.1016/j.renene.2004.05.009>
- Kolokotsa, D. (2016) The role of smart grids in the building sector. In *Energy and Buildings*, 116, p703–708. Available at: <https://doi.org/10.1016/j.enbuild.2015.12.033>
- Landscape Architecture Aotearoa. (2020) *New Zealand's first green, climate-resistant communities named*. Available at: <https://architecturenow.co.nz/articles/new-zealands-first-green-climate-resistant-communities-named/>
- Li, M., Zhang, X., Li, G., & Jiang, C. (2016) A feasibility study of microgrids for reducing energy use and GHG emissions in an industrial application. *Applied Energy*, 176, p138–148. Available at: <https://doi.org/10.1016/j.apenergy.2016.05.070>
- Miller Allan. (2020) *Economics of Utility-Scale Solar in Aotearoa New Zealand*. Available at: www.millercl.co.nz
- Ministry of Business, I. & E. (2020) *Energy in New Zealand*. Available at: <https://www.mbie.govt.nz/dmsdocument/11679-energy-in-new-zealand-2020>
- Moloney, S., Horne, R. E., & Fien, J. (2010) Transitioning to low carbon communities-from behaviour change to systemic change: Lessons from Australia. *Energy Policy*, 38(12), p7614–7623. Available at: <https://doi.org/10.1016/j.enpol.2009.06.058>
- Morris, G. Y., Abbey, C., Joos, G., Marnay, C., & Lawrence, E. O. (2011) *A Framework for the Evaluation of the Cost and Benefits of Microgrids Environmental Energy Technologies Division presented at the CIGRÉ International Symposium, The electric power system of the future-Integrating supergrids and microgrids*. Available at: <http://eetd.lbl.gov/EA/EMP/emp-pubs.html>
- Musio, M., Lombardi, P., & Damiano, A. (2010) Vehicles to grid (V2G) concept applied to a virtual power plant structure. *19th International Conference on Electrical Machines, ICEM 2010*. Available at: <https://doi.org/10.1109/ICELMACH.2010.5608261>
- Parhizi, S., Lotfi, H., Khodaei, A., & Bahramirad, S. (2015) State of the art in research on microgrids: A review. In *IEEE Access*, 3, p 890–925. Institute of Electrical and Electronics Engineers Inc. Available at: <https://doi.org/10.1109/ACCESS.2015.2443119>
- Romankiewicz, J., Marnay, C., Zhou, N., & Qu, M. (2014) Lessons from international experience for China's microgrid demonstration program. *Energy Policy*, 67, p198–208. Available at: <https://doi.org/10.1016/j.enpol.2013.11.059>
- Roslan, M. F., Hannan, M. A., Jern Ker, P., Begum, R. A., Indra Mahlia, T. M., & Dong, Z. Y. (2021) Scheduling controller for microgrids energy management system using optimisation algorithm in achieving cost saving and emission reduction. *Applied Energy*, 292. Available at: <https://doi.org/10.1016/j.apenergy.2021.116883>
- Soshinskaya, M., Crijns-Graus, W. H. J., Guerrero, J. M., & Vazquez, J. C. (2014) Microgrids: Experiences, barriers and success factors. In *Renewable and Sustainable Energy Reviews*, 40, p659–672. Elsevier Ltd. Available at: <https://doi.org/10.1016/j.rser.2014.07.198>
- Ustun, T. S., Ozansoy, C., & Zayegh, A. (2011) Recent developments in microgrids and example cases around the world - A review. In *Renewable and Sustainable Energy Reviews*, 15(8), p4030–4041. Elsevier Ltd. Available at: <https://doi.org/10.1016/j.rser.2011.07.033>
- Vector. (2018) *Working together on resilience*. Available at: <https://blob-static.vector.co.nz/blob/vector/media/vector/working-together-on-resilience.pdf>
- Vickers, J., Fisher, B., & Nebel, B. (2018) *Hotspot or not? Title: The carbon footprint of New Zealand's built environment: hotspot or not?* Available at: www.thinkstep-anz.com
- Wang, N., Phelan, P. E., Gonzalez, J., Harris, C., Henze, G., Hutchinson, R., Langevin, J., Lazarus, M. A., Nelson, B., Pyke, C., Roth, K., Rouse, D., Sawyer, K., & Selkowitz, S. (2017) *Ten questions concerning future buildings beyond zero energy and carbon neutrality*. Available at: <http://www.elsevier.com/open-access/userlicense/1.0/>

- Zhang, D., Shah, N., & Papageorgiou, L. G. (2013) Efficient energy consumption and operation management in a smart building with microgrid. *Energy Conversion and Management*, 74, p209–222. Available at: <https://doi.org/10.1016/j.enconman.2013.04.038>
- Zia, M. F., Elbouchikhi, E., & Benbouzid, M. (2018) Microgrids energy management systems: A critical review on methods, solutions, and prospects. In *Applied Energy*, 222, p1033–1055). Elsevier Ltd. Available at: <https://doi.org/10.1016/j.apenergy.2018.04.103>

Extended Abstracts

Real-Time Project Productivity Tracking System: Practical Case in Smart Construction Projects

Kambiz Radman, School of Built Environment, Massey University, Auckland, New Zealand.

Dr. Mostafa Babaeian Jelodar, School of Built Environment, Massey University, Auckland, New Zealand.

Dr. Ruggiero Lovreglio, School of Built Environment, Massey University, Auckland, New Zealand.

Prof. Suzanne Wilkinson, School of Built Environment, Massey University, Auckland, New Zealand.

Dr. Eghbal Ghazizadeh, Enterprise Security Tech Lead, Mercury, Auckland, New Zealand.

SYNOPSIS

The productivity and progress tracking systems are currently used in construction projects to acquire the site works data and converting to various digital reports. To date, capturing and transferring data processes are slow or inefficient because significant human errors occur in the process. Therefore, project managers can omit critical information, and no timely decision can be made related to delay and unproductivity.

The purpose of this paper is to encompass a real-time project productivity tracking system to register data and manage delays related to an Electrical and Instrument service trade involved in smart construction projects in New Zealand. The paper aimed to review industries delay reports, use expert judgment experience, and compare the proposed method with current ones.

The finding shows the proposed method uses a combination of smartphone and Ms Project real-time monitoring software to optimise the current site reporting procedure and workflow of productivity managing. The presented method should help construction decision-makers enhance time and cost-effectiveness and manage delay better alongside more effective decisions. Meanwhile, hours booked to collect data and update programs and models dropped by 24%.

KEYWORDS: Real-Time, Smart Device, Productivity, Smart Construction, Tracking System

INTRODUCTION

Generally, the project life cycle involves five (5) distinct phases: initiation, planning, execution, monitoring, and closure that combine to turn a project charter into a working product (Aronés, Mendoza, Rodriguez, & Ramirez, 2019). The monitoring phase must coordinate different areas such as design, procurement, logistic, and installation (resources, materials, equipment) from time and cost. The traditional progress tracking method collects the field information manually, mainly through meetings, and the captured ones are formatted to digital versions like spreadsheets. However, this activity is time-consuming with low productivity and, most of the time, causing delays and site job reworking, in other words, accuracy and fast delivery of data and information, leading to uncertainties for project decision-makers (Alizadehsalehi & Yitmen, 2021). Generally, once project decision-makers do not get timely site jobs information during the implementation phase, unsolved issues and potential delays will delay the project (Salehi & Yitmen, 2018). Many proposed productivity tracking solutions have been presented in previous literature, such as BIM, videogrammetry, laser scanner, photogrammetry, and combined solutions (e.g. RFID and laser scanner; RFID and photogrammetry). The studies show data acquisition time by using these solutions is reduced to 50% (Radman, Babaeian Jelodar, Ghazizadeh, & Wilkinson, 2021; You & Wu, 2019).

Likewise, studies show that combining the mentioned technologies improves data accuracy in the different phases of the construction project. General speaking, the role of technologies in reducing errors and reworks in projects and constructing a project management approach for timely decision-making is significantly considered (Khoshnava et al., 2020; Xu, Chong, & Liao, 2019). While previous literature presents various applications and solutions in progress tracking systems, this study aims to optimise project stockholders time in terms of the collection data and preparation of analytical decisions at the right time and with the right people (You & Feng, 2020; You & Wu, 2019).

RESEARCH AIM AND OBJECTIVES

This study aims to present a method for construction project decision-makers who will decide timely. Meanwhile, hours booked to collect data and update programmes and models dropped by 24%.

RESEARCH METHODS

The methodology for this study is collecting data from those construction projects that come to value over \$500 million, smart category (e.g., using at least one IoT based technology) and Electrical and Instrument service trade involved. To achieve our aim, using a before and after data flow diagram (DFD) is required (Table 1). This technique evaluates comparison between data acquisition applications on the smart thin devices such as SiteDoc, WhatsApp, Ms Teams. However, the analytical matrix will present the time of those consuming to collect data and transfer to end users such as planners and project managers to update the Ms Project program and make timely decisions.

Table 1: Before and after DFD

Step	Before (current)			After (Proposed)	
1	Engineering team →	Create Drawings	Current By App	Engineering team →	Create Drawings
2	Supervisors →	Review Drawing for changes		Supervisors → Review	Drawing for changes
3	Site team →	Implementing drawings		Site team →	Implementing drawings
4	Planner →	Collecting progress % for each phase and tasks		Planner →	collecting progress % with any changes and real-time critical issues
5	Planner →	Classify %		Planner →	create the classified and analytical reports
6	Planner →	Create an analytical report		Project manager →	Make decision
7	Project manager →	Make decision			

A general view through Table 1 shows the proposed process has saved one step more while using App in step 4. It means the project manager can decide a bit earlier than before.

PRELIMINARY FINDINGS

The finding shows the proposed method uses a combination of smart thin devices and Ms Project real-time monitoring software to optimise the current site reporting procedure and workflow of productivity managing. To achieve this goal, the current study has structured a simple process (Figure 1): a) identify the current process of data collection into case studies; b) classify the type of data and their importance; c) find gaps and re-structure the current one; d) create an evaluation matrix to measure accuracy and accurate timing of data accusation tools used in this research.



Figure 1: The proposed method process

RESEARCH SIGNIFICANCE

The presented method should help construction decision-makers enhance time and cost-effectiveness and manage delays better alongside more effective decisions. Meanwhile, hours booked to collect data and update programmes and models dropped by 24% (Table 2). Accordingly, the proposed method results compare times into construction projects before and after using the method (Figure 2). This one can be segregated into two stages: data collection and report preparation, making a strategic decision.

Table 2: Average of Time Comparison between Current and proposed methods

Stage	Current method	Proposed method
Data collection	3.1	2.4
Preparing Strategic reports	2.4	1.8
Total (h)	5.5	4.2 (24% saved)

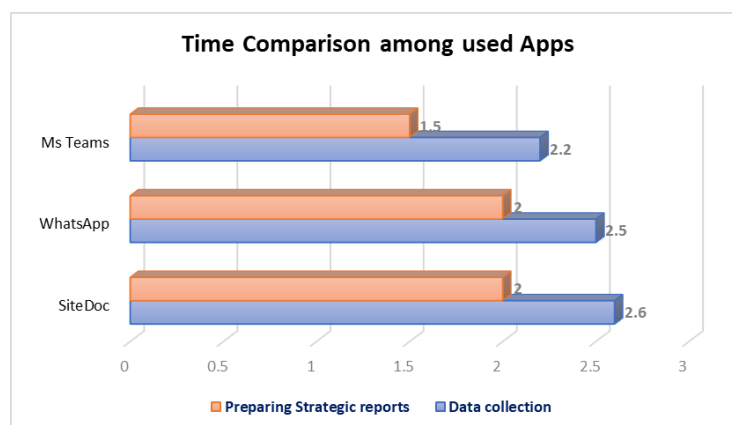


Figure 2: Time Comparison among used Apps

REFERENCES

- Alizadehsalehi, S., & Yitmen, I. (2021). Digital twin-based progress monitoring management model through reality capture to extended reality technologies (DRX). *Smart and Sustainable Built Environment*.
- Aronés, M., Mendoza, A., Rodriguez, S., & Ramirez, H. (2019). *Use of Data Acquisition Technologies to Optimise Construction Progress Monitoring Times in Residential Buildings*. Paper presented at the Brazilian Technology Symposium.
- Khoshnava, S. M., Rostami, R., Zin, R. M., Mishra, A. R., Rani, P., Mardani, A., & Alrasheedi, M. (2020). Assessing the impact of construction industry stakeholders on workers' unsafe behaviours using extended decision making approach. *Automation in Construction*, 118, 103162.
- Radman, K., Babaeian Jelodar, M., Ghazizadeh, E., & Wilkinson, S. (2021). Causes of Delay in Smart and Complex Construction Projects. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, 13(4), 05021006.
- Salehi, S. A., & Yitmen, I. (2018). Modeling and analysis of the impact of BIM-based field data capturing technologies on automated construction progress monitoring. *International Journal of Civil Engineering*, 16(12), 1669-1685.
- Xu, Q., Chong, H.-Y., & Liao, P.-C. (2019). Collaborative information integration for construction safety monitoring. *Automation in Construction*, 102, 120-134.
- You, Z., & Feng, L. (2020). Integration of industry 4.0 related technologies in construction industry: a framework of cyber-physical system. *IEEE Access*, 8, 122908-122922.
- You, Z., & Wu, C. (2019). A framework for data-driven informatisation of the construction company. *Advanced Engineering Informatics*, 39, 269-277.

Toward Improving Capacity and Capability of Prefabrication Construction in New Zealand's Construction Sector

Nazanin Kordestani Ghalenoei, School of Built Environment, Massey University, New Zealand.

Mostafa Babaeian Jelodar, School of Built Environment, Massey University, New Zealand.

Daniel Paes, School of Built Environment, Massey University, New Zealand.

Monty Sutrisna, School of Built Environment, Massey University, New Zealand.

SYNOPSIS

The construction sector has been a significant contributor to New Zealand's (NZ) economy; however, it still suffers from poor productivity, significant worker turnover, lack of skilled workforce, and innovation. In the face of these challenges, prefabrication as a new method has been implemented to meet the increased construction demand. Despite its benefits, the NZ construction sector has yet to leverage such a method to its full extent. While some studies have been carried out on the industry's capacity and capability, there is still very little information regarding the potential capacity versus the status. Therefore, this paper investigated the difference between potential capacity and current status in prefabrication to figure out the solutions to reduce this difference.

Data will be collected through industry reports and focus group sessions with industry experts. Results included classified factors that showed the reasons for not using the total capacity, insights on how much the sector could expand given its actual capacity, and the expenditure necessary to meet its demand. Findings provided an in-depth understanding of prefabrication current capacity in NZ. They assisted the industry in identifying the needs for implementing the solutions to improve the sector's ability and capability of prefabrication.

KEYWORDS: Capability, Capacity, Construction sector, New Zealand, Prefabrication.

INTRODUCTION

Like other countries, the construction industry in New Zealand has a significant impact on Gross Domestic Product (GDP) (Rice & Forgan, 2016), as in 2017, the construction industry contributed 6% of NZ's GDP (PrefabNZ, 2018a). The population of New Zealand (NZ) has risen dramatically in the last fifty years, and this trend is expected to continue at least until the second part of this century (Miller, 2017). Due to the growing number of populations, the need for urgent houses has been in demand (PrefabNZ, 2018b) and prefabrication is a solution to this crisis (Mirus, Patel, & McPherson, 2018; PrefabNZ, 2018a; Razkenari, Fenner, Shojaei, Hakim, & Kibert, 2020). Prefabrication is a construction method that involves fabricating building components in a factory before assembling them on the job site (Tam, Tam, Zeng, & Ng, 2007). Although prefabrication has the vast majority of benefits for buyers and builders, some challenges hampered its development (Gan, Chang, Zuo, Wen, & Zillante, 2018; Hong, Shen, Li, Zhang, & Zhang, 2018). Based on the research by BRANZ in NZ, 2.95 billion of prefabrication occurs, but the industry can do around 5 billion dollars each year (Page & Norman, 2014). Different types of prefabrication may have different uses and available capacities. For example, 77% of the component's capacities are used, and only 23% are left.

This number for the panel is 79 percent available and 23% used, which shows that lots of capacity are remaining. For complete building, the current capacity is 1200 per year (56%), while the actual capacity can be 3000 to 4000 houses per year (PrefabNZ, 2018a). A closer look at these numbers will illustrate some factors that make challenges to achieving the total capacity and capability in prefabrication. Although the importance of prefabrication, few studies have investigated the mentioned topic in NZ. Therefore, this study aims' are presented in the next section.

RESEARCH AIM AND OBJECTIVES

This study aims to identify and evaluate the factors that cause problems for actual capacity and capability in prefabrication and provide solutions to promote it. The key objectives include a) Identify and classify the challenges for capacity and capability in prefabrication in the New Zealand construction industry to find out the differences for actual and used capacity and capability; b) Evaluating the classified challenges through focus group among industry experts; c) Providing a framework for capacity and capability solution activities.

RESEARCH METHODS

A two-step approach is being used to achieve the study objectives. First, a review of the published industry reports in the NZ construction industry regarding prefabrication. Then, NVIVO 12 will be used to help the author to classify the challenges. Character-based coding, rich text capabilities, and multimedia functionality are essential aspects for qualitative data handling in NVivo (Zamawe, 2015). The next step will be conducting the focus group sessions with NZ experts to find out what solutions may be applicable to mitigate the challenges for full achievement in capacity and capability in prefabrication. The researcher can obtain a deep understanding of the subject by using a focus group. Rather than a statistically representative sample of a larger population, the method tries to acquire data from a purposefully selected group of individuals (O. Nyumba, Wilson, Derrick, & Mukherjee, 2018). As the experts are more familiar with the industry than anyone, the focus group will help the authors gain comprehensive data.

ANTICIPATED FINDINGS

Expected results are depicted in Figure 1 below. By reviewing the industry report, including statistics about the current usage of prefabrication, the current capacity and required, and the challenges that industry deals with in the New Zealand construction sector. The data from this step will be groups of challenges. Then focus group sessions will be done to figure out the solutions and strategies to solve the categorized challenges. The final result will help the industry decrease the challenges to improve the capacity and capability for prefabrication in New Zealand.

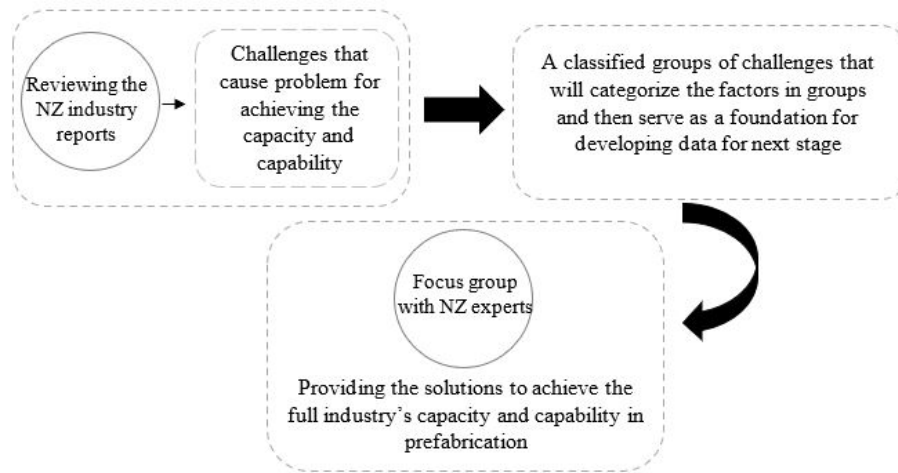


Figure 1: Anticipated research findings

RESEARCH SIGNIFICANCE

This study provides support to leveraging prefabrication in New Zealand. Findings can assist industry practitioners in better identifying and understanding their need for prefabrication development in New Zealand and beyond. Moreover, improvements in the prefabrication status will be possible through applying the solutions and strategies.

REFERENCES

- Gan, X., Chang, R., Zuo, J., Wen, T., & Zillante, G. (2018). Barriers to the transition towards off-site construction in China: An Interpretive structural modeling approach. *Journal of Cleaner Production*, 197, 8-18.
- Hong, J., Shen, G. Q., Li, Z., Zhang, B., & Zhang, W. (2018). Barriers to promoting prefabricated construction in China: A cost-benefit analysis. *Journal of Cleaner Production*, 172, 649-660.
- Miller, C. (2017). MBIE figures show nationwide housing shortage of 71,000. *NZ Herald, NZ Herald, New Zealand*.
- Mirus, A., Patel, Y., & McPherson, P. (2018). Prefabrication: New Zealand's golden ticket?
- O. Nyumba, T., Wilson, K., Derrick, C. J., & Mukherjee, N. (2018). The use of focus group discussion methodology: Insights from two decades of application in conservation. *Methods in Ecology and evolution*, 9(1), 20-32.
- Page, I. C., & Norman, D. (2014). *Prefabrication and standardisation potential in buildings*: Branz.
- PrefabNZ. (2018a). *CAPACITY AND CAPABILITY Report*. Retrieved from Retrieved from New Zealand:
- PrefabNZ. (2018b). *PREFAB ROADMAP: A WAY FORWARD for PREFABRICATION in NEW ZEALAND (2013-2018)*. Retrieved from Retrieved from New Zealand:
- Razkenari, M., Fenner, A., Shojaei, A., Hakim, H., & Kibert, C. (2020). Perceptions of offsite construction in the United States: An investigation of current practices. *Journal of Building Engineering*, 29, 101138.
- Rice, C., & Forgan, R. (2016). *Valuing the role of construction in the New Zealand economy*. Retrieved from New Zealand:
- Tam, V. W., Tam, C. M., Zeng, S., & Ng, W. C. (2007). Towards adoption of prefabrication in construction. *Building and environment*, 42(10), 3642-3654.
- Zamawe, F. C. (2015). The implication of using NVivo software in qualitative data analysis: Evidence-based reflections. *Malawi Medical Journal*, 27(1), 13-15.

The Worst-Case Scenario in Mass Urban Evacuation

Azin Fathianpour, School of Built Environment, Massey University, New Zealand.

Dr Mostafa Babaeian, School of Built Environment, Massey University, New Zealand.

Professor Suzanne Wilkinson, School of Built Environment, Massey University, New Zealand.

Dr Barry Evans, University of Exeter, UK.

SYNOPSIS

Tsunami is a highly destructive disaster that requires a comprehensive preparation and mitigation plan. Evacuation simulation models can be used as an effective measure for getting prepared and providing a reliable evacuation plan. Although various studies revolve around evacuation simulations, there is still room for improvement to make these models more realistic.

Different factors such as the earthquake centre, the population distribution, traffic jams during the event and individuals' behaviour can significantly influence the accuracy of the simulation's outcome. The first and foremost stage in evacuation simulation is to determine the circumstances. Depending on how the scenario is defined, the model could be either under or overestimated. Hence, to have a model capable of formulating evacuation protocols, the worst-case scenario needs to be taken into account. Therefore, finding the critical scenario is a vital step in any simulation model.

The main focus of this study is developing a method to identify the worst-case scenario for tsunami evacuation. First, the influential factors provided in the international literature review is outlined. Accordingly, a model containing the features for predicting the worst-case scenario is developed. The worst-case scenario of tsunami evacuation is identified by applying the model to Napier City as the case study. The results of this study could contribute toward boosting New Zealand cities' capability to cope with disasters.

INTRODUCTION

Natural hazards will disrupt human lives in many manners. A tsunami is a disaster that makes everyone in the inundation zone leave its place for higher ground. Hence, there is a need to get prepared beforehand. Evacuation simulations have been proved to have a productive contribution to tsunami preparedness (Tomoyuki Takabatake et al., 2020). The imagined scenario in evacuation planning plays a significant role in decision-making (Chen et al., 2019). In recent years there have been attempts to consider environmental attributes in evacuation simulation. However, the literature review has found an evident lack of considering a combination of spatial and social factors in their assumptions in the simulation models.

Earthquake centre and severity

The local source tsunami would cause the worst-case scenario since people should at the same time deal with the debris of an intensive earthquake as well as try to reach a safe zone in the short time until the area is inundated. Hence, the stronger and closer earthquake would lead to a harder evacuation scenario for individuals (Nirupama, 2009).

Population Distribution

Due to a long and strong earthquake, individuals in a tsunami evacuation zone are deemed to evacuate to high-ground levels. Therefore, the location individuals are located is a critical factor in evacuation planning and urban planning (Harnantyari et al., 2020). Beban and Fraser (2012) highlighted that it is possible to reduce the evacuation distance by placing new residential developments in minimum tsunami risk areas or near a safe tsunami zone, resulting in minimising the evacuation travel distance.

Traffic Jam

The traffic congestion is one of the critical obstacles to evacuation process. The vehicle by itself and the direction it travels would reduce the movement speed and even cause road blockage (T. Takabatake et al., 2020). The data that is normally collected in traffic management teams are mostly, the Average Daily Traffic (ADT) count, which depicts traffic flows as a singular value passing a given count location within 24 hours. However, traffic flows tend to vary over time, commonly consisting of two rush hour periods (one in the morning and one in the evening) that correspond to people travelling to and from their places of work. Via analysis of different states across the United States Hallenbeck et al. (1997) derived a dataset that depicts the percentage of traffic expected to be observed throughout the day with respect to their ADT values, with the data showing peak flows around 8:00 am and 4:00 pm, respectively (Figure 1).

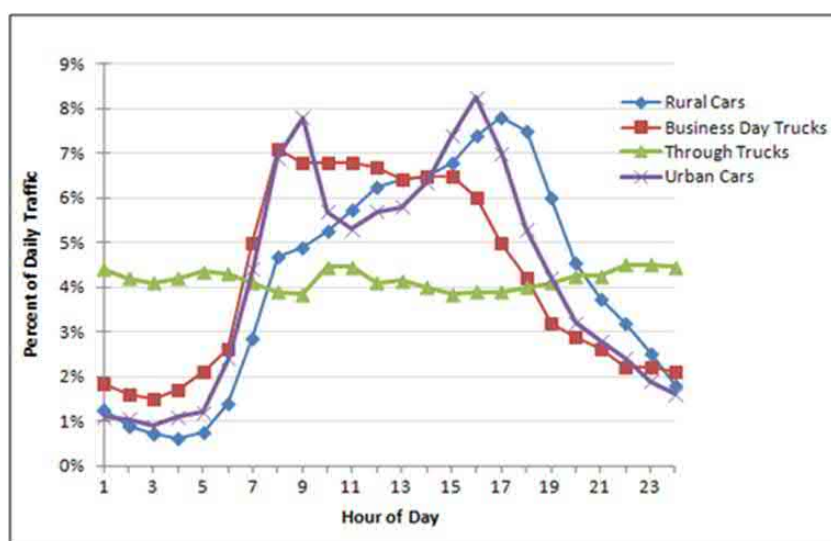


Figure 1. Distribution of Daily Traffic Flows (Hallenbeck et al. (1997))

Individual Behaviour

Each individual's behaviour depends on various factors, such as level of hazard awareness and preparedness (Arce et al., 2017), their familiarity with the evacuation plan, and their capability to deploy the protocols (Sun & Sun, 2019). Haghani et al. (2020) considered group behaviour for families, and Takabatake et al. (2018) evaluated a preparation time for residents to get out of the building.

RESEARCH AIM AND OBJECTIVES

This study aims to identify what would the worst-case scenario look like in a local-source tsunami event. The result would be used to simulate the scenario and provide improvement options for raising the survival rate accordingly.

RESEARCH METHODS

The worst-case scenario is identified through a narrative literature review (Pautasso, 2019). This method critiques the literature and summarises the literature to draw a clear conclusion about the topic.

ANTICIPATED (OR PRELIMINARY) FINDINGS

As no real data for hourly traffic flow distribution was available, this study looked to redistribute the ADT values over the day utilising reference data from another source. Utilising this graphical information as a reference, the ADT values for urban traffic within Napier were redistributed accordingly over the 24 hour period to provide an approximation of predicted traffic volume variations expected during the day. This data would be used in simulation as a benchmark of the normal condition. Hence, the survival rate during a tsunami could be evaluated by considering this scenario.

RESEARCH SIGNIFICANCE

The result of this study will be used in further policy draftings and would make a more realistic vision for the decision-makers.

REFERENCES

- Arce, R. S. C., Onuki, M., Esteban, M., & Shibayama, T. (2017). Risk awareness and intended tsunami evacuation behaviour of international tourists in Kamakura City, Japan. *International Journal of Disaster Risk Reduction*, 23, 178-192. <https://doi.org/https://doi.org/10.1016/j.ijdr.2017.04.005>
- Beban, J. G., & Fraser, S. (2012). *Modelling of the evacuation rates required to achieve an acceptable level of health and safety risk in Te Tumu from the Variation to the Southern Kermadec Scenario*.
- Chen, J., Yu, J., Wen, J., Zhang, C., Yin, Z. e., Wu, J., & Yao, S. (2019). Pre-evacuation time estimation based emergency evacuation simulation in urban residential communities. *International journal of environmental research and public health*, 16(23), 4599.
- Haghani, M., Sarvi, M., & Shahhoseini, Z. (2020). Evacuation behaviour of crowds under high and low levels of urgency: Experiments of reaction time, exit choice and exit-choice adaptation. *Safety science*, 126, 104679. <https://doi.org/https://doi.org/10.1016/j.ssci.2020.104679>
- Hallenbeck, M., Rice, M., Smith, B., Cornell-Martinez, C., & Wilkinson, J. (1997). *Vehicle volume distributions by classification*.
- Harnantyar, A. S., Takabatake, T., Esteban, M., Valenzuela, P., Nishida, Y., Shibayama, T., Achiari, H., Marzuki, A. G., Marzuki, M. F. H., & Aránguiz, R. (2020). Tsunami awareness and evacuation behaviour during the 2018 Sulawesi Earthquake tsunami. *International Journal of Disaster Risk Reduction*, 43, 101389.
- Nirupama, N. (2009). Analysis of the global tsunami data for vulnerability and risk assessment. *Natural hazards*, 48(1), 11-16. <https://doi.org/10.1007/s11069-008-9243-5>
- Pautasso, M. (2019). The Structure and Conduct of a Narrative Literature Review. In *A Guide to the Scientific Career* (pp. 299-310). <https://doi.org/https://doi.org/10.1002/9781118907283.ch31>
- Sun, Y., & Sun, J. (2019). Perception, preparedness, and response to tsunami risks in an aging society: Evidence from Japan. *Safety science*, 118, 466-474.

7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM
Creating Capacity and Capability for the Future of the Built Environment

- Takabatake, T., Fujisawa, K., Esteban, M., & Shibayama, T. (2020). Simulated effectiveness of a car evacuation from a tsunami. *International Journal of Disaster Risk Reduction*, 47, 101532.
- Takabatake, T., Nistor, I., & St-Germain, P. (2020). Tsunami evacuation simulation for the District of Tofino, Vancouver Island, Canada [Article]. *International Journal of Disaster Risk Reduction*, 48, Article 101573. <https://doi.org/10.1016/j.ijdr.2020.101573>
- Takabatake, T., Shibayama, T., Esteban, M., & Ishii, H. (2018). Advanced casualty estimation based on tsunami evacuation intended behavior: case study at Yuigahama Beach, Kamakura, Japan. *Natural hazards*, 92(3), 1763-1788. <https://doi.org/10.1007/s11069-018-3277-0>

Sustainable Transitions in Removal of Toxic Chemicals from Construction Materials and Waste: A Preliminary Theoretical Framework

Dr Emina Kristina Petrović, Victoria University of Wellington, New Zealand.

SYNOPSIS

As we reach international consensus that climate action is needed, the challenge remains how to drive the actual implementation of change. When it comes to carbon considerations, planetary impacts from the construction industry are recognised as significant. However, when it comes to the potential toxicity found in construction materials and waste there is still a need to increase recognition and accelerate change. Currently, it remains unclear how to drive and especially accelerate pro-sustainable change in construction, especially in the areas which are less recognised as a problem, like removal of toxicity from construction materials and waste.

The aim of this paper is to introduce a newly developed preliminary theoretical framework for sustainable transition towards the removal of toxic chemicals from construction materials and waste. The paper presents a transdisciplinary integration of several existing transition and change models including the transition dynamic framework, market diffusion, and Kubler-Ross change curve. These are brought into an integrated new systematic framework applied to construction materials.

The work identifies a range of actors, actions, and collaborations which are needed for a sustainable transition. These make it possible to evaluate and track progress with transition, and to identify areas where progress can be stimulated most effectively at any given time. The introduced preliminary theoretical transition framework supports pro-sustainable change in built environment and maps-out how to actively accelerate the pro-sustainable transition.

KEYWORDS: Construction materials; Construction waste; Toxicity; Transition dynamic framework; Sustainable transition

INTRODUCTION

While many construction materials are safe to use, for as many as 95% of chemicals used in construction products there is still insufficient information on their impact on health (Pacheco-Torgal, 2012). This should not surprise, given that even for high-volume synthetic chemicals there is only a limited understanding of their impacts on human health (Binetti et al., 2008). Chemicals harmful to humans tend also to present issues for natural ecosystems, but there are even greater limitations to the understanding of ecosystem degradation due to toxic impacts from the extraction, manufacture and disposal of construction materials (Petrović et al., forthcoming 2023). These limitations in the existing knowledge limit accuracy of Life Cycle Assessments (LCA) and reports such as Environmental Product Declarations (EPD Australasia, 2021), which are understandably based on the available knowledge. Historically, problem substances, such as lead and asbestos, were removed from construction materials only after there was substantive evidence that these are harmful (Petrović, 2017). Often such transitions would take thirty or more years. However, currently as part of efforts to reduce adverse impacts on the planet, it is paramount to develop effective strategies to accelerate

change while the needed scientific knowledge is still being developed. This paper presents on work which explores how to accelerate needed change within these complex contemporary contexts.

RESEARCH AIM AND OBJECTIVES

This paper aims to introduce a newly developed preliminary theoretical framework for sustainable transition leading to the removal of toxic chemicals from construction materials and waste. The objective is to develop a new way of considering the problem, which can help reframe it and identify how to more effectively stimulate change.

The work recognises that the relatively slow pace of change could be discouraging for those actors who are making the most significant positive contribution to it. Consequently, this paper aims to map-out realistic stages of transition, so that partial progress can still be seen, measured and valued for its contribution. This would also allow for more effective acceleration of change, if governments or industry had an interest to stimulate it.

RESEARCH METHODS

The new framework is developed through the transdisciplinary integration of several existing transition and change models, such as the transition dynamic framework (Brown, Rogers & Werbeloff, 2016; Brown, Farrelly & Loorbach, 2013), market diffusion model (Moore, 2014), and Kubler-Ross change curve (Kearney & Siegman, 2013; Kearney, 2002). Through this process, insights from different disciplines on how to drive/deal with transitions are brought together and applied to the unique context of the potential toxicity of construction materials. This process helps bridge disciplinary divides and integrate innovation from different disciplines through application into the context of the construction industry. Consequently, it is possible to identify new ways to approach and re-frame issues and drive an accelerated pro-sustainable change.

ANTICIPATED (OR PRELIMINARY) FINDINGS

One of the main anticipated findings of this work is that it will start to identify a range of actors, actions and collaborations which are needed for a sustainable transition. These will make it possible to track progress with transition, evaluate if the progress is adequate, but also more effectively stimulate transition at any given time.

RESEARCH SIGNIFICANCE

The paper introduces a preliminary theoretical transition framework for removal of toxic chemicals from construction materials and waste. This framework could play an important role in measuring progress with sustainable transition in this area, which can help both those doing the work to more easily see the results of their own work, but also those in governance to see that the progress is being made. The same framework could be used to anticipate and identify forthcoming steps in the transition, helping support and inspire proactive action and much needed innovation. Similarly, it would help identify areas where incentives could make the most significant positive impact for actual transition, enabling the government and industry organisations to financially support acceleration.

This work presents a contribution in an important area which needs more development and has potential to make a very real positive impact to how we respond to much needed climate action.

Given the current limitations in knowledge, this work might serve as an inspiration model for sustainable transitions in other areas of human activities beyond construction.

REFERENCES

- Binetti, R., Costamagna, F.M. & Marcello, I. (2008). Exponential growth of new chemicals and evolution of information relevant to risk control. *Ann Ist Super Sanità*, 44(1): 13-15.
- Brown, R., Rogers, B. & Werbeloff, L. (2016). Moving toward water sensitive cities: a guidance manual for strategists and policy makers. Clayton, Victoria: Cooperative Research Centre for Water Sensitive Cities Pty Ltd.
- Brown, R.R., Farrelly, M.A. & Loorbach, D.A. (2013). Actors working the institutions in sustainability transitions: the case of Melbourne's stormwater management. *Global Environmental Change*, 23: 701-718. doi: <http://dx.doi.org/10.1016/j.gloenvcha.2013.02.013>
- Environmental Product Declaration (EPD) Australasia*. Retrieved November 2021, from <https://epd-australasia.com/>
- Kearney, K.S. & Siegmán, K.D. (2013). The emotions of change: a case study. *Organization Management Journal*, 10(2): 110-119. doi: 10.1080/15416518.2013.801744
- Kearney, K.S. (2002). A study of the emotional effects on employees who remain through organizational change: a view through Kulber-Ross (1969) in an educational institution. PhD in Education at Oklahoma State University.
- Moore, G.A. (2014). *Crossing the chasm: marketing and selling high-tech products to mainstream customers*. Harper Business.
- Pacheco-Torgal, F. (2012). Introduction: types of potential toxic building materials. In P. Pacheco-Torgal, S. Jalali & A. Fucic (Eds.), *Toxicity of building materials* (pp.xv-xvii). Cambridge: Woodhead Publishing.
- Petrović, E.K. (2017). Part 3: Indoor toxicity from building materials. In E.K. Petrović, B. Vale & M. Pedersen Zari, *Materials for a healthy, ecological and sustainable built environment: principles for evaluation* (pp.137-236). Duxford, UK: Woodhead Publishing.
- Petrović, E.K., Gjerde, M., Chicca, F. & Marriage, G. (forthcoming 2023). *Sustainability and toxicity of building materials: manufacture, use and disposal stages*. Book in preparation for Elsevier: Woodhead Publishing.

Carbon Footprint of Residential Building Construction in Christchurch

Hossein Askarinejad¹, Luis Regidor III¹, Majeed Safa², Serdar Durdyev¹

¹ Department of Engineering and Architectural Studies, Ara Institute of Canterbury, New Zealand.

² Department of Land Management and Systems, Lincoln University, New Zealand.

SYNOPSIS

Construction projects ranging from small residential to commercial buildings produce significant proportion of carbon emissions in New Zealand. Christchurch is growing with an increasing rate with a large number of residential building construction projects currently in progress or being planned. In this research, the life cycle greenhouse gas (GHG) emissions and energy analysis of some typical residential houses built recently in Christchurch will be investigated. A life cycle assessment (LCA) will be carried out, taking into account the supply of construction materials as well as the construction activities. The life cycle GHG emissions and embodied energy of the case study buildings will be calculated. The project is currently in the early stages and this paper presents briefly the preliminary works undertaken so far and the anticipated results. It is expected the project will provide results on the GHG emissions and embodied energy associated with the construction of typical residential buildings in Christchurch where the critical stages in the construction process of the buildings that cause the major GHG emissions are identified and discussed.

KEYWORDS: Carbon footprint, GHG emissions, Life cycle assessment, Residential buildings

INTRODUCTION

Christchurch is expanding with significant number of new housings being approved and under construction in greater Christchurch so far this year. The city council consent data from Stats NZ show more than 3000 building consents were processed which is around 7% higher than 2020 and 27% higher than 2019. The data also show higher construction activities in Selwyn and Waimakariri (Stats NZ, 2021). In Christchurch, the typical system used in constructing modern residential houses include steel and timber framed buildings, with timber framing system being applied to majority of Christchurch houses (Buchanan et al., 2011).

Carbon footprint is the total amount of greenhouse gas emission produced by products or activities and the embodied energy is the total energy required within this process. In this research, the carbon footprint and embodied energy consumption in two equivalent residential buildings made of timber and steel frame systems are investigated. To achieve this, a Life Cycle Assessment (LCA) will be carried out taking into account the supply of construction materials, and the construction activities. Review of literature shows a number of studies are reported using LCA for assessing the environmental performance of buildings (Cheng et al. 2020, Biswas, 2014, Lemay, 2011; Bribia'n et al., 2009; Junnila and Horvath, 2003; Junnila et al., 2006).

RESEARCH AIM AND OBJECTIVES

The aim of this research is to assess the environmental performance of residential building construction in Christchurch with focus on typical new-built residential houses with timber and steel frame systems. The carbon footprint to be assessed are the greenhouse gas emissions as well as the associated embodied energy through the construction process. Demolition and waste treatment (disposal and recycling) are not included in the project scope at this stage.

RESEARCH METHODS

The Life Cycle Assessment (LCA) following ISO14040–44 guidelines, will be used in this research taking into account from the supply of construction materials and construction of building. The environmental impacts of two residential houses (one timber framed and one steel framed building) in terms of carbon footprint and embodied energy will be assessed. This LCA process includes below stages:

- GHG emissions produced from manufacturing of construction materials and transportation to the site.
- GHG emissions produced by construction activities.

A life cycle inventory analysis will be carried out by collecting any data related to the residential house to be checked and used for the input of analysis. These inputs are to be used for the calculation of total GHG emissions in relation to the LCA approach. The results from life cycle inventory analysis will then be used for impact assessment which can be converted into CO₂-equivalent for carbon footprint and MJ for embodied energy. BRANZ LCAQuick software or other similar software tools, plus BRANZ CO₂NSTRUCT database (BRANZ, n.d.) will be used for some parts of the GHG emission calculations. In the preliminary stage, below formulas are adopted here for carbon emissions calculations (Cheng et al., 2020).

$$G_{mp} = \sum_i Q_{mp,i} \times EF_{mp,i} \quad \text{Eq}_1$$

$$G_{mt} = \sum_i Q_{mt,i} \times EF_{mt,i} \times D_i \quad \text{Eq}_2$$

Where G_{mp} is the carbon equivalent produced by material production, with i as the material, $Q_{mp,i}$ is the quantity of the material with respect to carbon coefficient in tonnes, and $EF_{mp,i}$ is the carbon emission factor of the material in tonnes CO₂e/ton. G_{mt} is the carbon equivalent produced by material transport, $Q_{mt,i}$ is the quantity of transported building material in tonnes, $EF_{mt,i}$ is the carbon emission factor of the transport used in tonnes CO₂e/t-km, and D_i is the distance between production factory and the construction site in km. As observed from the formulas, both will give an environmental impact unit of tonnes CO₂e. For this research, environmental impacts will be calculated as kg CO₂e for carbon footprint and MJ for the energy consumption.

ANTICIPATED FINDINGS

Life cycle assessment is increasingly being used to determine the environmental impacts of building and construction projects. It is anticipated that this project will provide valuable results on the GHG emissions and embodied energy associated with the construction of typical residential buildings in Christchurch. The obtained quantities can be compared with the average quantities from other building types or other case studies. Based on the results, it is anticipated

the critical stages in the construction process in the context of Christchurch that cause the major GHG emissions to be identified and evaluated.

RESEARCH SIGNIFICANCE

In 2018, New Zealand has produced 78.9 million tonnes of CO_{2e} (StatsNZ, 2020), in which Christchurch has accounted 2.72 million tonnes of CO_{2e} or about 3.4 percent of country's gross greenhouse gas emissions (Christchurch City Council, 2020). Contribution of the built environment (including the production of building materials, construction and operational phases of a building is estimated to be 20% of the total GHG emissions in New Zealand (BRANZ, n.d.). The importance of this topic (climate change and GHG emissions) and limited studies available in the literature in the context of New Zealand residential construction, highlights an opportunity to contribute to this area. The expected findings can provide useful information for the construction industry in New Zealand, towards reducing their GHG emission contribution in the residential construction sector.

REFERENCES

- Biswas, W. K. (2014). Carbon footprint and embodied energy consumption assessment of building construction works in Western Australia. *International Journal of Sustainable Built Environment*, 3(2), 179-186.
- BRANZ. (n.d.). *BRANZ CO₂NSTRUCT*. Retrieved from <https://www.branz.co.nz/environment-zero-carbon-research/framework/branz-co2nstruct/>
- BRANZ. (n.d.). Reducing greenhouse gas emissions in the construction industry, Retrieved from <https://www.branz.co.nz/sustainable-building/climate-change/reducing-greenhouse-gas-emissions-construction-industry/>
- Bribia'n, Z.I., Uso'n, A.A., Scarpellini, S., (2009). Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification. *Building and Environment*, 44(12), 2510–2520.
- Buchanan, A., Carradine, D., Beattie, G., & Morris, H. (2011). Performance of houses during the Christchurch earthquake of 22 February 2011. *Bulletin of the New Zealand Society for Earthquake Engineering* 44(4), 342–357.
- Cheng, B., Li, J., Tam, V. W., Yang, M., & Chen, D. (2020). A BIM-LCA Approach for Estimating the Greenhouse Gas Emissions of Large-Scale Public Buildings: A Case Study. *Sustainability*, 12(2), 685.
- Christchurch City Council. (2020). *Christchurch district's greenhouse gas emissions*. Retrieved from <https://ccc.govt.nz/environment/climate-change/our-footprint>
- ISO (International Standard Organization), (2006). Environmental Management – Life Cycle Assessment – Principles and Framework. ISO 14040. International Organization for Standardization (ISO), Geneva.
- Junnila, S., Horvath, A. (2003). Life-cycle environmental effects of an office building. *Journal of Infrastructure Systems*, 9(4), 157–166.
- Junnila, S., Horvath, A., Guggemos, A. (2006). Life-cycle assessment of office buildings in Europe and the United States. *Journal of Infrastructure Systems*, 12(1), 10–17.
- Lemay, L. (2011). Life Cycle Assessment of Concrete Buildings, Concrete Sustainability Report, CSR04. *National Ready Mixed Concrete Association*.

7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM
Creating Capacity and Capability for the Future of the Built Environment

StatsNZ. (2020, October 15). New Zealand's greenhouse gas emissions. Retrieved from <https://www.stats.govt.nz/indicators/new-zealands-greenhouse-gas-emissions>

StatsNZ. (2021, July). Building consents issued: May 2021, Retrieved from <https://www.stats.govt.nz/information-releases/building-consents-issued-may-2021>

Critical Factors for Lean-BIM Integration in Construction Practice New Zealand

Likita Ayuba Jerry, School of Built Environment, Massey University, New Zealand.
Mostafa Babaeian Jelodar, School of Built Environment, Massey University, New Zealand.
Rotimi James, School of Built Environment, Massey University, New Zealand.
Vilasini Nimesha, School of Built Environment, Massey University, New Zealand.

SYNOPSIS

The construction industry is becoming more innovative, competitive, and complex; and more participants are involved in construction projects, yet the industry is inefficient in terms of quality products worldwide, including in Australia and New Zealand. The construction industry important in any country including New Zealand does not have a reliable reputation due to issues in quality, efficiency, productivity, cost, and time management. The industry needs new theories of production to support a renewed drive for greater performance improvement. BIM benefits are in line with the benefits of lean construction, still less intake of BIM, Lean implementation in industry, when BIM and lean construction principles are used together the construction process becomes even more enhanced.

This paper aims to review and discuss the critical factors for integrating Lean, and BIM implementation globally and within the New Zealand construction sector. A systematic review of relevant literature, subject matter expert interviews, from the construction sector in New Zealand was used to identify various factors for the implementation of Lean-BIM integration in construction projects.

The construction industry is more innovative, competitive, and complex, with more integrated collaboration, especially during the design stage of the construction life cycle process, to generate information, make decisions, and improve the process of delivering facilities in construction project New Zealand. This study would activate the management knowledge on how to minimize inefficiencies and enhance the value delivered during design, construction, and operation, through Lean-BIM implementation in the construction project.

KEYWORDS: BIM-Lean, Building, Construction, Engineering, Productivity

INTRODUCTION

The construction industry significant in any country does not have a reliable reputation due to issues in quality, efficiency, productivity, cost, and time management, causes for that are complex and multi-discipline projects (Yap, Chow *et al.* 2019). For this complexity issue, the construction industry needs new theories of production or construction to support a renewed drive for greater performance improvement (Li, Greenwood *et al.* 2019). The growing interest in different theories and practices such as Lean Construction, Building Information Modelling (BIM), Integrated Project Delivery (IPD). However, still find challenges and barriers to the implementation of those theories (Durdyev and Hosseini 2019). However recent studies pay attention to combining those concepts to obtain the synergy effect to better manage projects (Oraee, Hosseini *et al.* 2019). Lean is heavily based on experimentation and improvement at

the production level (Goh and Goh 2019). Application of BIM with Lean construction is an area that is yielding opportunities for innovation and differentiation (Evans, Farrell *et al.* 2021).

Integrating BIM and Lean in a construction project strongly relates to building our future in the sense that more benefits are derived which could be without compromising the quality throughout the lifecycle of the project executed. Lean benefits for construction can achieve better quality results a third quicker and a third cheaper than traditional practices (Benachio, Freitas *et al.* 2021). More so, benefits achieved through BIM in the construction industry are vital, invest in better quality, lower costs, greater safety, and higher customer satisfaction, similarly project utilizing BIM have a greater chance of success and maximize effectiveness across every stage of the project lifecycle and beyond (Ahuja, Sawhney *et al.* 2017). The complexity in the construction industry can be correlated to the inefficiency of the operation, uncertainties, and interdependence making the way for an increase in complexity of the industry as shown by (Kreye 2019). Thus, the construction industry has significant impacts on the growth of nations. Thus, this paper aims to review and discuss the critical factors for integrating Lean, and BIM implementation globally and within the New Zealand construction sector. Therefore, this study aims are presented in the next section.

Table 1. Collaborative benefits for Lean-BIM implementation

COLLABORATIVE BENEFITS		BIM	LEAN	BIM +LEAN	REFERENCE
P R O C E S S	- Improved planning and collaborative, integrated, and visible construction process - Enable the best project delivery process - Effectively enable the use of each other for construction projects		√	√	Fakhimi, Sardroud et al. (2016), Guerriero, Kubicki et al. (2017)
	Solve more of the issues (cost, constructability, schedule, quality, sustainability, waste, etc. during the project lifecycle)			√	Koskela and Howell (2002)
	Increase productivity and efficiency, and generate more added value for the client			√	Daniel and Pasquire, 2019: Yap <i>et al.</i> 2020: Zhang, X. <i>et al.</i> 2018: Chan <i>et al.</i> 2019: Fakhimi, Sardroud et al. (2016)
	Reduce the amount of unnecessary data	√		√	(Ibem <i>et al.</i> 2019: Georgiadou, 2019: Daniel and Pasquire, 2019)
					Zima, Plebankiewicz et al. (2020)

7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM
Creating Capacity and Capability for the Future of the Built Environment

P E O P L E	• Enable sharing of information • Enhance project relationships	√		√	Fakhimi, Sardroud et al. (2016), (Sacks, Eastman et al. 2018, Andújar-Montoya, Galiano-Garrigós et al. 2020).
	• Present significant improvement in prescribed and lawful matters			√	Sacks, Korb et al. 2017
	• Risk and reward could be disseminated amongst the project team	√		√	Piroozfar, Farr et al. (2019)
	• Facilitate closer collaboration from the early stages of the project • Suppliers will be integrated into the processes of the construction industry		√	√	Okakpu, <i>et.al.</i> 2020: Taye B. A. <i>et.al.</i> 2018
	• Help work teams to do the work with higher performance		√	√	Koskela and Howell 2002: Zhang, X. <i>et. al.</i> 2018).
T O O L S	• BIM acts as an excellent team-building tool and accelerates the formation and strategies of IPD	√		√	Sacks, Eastman et al. (2018) Fakhimi, Sardroud et al. (2016)
	• BIM provides a data storage exchange service	√		√	Li, Xue et al. (2018)

RESEARCH AIM AND OBJECTIVE

The objective of this study is to identify whether Lean construction and BIM can play all together synergistically and identify the critical factors and benefits through archival study. and subject matter expert (SME) interview.

RESEARCH METHOD

A two-step approach was adopted to achieve the study objectives. The first stage, systematic literature review, globally and within New Zealand was used to identify various challenges and benefits in the implementation of BIM and lean construction. In the second stage, an interview was conducted with a subject matter expert (SME), from the NZ construction industry, an expert in the field of Lean, and BIM. A qualitative data analysis called NVIVO was adopted to analyze the data obtained from SME interviews. involving the adoption of Lean, and BIM in construction projects within New Zealand viewpoint, to find out what solutions may be applicable to ease the challenges and enhance construction project practice through the adoption of Lean, and BIM integration in the construction projects.

ANTICIPATED FINDINGS

Based on a theoretical viewpoint, the synergies of BIM and Lean construction have been defined in much research. The common denominator of the scientific findings on BIM-Lean synergy is that BIM and Lean are conceptually not dependent on each other and can therefore in principle be used separately, however, a great could be achieved when both approaches are combined.

RESEARCH SIGNIFICANCE

The study would eventually assist different stakeholders in applying Lean-BIM integration viewpoints into construction practice. Consequently, there is low acceptance and implementation of BIM-Lean integration in the New Zealand construction industry, mainly due to a lack of trained personnel or expert, lack of focus on research, and lack of awareness within the professional stakeholders.

ACKNOWLEDGEMENT

Considering this as a component of a Ph.D. research work, the authors of this paper would like to thank the School of Built Environment (SBE), Massey University for sponsorship of the main research.

REFERENCES

- Ahuja, R., et al. (2017). "Driving lean and green project outcomes using BIM: A qualitative comparative analysis." International Journal of Sustainable Built Environment **6**(1): 69-80.
- Andújar-Montoya, M. D., et al. (2020). "BIM-LEAN as a Methodology to Save Execution Costs in Building Construction—An Experience under the Spanish Framework." Applied Sciences **10**(6): 1913.
- Benachio, G. L. F., et al. (2021). "Interactions between Lean Construction Principles and Circular Economy Practices for the Construction Industry." Journal of Construction Engineering and Management **147**(7): 04021068.

7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM
Creating Capacity and Capability for the Future of the Built Environment

- Durdyev, S. and M. R. Hosseini (2019). "Causes of delays on construction projects: a comprehensive list." International journal of managing projects in business.
- Evans, M., et al. (2021). "Competency framework to integrate lean construction and integrated project delivery on construction megaprojects: towards a future of work global initiatives in multinational engineering organisations." Benchmarking: An International Journal.
- Fakhimi, A., et al. (2016). How can Lean, IPD and BIM work together? ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction, IAARC Publications.
- Goh, M. and Y. M. Goh (2019). "Lean production theory-based simulation of modular construction processes." Automation in Construction **101**: 227-244.
- Guerriero, A., et al. (2017). BIM-enhanced collaborative smart technologies for LEAN construction processes. 2017 International Conference on Engineering, Technology and Innovation (ICE/ITMC), IEEE.
- Kreye, M. E. (2019). "Does a more complex service offering increase uncertainty in operations?" International Journal of Operations & Production Management.
- Li, C. Z., et al. (2018). "An Internet of Things-enabled BIM platform for on-site assembly services in prefabricated construction." Automation in Construction **89**: 146-161.
- Li, J., et al. (2019). "Blockchain in the built environment and construction industry: A systematic review, conceptual models and practical use cases." Automation in Construction **102**: 288-307.
- Oraee, M., et al. (2019). "Collaboration barriers in BIM-based construction networks: A conceptual model." International Journal of Project Management **37**(6): 839-854.
- Piroozfar, P., et al. (2019). "Facilitating building information modelling (BIM) using integrated project delivery (IPD): A UK perspective." Journal of Building Engineering **26**: 100907.
- Sacks, R., et al. (2018). BIM handbook: A guide to building information modeling for owners, designers, engineers, contractors, and facility managers, John Wiley & Sons.
- Yap, J. B. H., et al. (2019). "Criticality of construction industry problems in developing countries: Analyzing Malaysian projects." Journal of Management in Engineering **35**(5): 04019020.
- Zima, K., et al. (2020). "A SWOT analysis of the use of BIM technology in the polish construction industry." Buildings **10**(1): 16.

The Cost-Benefit Implications of Low-Emissions Concrete for Exterior Concrete Works

Lauren Wilson, Unitec Institute of Technology, New Zealand.

Linda Kestle, Unitec Institute of Technology, New Zealand.

SYNOPSIS

Globally, the manufacture of cement is responsible for 5-8% of total annual emissions, and the volume produced increases by approximately 2.5% every year. Despite low-emissions blends being available in the New Zealand market, only 1-2% of the total concrete volume placed each year is a low-emissions product. These blends are assumed to exhibit detrimental performance impacts, while carrying a cost premium. Previous research undertaken in this area tends to focus on only one blend, and either performance or emissions effects. The aim of this research was to examine a wider range of alternatives to Ordinary Portland Cement that may enable an emissions reduction, alongside the performance outcomes of each, and evaluate the accuracy of common cost perceptions. A literature review was conducted to identify the Supplementary Cementitious Materials both available commercially and currently under review. These findings were applied to and compared with a case study project, followed by a conducting a quantitative analysis of costs and emissions of commercially available SCMs. Preliminary findings suggest that a low-emissions cement blend using 20% fly ash is commercially available in the New Zealand market with no cost premium. Significantly, there appears to be no detrimental impact on performance, and emissions are reduced by 17.5%. The research is intended to be of value to construction project owners, developers, construction consultants and contractors.

KEYWORDS: carbon emissions, low-emissions concrete, supplementary cementitious materials

INTRODUCTION

Global carbon emissions are rapidly increasing, to which cement contributes 5-8% (Andrew, 2018; Font, Soriano, de Moraes Pinheiro, Tashima, Monzo, Borrachero & Paya, 2020). Despite the urgent need to reduce emissions, global cement production has increased exponentially since the 1930s, leading to significant increases in CO₂ emissions. At a production increase of 2.5% per year (CEMBUREAU, 2017), low-emissions solutions are urgently needed in order to limit and reduce the detrimental environmental impacts of cement.

Previous research has established that cement can be created utilising blends that contain partial substitutes for Ordinary Portland Cement (OPC) and equivalent or better physical performance has been verified. Commercially available solutions including fly ash, blast furnace slag, silica and limestone powder are already approved for use under NZS3122:2009 (Standards New Zealand, 2009). Further waste products demonstrating appropriate pozzolanic or hydraulic behaviours are also being researched. Despite the availability of low-emissions blends in the New Zealand construction market, the uptake of these blends comprises only 1-2% of the total concrete volume placed each year (Gamage, Vickers, Fisher & Nebel, 2019). A key barrier to the uptake of low-emissions concrete is the perception that cost premiums apply to low-emissions products. This research tests that perception by seeking actual cost data from concrete suppliers, and applies the emissions data to a case study to determine the volume of emissions that could have been saved had low-emissions blends been specified. The research findings will provide clients, consultants and contractors with a broader understanding of the value low-emissions concrete could potentially bring to their projects.

RESEARCH AIM AND OBJECTIVES

The overall aim of this research was to determine whether low-emissions concrete blends are more expensive than OPC blends, and the extent of emissions' reductions possible with commercially available SCMs.

What are the costs and mix designs of low-emissions concrete for equivalent strength and performance?

This question sought to identify the alternative concrete blends available on the market, the types and quantities of SCMs used in commercial concrete blends, and the costs of those blends. This information was obtained from readymix concrete suppliers, who were asked to provide pricing for the alternatives they had available.

To what extent could CO₂ emissions have been reduced on the case study project by specifying low-emissions concrete of equivalent performance to that actually specified?

The cement content has a large impact on the overall emissions of concrete. This question compared the emissions of OPC-based concrete blends with those of equivalent low-emissions blends, in order to identify the extent of the benefit that could be realised. Emissions data for the mix designs provided by the readymix suppliers was obtained from the publicly available CO₂NSTRUCT database by BRANZ. Data was obtained for unreinforced concrete, to ensure that the concrete data was isolated from other materials. To convert the emissions data to the required unit of measure, concrete densities were applied in accordance with publicly available Environmental Product Declarations.

What effect does the cost of carbon have on the cost-benefit of low-emissions concrete?

This question recognised that the costs of offsetting emissions under the Emissions Trading Scheme are likely to be included in the supply costs of concrete. The daily market rates of the leading broker for New Zealand Units are publicly available. By isolating this cost, it was possible to quantify the cost of carbon by volume.

RESEARCH METHODS

This research was undertaken in three stages – firstly a literature review to gain an understanding of the performance and emissions potential of various SCMs. The literature findings were then applied and compared with a case study for an exterior concrete works package that reflected a fairly typical concrete works package in Auckland. The concrete specifications for the case study were examined to generate a list of the types of concrete selected for the project, and drawings measured to obtain the quantity of each. These findings were compared with the invoices submitted to the contractor by the readymix supplier to reconcile any differences, and make sure that variations were included in the totals. With the specifications and volumes of concrete obtained, the research moved into the final (third) phase, quantitative analysis.

To establish the cost implications of low-emissions' concrete, the list of specified concrete types was provided to readymix suppliers, who responded with pricing for both the specified blends and equivalent low-emissions blends. The specification of the low emissions blends was left

open for the suppliers to submit data for any blends they make available to the market. The only criteria was the compressive strength. Following receipt of this information, the emissions volumes were quantified for both types of concrete, using published data from BRANZ and suppliers' EPDs. These results were applied to the volumes of concrete placed in the case study project, to provide actual emissions volumes that can be referenced by project teams considering the benefits of low-emissions concrete for their own projects.

PRELIMINARY FINDINGS

Readymix suppliers provided data for 20% fly ash blends as the low emissions option and confirmed that no other low emissions blends are currently provided to the Auckland market. This is due to a combination of fly ash availability and lack of demand from commercial clients.

Preliminary findings suggest that there is no cost premium attached to fly ash blends in the commercial readymix market. From some suppliers, high-strength fly ash blends are priced lower than standard OPC blends. One supplier advised that fly ash is cheaper to source than OPC, but the cost benefit is offset by the need to provide separate storage facilities at the plant prior to batching.

The literature review confirmed that there is no detrimental performance impact where the fly ash component remains below 30% (Standards New Zealand, 2009). This suggests that industry concern regarding poor performance of low emissions blends may be unfounded, historical, or require further investigation.

The emissions data provided by BRANZ (2019) and suppliers' EPDs enabled quantification of the carbon emissions actually generated by the case study project. The emissions data of each source is shown in Figure 1. The publicly available data by Firth (2020) reports their blends at consistently lower emissions volumes than BRANZ (2019) or Allied Concrete (2019). However, this is explained within their EPD, as Firth report that they typically use 10% SCMs in their standard blends.

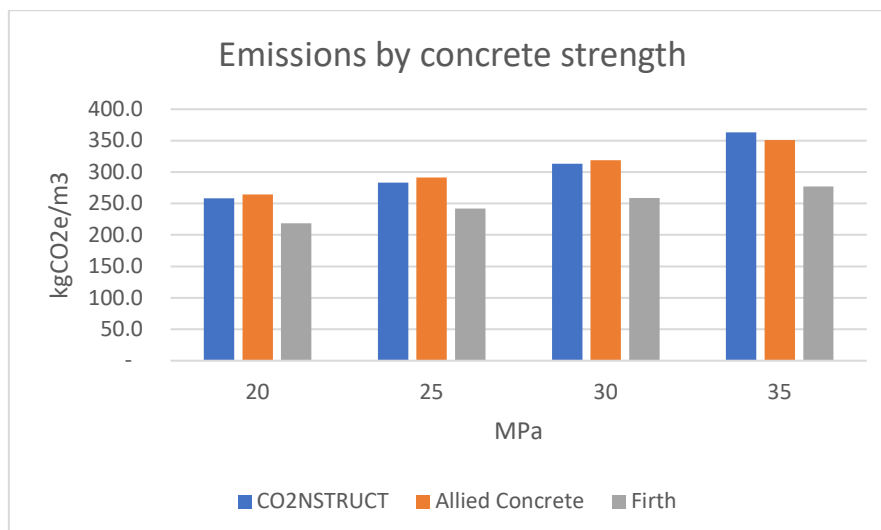


Figure 1. Volume of emissions per unit of concrete.

For the purposes of this research, figures from BRANZ (2019) were utilised as the baseline. The total volume of concrete for the project was 276m³, which generated 78.9 tonnes CO₂e.

7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM

Creating Capacity and Capability for the Future of the Built Environment

Utilising the figures from Gamage et al. (2019), this is equivalent to the emissions generated annually by 31 cars.

As discussed above, fly ash blended concretes were provided by suppliers as a viable alternative. Had these blends been used, a decrease in emissions of 13.8 tonnes could have been achieved, which represents 17.5% of the project total.

Table 1: Cost and emissions of the specified concrete blends

Concrete specification	\$/m3	kgCO ₂ eq/kg	kgCO ₂ eq/m3	Project emissions (kg)	% reduction
20MPa 100% OPC	186.50	0.11	258.50	22,696.30	
20MPa 20% FA	186.50	0.09	211.50	18,569.70	18%
25MPa 100% OPC	197.50	0.12	283.20	39,704.64	
25MPa 20% FA	197.50	0.10	236.00	33,087.20	17%
30MPa 100% OPC	204.50	0.13	313.30	5,639.40	
30MPa 20% FA	204.50	0.11	265.10	4,771.80	15%
35MPa 100% OPC	218.00	0.15	363.00	10,853.70	
35MPa 20% FA	218.00	0.12	290.40	8,682.96	20%

As at 23 October 2020, the current market rate was \$35.15/NZU (Carbon News, 2020). At this rate, the carbon offset price was \$2,773.34. By using the fly ash alternatives, this would have reduced to \$2,288.27, indicating that cost savings may be possible by considering low emissions alternatives.

New SCMs continue to be researched globally, including rice husk ash, olive-stone biomass ash, and waste glass powder. All three are waste products of other industries, and considered to be zero emissions for the concrete industry as they were produced elsewhere. Rice husk ash and olive-stone biomass ash are producing positive results, especially when used together. These three waste products generally are demonstrating strong beneficial properties and the market would profit from further research in this area.

RESEARCH SIGNIFICANCE

These findings will benefit both construction contractors and consultants, particularly for those projects that target low-emissions and ‘green’ ratings, such as GreenStar certification. The intention is that this research may encourage clients and consultants to engage in a dialogue with suppliers, ultimately increasing the demand for low-emissions’ cement blends and improving commercial viability for suppliers.

REFERENCES

Allied Concrete. (2019). *Environmental product declaration: Ready mixed concrete using Holcim supplied cement*. Retrieved from <https://www.alliedconcrete.co.nz/assets/technicalresources/files/Sustainability/Allied-Concrete-Environment-Product-Declaration-2019.pdf?vid=3>

7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM

Creating Capacity and Capability for the Future of the Built Environment

- Andrew, R. M. (2018). Global CO₂ emissions from cement production. *Earth System Science Data*, 10, 195-217. <https://doi.org/10.5194/essd-10-195-2018>
- BRANZ. (2019). *CO2NSTRUCT database* [version 1.0]. Retrieved from <https://www.branz.co.nz/environment-zero-carbon-research/framework/branzco2nstruct/>
- Carbon News. (2020). OMF NZ carbon market review. Retrieved from <http://carbonnews.co.nz/page.asp?id=2028816253036GIK>
- CEMBUREAU (2017). *Activity report 2017*. Retrieved from <https://cembureau.eu/media/1716/activity-report-2017.pdf>
- Firth. (2020). *Environmental product declaration for ready-mixed concrete*. Retrieved from <https://epd-australasia.com/wp-content/uploads/2020/09/FirthEPD-Ready-mixed-concrete-Sep-20-WEB.pdf>
- Font, A., Soriano, L., de Moraes Pinheiro, S. M., Tashima, M. M., Monzo, J., Borrachero, M. V., & Paya, J. (2020). Design and properties of 100% waste-based ternary alkali-activated mortars: Blast furnace slag, olive-stone biomass ash and rice husk ash. *Journal of Cleaner Production*, 243, 118568. <https://doi.org/10.1016/j.jclepro.2019.118568>
- Gamage, G., Vickers, J., Fisher, B., & Nebel, B. (2019). *Under construction: Hidden emissions and untapped potential of buildings for New Zealand's 2050 zero carbon goal*. Retrieved from <https://www.thinkstep.com/content/hidden-emissions-and-untapped-potential-buildings-new-zealands-2050-zero-carbon-goal>
- Standards New Zealand. (2009). *Specification for Portland and blended cements (general and special purpose) (NZS 3122:2009)*. Retrieved from <https://shop.standards.govt.nz>

Consideration Watchpoints When Utilising “ArchiCAD” Software Across a VDI Network

Malachy McGarrigle, Unitec Institute of Technology, New Zealand.

SYNOPSIS

This research identifies factors to be considered in the adoption of a Virtual Desktop Infrastructure (VDI) accommodating the software needs of a tertiary institution. The study discusses the potential advantages and disadvantages of VDI focussing specifically on the performance of the architectural software “ArchiCAD” when used virtually. The findings will be relevant to similar programmes such as Revit and software used in other disciplines especially where processing power is important. Aims discussed include reducing high specification computers rarely used to capacity, assessing user experience and feasibility of VDI remote access. Primarily a case study this project centres around delivery of NZDAT papers which employ ArchiCAD. Software efficiency and performance was monitored throughout teaching across numerous semesters. Incidents were logged and VDI operation tracked especially during complex tasks such as image rendering. Load testing was also done to assess the implications of large user numbers simultaneously performing such complex tasks. Project findings indicate that “ArchiCAD” performance depends on the design and specification of the Virtual platform. Factors such as processing power, RAM allocation and ratio of users to virtual machines proving crucial. Tasks executed by the software and how software itself uses hardware are other considerations. This research is important as its findings could influence the Information Technology strategies of both academic institutions and industry in coming years. Virtual computing provides many benefits and this project could provide the confidence for stakeholders to adopt new strategies using VDI instead of the traditional approach of computers with locally installed software applications.

KEYWORDS: Virtual, ArchiCAD, Software, VDI, Performance

INTRODUCTION

This research project developed from a decision taken by Unitec New Zealand to roll out a Virtual Desktop Infrastructure (VDI) to meet the software needs of its lecturers, administration staff and students. The research aims to generate findings to inform the deployment of VDI across Unitec in other departments, especially where specialised software is crucial to enabling students achieve necessary learning outcomes. Literature identifies many benefits such as VDI flexibility (Berryman, Calyam, Honigford & Lai, 2010) and system management (Berryman et al., 2010; Chrobak, 2014; Harbaugh, 2012; Miller & Pegah, 2007) which the project will explore including also the potential of VDI to reduce the need for students to procure expensive high end computers. (Nakhai & Anuar, 2017) Reduced costs to educational establishments were highlighted also resulting from less expenses in procurement, maintenance and overall IT operational expenditure. (Chong, Wong, & Wang, 2014; Xu, Yang, & Lei, 2015) Potential savings were identified in many areas and the economic and organizational cases for VDI implementation into academic institutes justified by a possible 75% reduction in hardware costs and 90% reduction in user energy footprint. (Agrawal, Biswas, & Nath, 2014) Operational efficiency was also noted as contributing to higher cost savings. (Lee, Kumano, Matsuki, Endo, Fukumoto & Sugawara, 2017) Earlier literature omits aspects such as potential VDI software update issues though more recent studies address. (Lee, Shin, Kwon, Cho & Chung, 2021) Most testing in literature was done after system deployment but none during VDI development to

inform final platform set up. One study however did very detailed simulation testing with an architectural practice recording similar data to the tests in this paper. (Lee, Shin, Kwon, Cho & Chung, 2021) There appeared little evidence of how end user briefing discussions were carried out to generate VDI proposals meeting software performance requirements. Costs discussed focussed more on savings rather than capital and running costs and very little information assessed VDI system architecture such as CPU cores or speed needed for specific AEC demands. One paper did focus however on using VDI for Building Information Modelling in an architectural practice. (Lee, Shin, Kwon, Cho & Chung, 2021)

RESEARCH AIM AND OBJECTIVES

This study will identify the potential advantages and disadvantages of VDI across the general computing spectrum by reference to literature. Empirical investigation through software testing checks whether Archicad can run virtually without compromising performance and end user experience. The study will establish what VDI configuration is necessary to permit an acceptable standard of Archicad performance, including whether Archicad access can be provided remotely, what steps are necessary to provide student access with necessary security, and impacts if any on performance and resultant end user experience.

RESEARCH METHODS

This research focussed on two papers in the Unitec New Zealand Diploma in Architectural Technology, Scoping and Preliminary Design, and Documentation for Small Buildings. The methodology included informal monitoring of Archicad performance in use during teaching of the above papers, semi structured interviews with various professionals such as architects, Unitec IT staff and various external IT vendors, and testing designed to replicate on Archicad the tasks necessary to satisfy the course learning outcomes.

Initial informal monitoring consisted of recording any incidents that occurred during teaching of Archicad in the VDI lab and noting the context and circumstances of what students were trying to achieve, and active numbers using the VDI platform at the time. This basic logging process was not actually required very often either on initial VDI set up and later evolutions. Semi structured interview discussions were held in person or on the telephone and not rigidly structured though questionnaires were employed, primarily as a starting point for discussion.

Early tests on the initial VDI design were arranged at Unitec with a basic objective of trying to break the system whilst carrying out simple though typical Archicad tasks. Testing methods evolved into assessing the performance of a single VDI computer when performing typical tasks required in the two papers under study. The rendering tasks required in Scoping and Preliminary Design were thought to be the most processor intensive. An IT colleague downloaded a benchmarking tool to view the performance of the processors under load to note any particular characteristics of the software and this helped evolve the VDI design.

Load testing with multiple users involved getting times actually taken by VDI to complete specific operations. Users were provided with an Archicad project file of a medium size two storey dwelling. They then executed particular tasks whilst recording the time taken. This was to measure end user experience to compare with that of a traditional Desktop workstation. Later testing of upgraded VDI platforms again involved tasks including rendering to compare operation times, factors such as latency and to precipitate and identify any software issues.

ANTICIPATED (OR PRELIMINARY) FINDINGS

Unitec and the participants are very aware of the potential benefits of VDI such as flexibility, system management and security but the VDI design had to be the result of thorough initial briefing. Costs were inevitable considerations but the potential to reduce under-utilized desktops, provide mobile and remote access all within a traditionally comparable end user experience were seen as attractive features of VDI. Tests confirmed suspicions that tasks such as photo rendering would be the most demanding of the VDI system. A crucial finding revealed how Archicad uses processors and graphics cards when executing complex tasks and the stress on the CPU during rendering was of particular note and unexpected. This informed later Unitec VDI configurations by reducing the maximum users allocated to virtual machines from ten to two thereby decreasing demand on the virtual machine CPU. Archicad on a VDI is feasible even when accessed remotely but acceptable end user experience and performance requires a high specification VDI cognisant of how the software uses components such as processors.

RESEARCH SIGNIFICANCE

This research is important as it signals a potential sea change in how Information Technology services are provided both within academia and industry. VDI it appears can work even with sophisticated professional software and VDI features can benefit both sectors. For IT administrators VDI system management allows efficient operation of server resources based on CPU and memory (Berryman et al.,2010) whilst reducing dependence on rarely used high performance workstations (Harbaugh,2012;Miller and Pegah,2007) Central management reduces maintenance concerns including constant security updates and operating system patches thus avoiding the “break fix endless loop”(Chrobak,2014) This study has significance for colleges and beyond as it helps identify important factors for consideration in the design of a proposed VDI platform. These will influence the platform design and configuration which should be based on reliable end user briefings and knowledge of specific software characteristics. Stakeholders will see evidence that VDI is feasible even for discipline specific packages like Archicad and the findings could apply to software applications in other sectors such as music or video editing where processing ability could be crucial. The study also demonstrates the potential of remote access to a VDI system which can provide bespoke discipline or qualification specific application suites. An attribute especially attractive to schools or colleges where students often struggle to afford the computers required to run the software necessary for their studies. It also off sets frequent software issues encountered on a student’s home computer which can be complex to resolve. The pilot study at Unitec of an upgraded VDI platform with a limited ratio of users to virtual machines shows promise and this includes the ability to access the system remotely. Some students who have reported problems with their machines are being provided with remote VDI access and this is a support measure worthy of development. Security concerns can present VDI access barriers and simplicity is a key factor here if possible to help allay concerns or stress students may already be under due to personal computer issues at home.

REFERENCES

- Berryman, A., Calyam, P., Honigford, M., & Lai, A. M. (2010). VDBench: A benchmarking toolkit for thin-client based virtual desktop environments. *Proceedings - 2nd IEEE International Conference on Cloud Computing Technology and Science, CloudCom 2010*, 480–487. <https://doi.org/10.1109/CloudCom.2010.106>
- Chrobak, P. (2014). Implementation of Virtual Desktop Infrastructure in academic laboratories, 2, 1139–1146. <https://doi.org/10.15439/2014F213>

7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM

Creating Capacity and Capability for the Future of the Built Environment

- Chong, H. Y, Wong J.S., & Wang, X. (2014). An explanatory case study on cloud computing applications in the built environment. *Automation in Construction*, 44, 152-162. <https://doi.org/10.1016/j.autcon.2014.04.010>
- Harbaugh, L. G. (2012). TECH AUDIT The Pros and Cons of Using Virtual Desktop Infrastructure. *PC World*, 30(June 2012), 32. Retrieved from <http://search.ebscohost.com/login.aspx?direct=true&db=aph&AN=75175726&site=ehost-live>
- Lee, C. Kumano, T. Matsuki, T. Endo, H. Fukumoto, N. & Sugawara, M. (2017) Understanding storage traffic characteristics on enterprise virtual desktop infrastructure. *Proceedings of the 10th ACM International Systems and Storage Conference (SYSTOR 2017) Association of Computing Machinery , New York, NY, USA, Article13, 1-11. <https://doi.org/10.1145/3078468.3078479>*
- Lee, K.; Shin, J.; Kwon, S.; Cho, C.-S.; Chung, S. (2021) BIM Environment Based Virtual Desktop Infrastructure (VDI) Resource Optimization System for Small to Medium-Sized Architectural Design Firms. *Appl. Sci.* , 11, 6160. <https://doi.org/10.3390/app11136160>
- Miller, K., & Pegah, M. (2007). Virtualization , Virtually at the Desktop. *Proceedings of the 35th Annual ACM SIGUCCS Fall Conference.*, 255–260. <https://doi.org/10.1145/1294046.1294107>
- P. H. Nakhai and N. B. Anuar, "Performance evaluation of virtual desktop operating systems in virtual desktop infrastructure," 2017 IEEE Conference on Application, Information and Network Security (AINS), 2017, pp. 105-110, doi: 10.1109/AINS.2017.8270433.
- Z. Xu, L. Yang and J. Lei.(2015) "Conception and Design of Desktop Virtualization Cloud Platform for Primary Education: Based on the Citrix Technology," 2015 International Conference of Educational Innovation through Technology (EITT), 2015, pp. 226-230, <https://doi:10.1109/EITT.2015.55>.

Numerical/Computational Study of the Effect of Braced Stiffness Equipped with Nonlinear Viscous Dampers on the MDOP System

H.S. Ahmed, School of Built Environment, Massey University, Auckland, New Zealand.

V. Vishnupriya, School of Built Environment, Massey University, Auckland, New Zealand.

G.W. Rodgers, Department of Mechanical Engineering; University of Canterbury, New Zealand.

Wilkinson, S, School of Built Environment, Massey University, Auckland, New Zealand.

SYNOPSIS

We intend to investigate the efficacy of viscous damper and brace flexibility together in reducing lateral displacement and base shear in structures induced by ground motion. These efforts may allow us to validate the use of dampers in retrofitting or installing dampers in newly constructed structures while employing the Opensees software framework as a motivating factor for this investigation. Interaction between braced stiffness and damper subsystem stiffness have been studied extensively; however, the usefulness of nonlinear viscous damper interaction in multistory buildings has yet to be examined in any depth. Further research is desirable to construct earthquake-safe buildings in seismically active areas such as New Zealand.

By using Nonlinear Viscous Dampers (NVD) to reduce the dynamic response and base shear in building prone to earthquakes, the purpose of this research is to develop a theoretical framework for understanding the usefulness and outweigh of a nonlinear viscous damper over linear viscous damper.

The research data in this thesis will be drawn from previous research to reanalyze and verify their findings by developing their models in Opensees. A further step is an investigation of brace flexibility with a subsystem of a damper by using the MDOP system. The final step is to follow a case-study design, with an in-depth analysis of the newly designed building equipped with a viscous damper and a building retrofitted by inserting a viscous damper.

This work introduces a critical difference between linear and nonlinear viscous dampers in the SDOF and MDOP systems. There are several important areas where this study makes an original contribution to the usefulness of linear and nonlinear viscous dampers in designing a new building using these devices to control or reduce the catastrophic consequences of the structures during earthquakes. This project also provided an essential opportunity to develop a new scientific methodology for retrofitting buildings affected by earthquakes.

KEYWORDS: Viscous Damper, Seismic Response, Brace flexibility, Degree of freedom, Opensees

INTRODUCTION

In recent decades, the construction of tall buildings with a high degree of irregularity has grown despite the challenges structural engineers confront while designing structures in seismically active zones. Structures in such conditions are prone to failure and can cause probable life-threatening events. Typical strategies have been well provided in many building codes to improve the response to moderate or high seismic forces. However, these design procedures require a moment frame, special moment frame or dual system structures to increase inertial or restoring forces, which would be impractical and environmentally unfriendly. Another solution to the problem has been suggested in which supplemental damper devices are inserted within the frame of the structure to increase the damping force for controlling dynamic response amplification and limiting inelastic deformations (Romero, 1995; Soong & Spencer Jr, 2002).

Having greater insight into damper installation as a mitigatable approach for retrofitted or newly designed structures would take on a formidable challenge to precisely design these devices' capacity and placement, as well as its interaction with the stiffness of braced members. It is essential to investigate the contribution of brace stiffness and damping system in reducing the seismic response in structures.

Most of the current evidence, numerically and mathematically, support the design of the structural frame considering the interaction between brace stiffness and coefficient of linear or nonlinear viscous damper devices (Losanno et al., 2018; Losanno et al., 2015; Losanno et al., 2019; Xie et al., 2021). Losanno et al. (2015) succeeded in modelling SDOF systems equipped with elastic, viscous and friction dampers to obtain optimal design theoretically and numerically using iterative methods. They could independently investigate different stiffness ratios between elastic braced stiffness and frame stiffness corresponding to different damping coefficients supplied by both types of dampers. However, the authors' analysis does not consider nonlinear viscous damping, nor have they examined the MDOF system. In the case of increasing damping ratio, Xie et al. (2019) concluded that the stiffer subsystem damper corresponding to the brace stiffness is, the more lateral displacement reduction and base shear reduction can be obtained under simulating ground motion. This study sheds light on some important approaches, such as the proportional relationship between the reduction in the displacement and the stiffness ratio between the subsystem supporting viscous dampers and the frame when the structural period is higher than 0.5 seconds based on the identical Maxwell model. Parallel to the previous approach, it also plots the relationship between the linearity of the viscous damper and the base shear reduction. In the same context, an observational study has demonstrated the effect of combining the viscous damper with the elastic supporting system in alleviating the structural dynamic response and increasing energy absorption of the MDOF buildings (Losanno et al., 2018). Their study used a 3-DOF frame system with different viscous damping configurations. It was found that both damping coefficient and stiffness ratio parameters affect the global behaviour of dissipative braced frames. Other researchers looked at wall-viscous frame systems rather than braced-viscous frame systems. They observed that the increase in damping between coupled shear walls produces more reduction in inter-story drift, and a further increase in damping force will subject to greater axial loads on the column (Lavan & dynamics, 2012). However, as braced viscous damper stiffness was not considered, there is a lack of clarity regarding this aspect. Thus, it is essential to consider the optimization of the brace-viscous damper stiffness in designing structures to control seismic responses.

Despite the wealth of literature available in the field, there is a lack of study around plotting the mathematical and or numerical relationship between nonlinear viscous dampers and braced stiffness ratios in MDOF systems. Although linear viscous dampers are employed in actual structures to manage and reduce shear stress and structural amplification, nonlinear viscous dampers can absorb more energy. Therefore, this would be a more accurate simulation to design new buildings or retrofit existing ones by equipping nonlinear viscous dampers.

RESEARCH AIM AND OBJECTIVES

This project aims to develop a framework to investigate the reduction of seismic responses by inserting linear and nonlinear viscous dampers in the MDOF systems and further understanding the effectiveness of brace flexibility with subsystem stiffness. While the objectives of this study are:

7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM

Creating Capacity and Capability for the Future of the Built Environment

- Verify and develop SDOF system models that have been simulated in previous studies by using Openses Software.
- Build MDOF systems in Openses to determine the level of the robustness and strength of viscous damper placed with the diagonal bracing system or V-inverted bracing system as seen in Figures (1a and 1b).
- Investigate the influence of brace flexibility with damper subsystem on seismic response reduction.
- Develop the relationship between the stiffness ratio between the damper and the braced member's stiffness with a reduction in lateral displacement and base shear.
- Devise a method to use the database of the newly designed building in which viscous dampers are used and case studies of the building required to be retrofitted by the viscous damper to increase the stability of the buildings against earthquake.

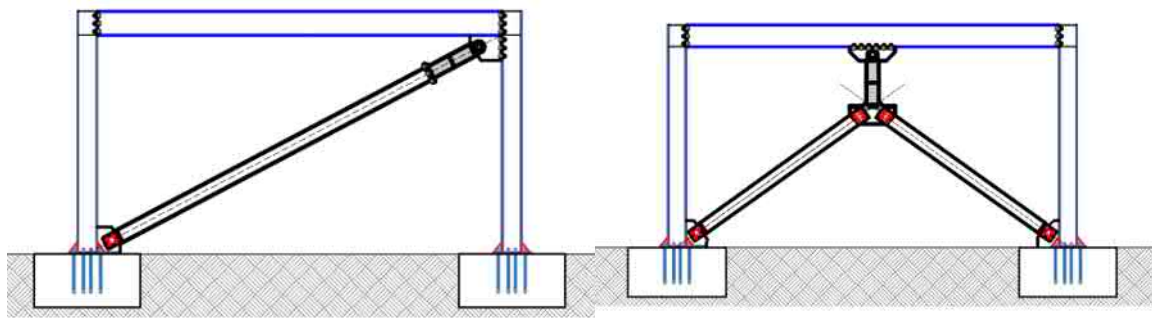


Figure 1: Viscous Damper placement a) installed with diagonal bracing b) with V-Inverted bracing system

RESEARCH METHODS

We will conduct a literature review of studies researching the methodology for reducing seismic response by inserting viscous dampers for the first phase. This research phase may also entail the inclusion of existing case study buildings. Based on the data acquired from the first phase, a new simulation for SDOF systems and MDOF systems can be presented for phase 2.

Phase 1

This phase highlights the identification and investigation of several studies in the literature that have been conducted in different aspects. The primary examples of these aspects are supplemental dampers in SDOF and MDOF systems, optimal size and placement of dampers throughout a building, and the effectiveness of rigid damper subsystem in reducing seismic response.

Phase 2

Case study frames identified in phase 1 of the investigation of rigid damper subsystems to reduce seismic response will be subjected to an in-depth reanalysis. A damper-brace flexibility

7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM

Creating Capacity and Capability for the Future of the Built Environment

investigation may also be helpful in SDOF and MDOF systems. A further step in this phase might be using the newly constructed database with installing viscous dampers or retrofitted buildings with viscous dampers.

ANTICIPATED (OR PRELIMINARY) FINDINGS

- 1- As a result of recent advances in the OpenSees software framework, the outcome may become more reliable and valid for future researches.
- 2- Given the strong association between the linear viscous damper and brace flexibility, it is better to understand the relationship between the nonlinear viscous damper and brace flexibility
- 3- Many new supplemental damper devices to prevent the seismic response are being developed today, which are expected to better design and retrofit buildings. Results of case studies may show the usefulness of using nonlinear viscous dampers in the future more than other devices.

RESEARCH SIGNIFICANCE

The combination of supplemental dampers with braced members can be placed to achieve a more efficient and resilient design for high-rise buildings by minimizing base shear and inter-story drift caused by earthquakes. Compared to a building with no dampers, this technique has two environmental advantages. First, the primary structural frame elements would be smaller when using viscous dampers. We will construct buildings without wasting massive amounts of steel and concrete from a sustainability perspective. As a second benefit, limiting lateral displacement increases safety by limiting the movement of structural and non-structural components. Undoubtedly, the study intends to benefit industry practices. It is particularly beneficial to countries heavily relying on seismic resisting steel systems and susceptible to a high degree of earthquakes, such as Japan, China, and New Zealand.

REFERENCES,

- Lavan, O. J. E. e., & dynamics, s. (2012). On the efficiency of viscous dampers in reducing various seismic responses of wall structures. *41*(12), 1673-1692.
- Losanno, D., Londono, J., Zinno, S., Serino, G. J. C., & Structures. (2018). Effective damping and frequencies of viscous damper braced structures considering the supports flexibility. *207*, 121-131.
- Losanno, D., Spizzuoco, M., & Serino, G. J. E. S. (2015). An optimal design procedure for a simple frame equipped with elastic-deformable dissipative braces. *101*, 677-697.
- Losanno, D., Spizzuoco, M., & Serino, G. J. J. o. E. E. (2019). Design and retrofit of multistory frames with elastic-deformable viscous damping braces. *23*(9), 1441-1464.
- Romero, E. M. J. T. S. d. o. T. B. (1995). Supplementary energy dissipators for maximum earthquake protection of tall building structures. *4*(1), 91-101.
- Soong, T., & Spencer Jr, B. J. E. s. (2002). Supplemental energy dissipation: state-of-the-art and state-of-the-practice. *24*(3), 243-259.
- Xie, R., Rodgers, G., & Sullivan, T. (2019). Influence of Damper Sub-System Stiffness on the Structural Performance of a System Equipped with a Viscous Damper.
- Xie, R., Rodgers, G., & Sullivan, T. J. J. o. E. E. (2021). Effect of Damper Sub-System Stiffness on the Response of a Single Degree of Freedom System Equipped with a Viscous Damper. 1-20.

Thinking Musically About Garden Design for a More Immersive Experience

Stephen Fischer, Queensland University of Technology, Australia.

Assoc. Prof. Mirko Guaralda, Queensland University of Technology, Australia.

Dr. Paul Donehue, Queensland University of Technology, Australia.

Dr. Brett Painter, Environment Canterbury, New Zealand.

SYNOPSIS

While sound is generally recognised as an important sense, it is not often explored in landscape architecture as a driver of design in enhancing well-being (Cerwén, 2017). Additionally, Olin (2013) suggests that restorative aspects of nature “can be brought to the city” through landscape design, and Cerwén (2017) identifies that positive healing outcomes are associated with exposure to ‘nature sounds’ in certain situations. Other existing research has shown that consideration of soundscapes within built environments can be utilised in mitigating unwanted sounds such as traffic in the urban environment for a therapeutic benefit (Marcus, 2007). According to Cerwén (2017, p. 26), there remains gaps in the research in clarifying “contextual cues, types of sounds involved, physical properties of sounds and interactions with other sensory inputs” and in finding opportunities to employ sound as a positive contribution to space. Thus, this paper introduces the idea of ‘composing’ the soundscape of a space through a musical process. With a focus on aural experience in gardens, the project is establishing what types, combinations and intensities of sounds offer interest and distraction and capture unconscious and conscious attention. Just as forms, textures and materiality are already considered in the landscape design process, these ‘sound materials’ will be incorporated into considerations for design thinking.

KEYWORDS: Cross-disciplinary, Design, Inter-disciplinary, Landscape, Soundscape

INTRODUCTION, RESEARCH AIM AND OBJECTIVES

In the not too dissimilar experiential design discourse of Japanese Gardens, importance is placed on sourcing materials that reflect the premise of the experience designed and being constructed. Design intentions are categorised early on in the design process as a way to order and categorise along the journey (naturalistic experiences over time) of the garden with appropriate materiality reflecting the value of each intention as it unfolds (Suzuki, 2004).

Thinking about journeys through gardens, this project is taking the human-centred stereo experience over time and relates this unfolding aural experience to listening to music where one also encounters a real-time stereo, designed aural experience. As a Musician and Landscape Architect, Cerwén's work (2017) has set the stage for going beyond just ‘noise mitigation’. This project's interpretation has been to consider elements in the landscape like instruments in the orchestra, suggesting that spatial layout, material choices as well as installed features in the landscape and their orchestration, all contribute to a ‘musical score’. Each listener's experience will be different as it is with great musical performance, however, it is the ‘composer's intentions’ this project is aiming to facilitate. By pulling apart a masterpiece, one can discover orchestration tools, combinations of timbres, and the interplay

7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM

Creating Capacity and Capability for the Future of the Built Environment

between instruments that can be applied to other new or existing compositions and we believe this to be the case also with other sound environments.

RESEARCH METHODS

Recording: The first aspect of the project has been to consider how to record gardens in a way that is useful. As sounds occur in space at various places along both horizontal and vertical planes, considering their locations, qualities and ultimately value could become quite complex. Some research into traditional field recording techniques was executed as well as other forms of soundscape studies. During this process, 'bin-aural' microphones/earphones were identified and it was ultimately decided that this recording technique involving 'microphones at the ears' was to be adopted for the project for two reasons. The first is that it's very difficult for the human brain to distinguish between sounds forward or backward of them without other sensory cues (Yuhas, 2012). The second is that an aural perspective can be notated a point in space using a left to right axis in accounting for potential experience at any given point in time (along a journey). Recordings were taken at three different gardens, split into four journeys, and used to represent a stereo soundscape experience over time.

Transcription: In the practice of music, especially modern music with less traditionally published scores, transcription becomes a secondary means of documenting sound with published recordings (or 'records' as commonly referred to still in the United States) being primary. However, while transcription is only really useful to those with developed aural skills, it then facilitates the scoring of music in order for learners to access the fundamental instructions which make such music. In this project, the resultant bin-aural recordings were viewed as wave forms. These were also manipulated and plotted around the journey path taken before being colour coded to align to the researcher's critical listening experience of when and where dominant sounds occur, their type and qualities. As per Figures 1 & 2, one showing a full journey, and the other a segment of that journey. The dominant water sound is coloured blue, however other secondary and tertiary sounds noted in the soundscape were transcribed and documented also (in Figure 2).



Figure 1

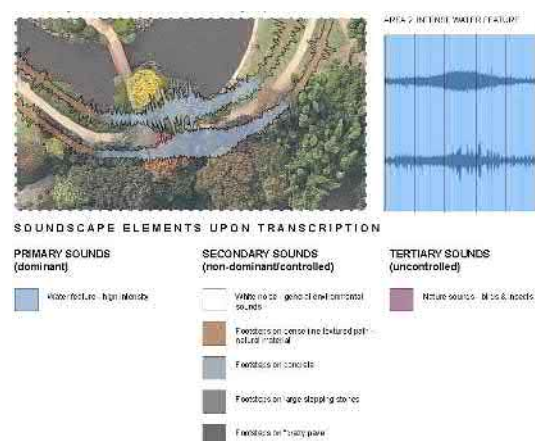


Figure 2

ANTICIPATED (OR PRELIMINARY) FINDINGS

By breaking the soundscape down into these primary, secondary and tertiary elements (or sounds, or instruments etc.), we have established the opportunity now to work with sound in

7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM

Creating Capacity and Capability for the Future of the Built Environment

new ways. ‘Timbre’ or textures in music consider the quality of not just one instrument or voice, but combinations of two or more playing at once for an enhanced sonic phenomenon. Through such considerations in a design context, the Landscape Architect will be able to extend upon the term ‘composition’ to now include potential soundtracks in addition to how the movie (visual experience) plays, hopefully bolstering real-time immersion, and certainly connecting experiences and memories (Istvandity, 2014).

RESEARCH SIGNIFICANCE

Sounds in the landscape could be arranged in the same way we design planting layouts for a resultant form or even ‘vibe’. By facilitating the use of sounds as elements and as a form of materiality to be specified in accordance with a certain desired experience, we have opened up the possibility of creating new worlds to become immersed in that go beyond the predominant ‘visual’.

ACKNOWLEDGEMENT

This PhD project is supported by the Australian Government’s ‘Research Training Program’ funded jointly with the Queensland University of Technology.

REFERENCES

- Cerwén, G 2017, *Sound in Landscape Architecture* (Vol. 2017).
- Foundation, T C L (Producer) 2013, Laurie Olin on Design: Evoking Nature in the City.
- Istvandity, L. (2014). The lifetime soundtrack: Music as an archive for autobiographical memory. *Popular Music History*, 9(2).
- Istvandity, L 2017, Combining music and reminiscence therapy interventions for wellbeing in elderly populations: A systematic review. *Complementary therapies in clinical practice*, 28, 18-25.
- Marcus, C C 2007, Healing gardens in hospitals. *Interdisciplinary Design Research*, 1(1), 1-27.
- Suzuki, A 2004, The Learning Process Of Japanese Gardens. In *Graduate School of Engineering, Urban Design Research Seminar Proceedings*.
- Yuhas, D 2012, Sound Science: Where Did That Noise Come From?. Retrieved 29 October 2021, from <https://www.scientificamerican.com/article/bring-science-home-two-ears-sound/>

The Role and Challenges of Real-Time Employee Monitoring Technology (REMT) in the Digitalisation Transformation Process of the New Zealand Construction Sector

Raymond Wei Wu, School of Built Environment, Massey University, Auckland, New Zealand.

Tak Wing Yiu, School of Built Environment, Massey University, Auckland, New Zealand.

Mostafa Babaeian Jelodar, School of Built Environment, Massey University, Auckland, New Zealand.

SYNOPSIS

The New Zealand construction industry is exploring more comprehensive and advanced technologies to improve workplace health & safety, and productivity in the post-Covid environment. Real-time Employee Monitoring Technology (REMT) is a necessary infrastructure in the digitalisation process. Still, monitoring frontline workers have not been welcomed, which indicates some concerns for applying these technologies in the sector.

The benefits and concerns for REMT have been studied in many different forms. However, the role and challenges in the New Zealand construction context remain unstudied. This paper aims to review the challenges of REMT adoption in the NZ construction industry, identify and explain the influence factors, and draw on practical considerations in terms of the broad adoption of REMT in the near future. This study adopts reviews of recent industry reports, surveys and a national position paper, discover the role and challenges of REMT in the process of Digitalisation in the NZ construction sector.

The preliminary result identified the influence factors on REMT adoption and showed the NZ construction industry's initial readiness. The previous survey results have been reviewed and discussed. The role and challenges of REMT will play a functional role to build up a baseline to design a best practice guideline for REMT adoption in the NZ construction sector.

KEYWORDS: Monitoring technologies, Real-time frontline worker monitoring, Impacts on construction worker monitoring, Digitalisation in the NZ building industry

INTRODUCTION

Digital technologies have been applied to almost every sector to improve their products and services (IDC, 2020). International building companies have demonstrated the benefits that digital technologies can produce (Jones et al., 2020). New Zealand construction industry lagged behind other sectors in the improvements and adoption of technologies (Wilkinson et al., 2017). Real-time Employee monitoring Technology (REMT), one of the essential and necessary infrastructures for future connected construction sites, has aroused significant interest in recent years from the sector (Hagen et al., 2018). In the presence of the Covid work environment, technologies, including contact tracing and behaviour monitoring, have been quickly introduced at the construction sites (Juha, 2020). REMT applications are becoming popular to enable the contemporary practice of capturing and analysing health and behaviour-related data for a safer industrial approach (Lin et al., 2013; Michael et al., 2006). The development of monitoring technologies—such as artificial intelligence with increasingly sophisticated systems that gather multitudes of data across diverse industries and working environments—is rapidly evolving internationally (Holland et al., 2015). The global construction sector receives

considerable support from new monitoring technologies. New Zealand building companies are also exploring digital monitoring technologies to reduce health & safety issues and improve productivity (Keall, 2020).

This study identified the role of REMT and compared it with other digital technologies used in the NZ building industry, which indicated that with the higher impact of technologies, a more likely adoption would be in the sector. Research also showed that REMT has extensive value in the phrase of constructing and operating (Jones et al., 2020). Figure 1 illustrates the role of REMT in the current NZ building industry by showing the impact and likeliness of the adoption of digital technologies.

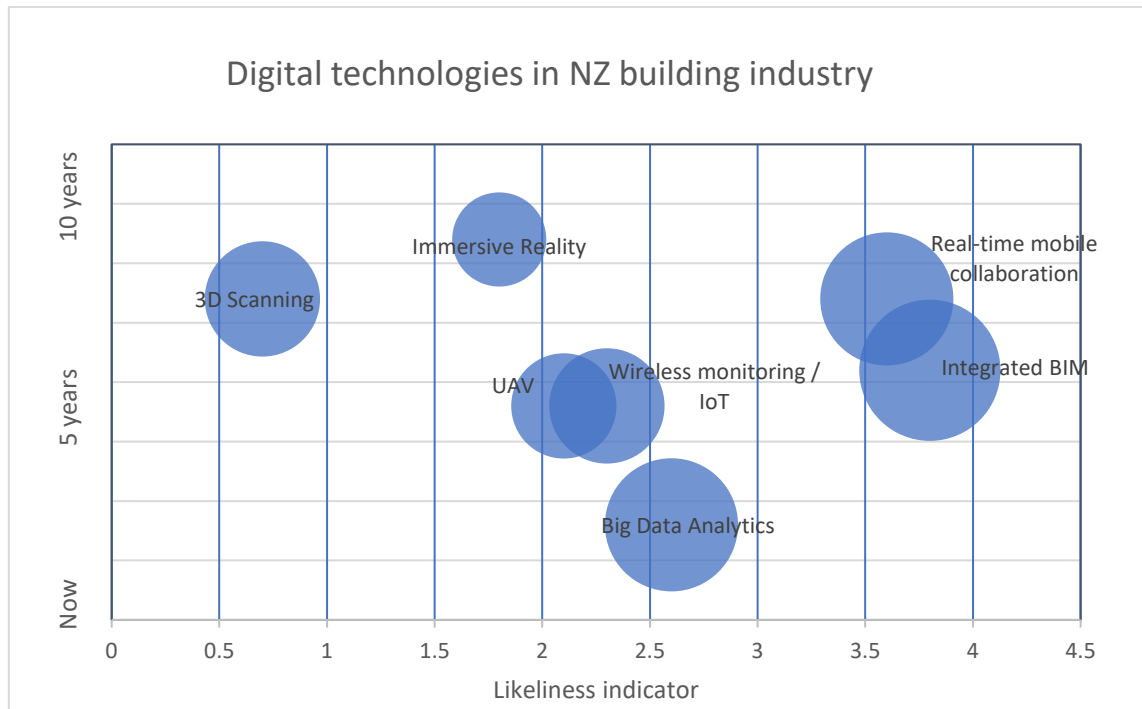


Figure 1. The role of REMT in the NZ building industry

Although REMT can address some of the critical challenges plaguing the labour-intensive construction sector, including low productivity and health & safety issues, such technologies and applications to track individual workers have not been universally welcomed in New Zealand (Jones et al.). Robust debates exist between employers and employees—employers consider these a new norm (e.g. safety outweighs privacy). In contrast, employees tend to disagree with this proposition and keep requesting open and transparent policies on using these technologies. A previous study has argued that workplace surveillance could significantly impact the employment relationship, creating trust barriers between the parties (Connolly, 2019). Moreover, REMT functions as a performance review, which can potentially damage work motivation, and it may cause employees to engage in deviant or counterproductive behaviours under the monitored environment (Alder et al., 2007). Data security and privacy have become critical considerations for digital transformation (DX) and innovations. Lack of understanding of REMT, data standards and privacy management strategy set a barrier for the monitoring technologies deployment in the NZ construction industry. In conclusion, further studies will be recommended for the construction community to get our readiness to adopt digital real-time monitoring tools.

RESEARCH AIM AND OBJECTIVES

7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM

Creating Capacity and Capability for the Future of the Built Environment

This paper aims to review the challenges of REMT adoption in the NZ construction industry, which is achieved by examining NZ industry awareness of technologies, identifying and explaining the influence factors, and drawing on practical considerations regarding the broad adoption of REMT in the near future.

RESEARCH METHODS

The research method for this study is reviewing some recent industry reports, discussing survey results and a national position paper, discovering the role and challenges of REMT in the digitalisation process of the NZ construction sector.

PRELIMINARY FINDINGS

The New Zealand building industry needs to build a solid foundation to provide a legitimate and secure way to monitor frontline workers and future affiliated construction sites. The study firstly exam the survey results for the readiness of REMT in the New Zealand construction sector. Many monitoring technologies are widely used and provide value to the industry. However, there are many challenges and oppositions to set a roadblock for building companies to adopt such technologies. There is no one-size-fits-all solution to solve the problems. This study proposes a potential solution to address the current challenges—developing a best practice guideline to regulate employee monitoring and balancing ethical, privacy, and security concerns reasonably.

RESEARCH SIGNIFICANCE

The survey question responses have been reviewed and discussed, finding the significant roadblocks of REMT adoption in the NZ construction sector. (1) Need for common standards and monitoring instruction; (2) Workforce mindset needs to be changed, especially negative mindset and building company culture; (3) Understanding of cost and benefits. The role and challenges of REMT established a valuable resource to set up a baseline to design a best practice guideline for REMT adoption at the NZ construction sites.

ACKNOWLEDGEMENT

This work was supported by the Building Research Levy of the Building Research Association New Zealand (BRANZ) [LR12095].

REFERENCES

- Alder, Schminke, M., & Noel, T. (2007). The Impact of Individual Ethics on Reactions to Potentially Invasive HR Practices. *Journal of Business Ethics*, 75(2), 201-214. <https://doi.org/10.1007/s10551-006-9247-6>
- Connolly, C. M. R. (2019). *Employee Monitoring in the Digital Era- Managing the Impact of Innovation* Entrenova,
- Hagen, C. S., Bighash, L., Hollingshead, A. B., Shaikh, S. J., & Alexander, K. S. (2018). Why are you watching? Video surveillance in organisations [Article]. *Corporate Communications*, 23(2), 274-291. <https://doi.org/10.1108/CCIJ-04-2017-0043>
- Holland, P., Cooper, B., & Hecker, R. (2015). Electronic monitoring and surveillance in the workplace. *Personnel Review*.
- IDC. (2020). *Autodesk-IDC-Digital Transformation_The-Future-of-Connected-Construction*
- Jones, D., Amor, R., & Bellamy, L. (2020). *<BIP-Digitalisation-of-the-New-Zealand-Building-Industry-Position-Paper-digital-version.pdf>*.

7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM

Creating Capacity and Capability for the Future of the Built Environment

- Juha, H., Johanna, K., Satu, M., Janne S. (2020). IoT-based safety monitoring from the perspective of construction site workers. *International Journal of Occupational and Environmental Safety*, 4(1), 1-14. [https://doi.org/https://doi.org/10.24840/2184-0954_004.001_0001](https://doi.org/10.24840/2184-0954_004.001_0001)
- Keall, C. (2020). Fletcher Building turns to NZ developer for contact-tracing and Covid-19 safety app. *New Zealand Herald*. https://www.nzherald.co.nz/technology/news/article.cfm?c_id=5&objectid=12330520
- Lin, P., Li, Q., Fan, Q., & Gao, X. (2013). Real-Time Monitoring System for Workers' Behaviour Analysis on a Large-Dam Construction Site. *International Journal of Distributed Sensor Networks*, 9(10). <https://doi.org/10.1155/2013/509423>
- Michael, K., Mnamee, A., & Michael, M. (2006). The Emerging Ethics of Humancentric GPS Tracking and Monitoring. International Conference on Mobile Business, Sydney.
- Wilkinson, S., Tookey, J., Patangaroa, R., MacGregor, C., Milicich, M., Ghodrati, N., Adafin, J., Stocchero, A., & Bayne, K. (2017). *Transforming the Building Industry State of Nation Knowledge report*.

A Review of the Impacts of COVID-19 on the Construction Industry in Auckland, New Zealand

Seyedeh Faezeh Mirhosseini, Massey University, New Zealand.

Suzanne Wilkinson, Massey University, New Zealand.

Mostafa Babaeian Jelodar, Massey University, New Zealand.

SYNOPSIS

The construction industry is one of the largest industries in New Zealand, and changes to the industry affect the New Zealand economy. COVID-19 has posed tremendous hardship on the construction industry. As a prominent and populated city with many construction projects, Auckland's construction sector has suffered some of the most severe effects from COVID-19. The effects of the COVID-19 pandemic have been studied in different fields; however, the impacts of COVID-19 on the construction industry in Auckland have not been studied in detail.

The purpose of this paper is to show the extent of COVID-19 challenges and impacts on the construction industry in Auckland and, consequently, to understand how Auckland construction confronted the related issues. The paper is in the form of a literature review. The paper's aim was achieved through a document review, including research papers, government resources, and released news and statistics.

The findings show that Auckland tackled the impacts of COVID-19 on its construction industry using different techniques, depending on the problem anticipated. Auckland is the most populated city in New Zealand, where many construction projects are undertaken and where construction workers reside. Investigating the impacts of COVID-19 on the construction industry in Auckland and how Auckland managed the impacts is useful for other companies and project managers to help mitigate COVID-19 adverse effects.

KEYWORDS: Auckland, Construction Industry, COVID-19, New Zealand.

INTRODUCTION

The construction sector in Auckland produces jobs and develops infrastructure while supporting its suppliers' businesses (Vrijhoef & Koskela, 2000). Residential and commercial construction and infrastructures, such as roads and energy services, are all part of the construction industry in New Zealand (Statista, 2021).

Due to the demand for housing, offices, roads, energy, fibre installation, and water supply, the construction sector in New Zealand has grown steadily over the last five years, adding approximately 15.82 billion NZ dollars to the country's GDP (year-end March 2021). The construction sector makes a further contribution to the country's economy, with over 170,000 individuals employed in the first quarter of 2021 (Statista, 2021)

The property market in New Zealand has been a hot topic in recent years. Population increase in the North Island has fuelled home construction in Auckland. Over the last few years, the number of new houses in the Auckland region has steadily increased, owing to the strong demand for residential properties. As a result of the shortages, residents of this large urban area have seen house prices rise (Statista, 2021). Furthermore, Auckland is home to over three-

7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM

Creating Capacity and Capability for the Future of the Built Environment

quarters of New Zealand's businesses. In 2020, the *COVID-19* caused a minor drop in building work (Statista, 2021). In New Zealand, *COVID-19* impacts were predicted to cause shortages, low-quality buildings, affordability challenges for delivering adequate housing, and slowing of the current building (Shooshtarian et al., 2021). According to (Dodd & Liao, 2020), businesses in Auckland are particularly heavily hit by the border shutdown and lockdowns. The stock market performance was particularly severe for companies headquartered in Auckland. According to William (2021), the building and construction sector remained resilient despite all these issues. The industry has been in a stronger position to lead economic recovery from COVID-19.

RESEARCH AIM AND OBJECTIVES

This study aims to investigate the impacts of COVID-19 on the construction industry in Auckland. The purpose of this paper is to show the extent of COVID-19 challenges and effects on the construction industry in Auckland and, consequently, to understand how Auckland construction confronted the related issues.

RESEARCH METHODS

The paper is in the form of a literature review. The paper's aim was achieved through a document review, including research papers, government resources, and released news and statistics. The main methodology for this study is reviewing online documents and media News and media related to construction issues in Auckland due to COVID-19 were studied. Data was primarily derived from the "Knowledge Basket" website, which is the New Zealand news and information archive. The primary searched keywords were "construction", "COVID-19", "New Zealand," and "Auckland". The same step was followed by changing the term "COVID-19" to "Corona Virus" and repeating the process. The period set was from 31 Dec 2019 (when the new virus was reported to the World Health Organisation) to 01 Nov 2021. The initial result consists of 324 sources. After filtering the results, ten resources were finally analysed for content about the impacts of COVID_19 on the Auckland construction market. These ten sources represented the range of effects and challenges reported in the media.

PRELIMINARY FINDINGS

Table 1 shows the range of media information available on the impacts of COVID_19 on the Auckland construction industry.

Table 2: The released news and its date and source (Authors, 2022)

Source	Date	Quote	Key Factor
interest.co.nz	14 Jan 2021	Auckland had record levels of new homes consented to in November 2020. These consents are an intention to build, <i>though COVID-19 may have caused delays</i> for some projects. Consent increase helps set up a "<i>low supply</i>" situation that underpins <i>high house prices</i> - and <i>declining affordability</i>.	• Delay • Short supply • Increasing price

7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM

Creating Capacity and Capability for the Future of the Built Environment

STUFF.CO.NZ	8 MAR 2021	The pandemic reports <i>affect the price and availability of building supplies</i> in Auckland's residential market. A Statistics New Zealand survey on the impact of Covid-19 on Auckland's residential building projects found six out of 10 respondents had had <i>difficulty sourcing materials or equipment</i>.	- Increasing price - Short supply
Radio New Zealand Newswire	04 Sep 2021	Auckland's level 4 lockdown has <i>cut off both the manufacture and distribution of all but essential supplies</i> .	Short supply
Foreign Affairs	09 Sep 2021	Government announcement regarding a rule change that should <i>enable the release of critical building materials stuck in Auckland</i> provides relief for building and construction businesses 72% of businesses said that their business was <i>experiencing supply chain delays</i> due to alert levels and or port backlogs	- Short supply - Delivery time
Foreign Affairs	16 Sep 2021	While most of New Zealand's construction industry returned to work under Alert Level 3, <i>Auckland waits with bated breath to see whether they will be able to return to work</i> next week.	Delivery time
Foreign Affairs	21 Sep 2021	Level 3 provides <i>some limited extra freedoms to Aucklanders</i> and will allow some businesses such as the construction industries <i>to restart operations</i> as well as click-and-collect from retail and hospitality industries	Delivery time
Live News	22 Sep 2021	Auckland Council's upgrade of Takapuna's main street is in its final stage of construction, and contractors will be <i>working hard to make up for the five weeks of lost time resulting from Alert Level 4</i> restrictions.	Delivery time
Live News	24 Sep 2021	In response to disruptions to <i>building material supply and construction labour shortages</i> we have, as a short-term measure, <i>restarted the manufacturing of critical building products in Auckland in Alert Level 4</i>	- Short supply - Workforce shortage
Foreign Affairs	20 Oct 2021	<i>During Level 4, the site had to close except for essential maintenance.</i> With stringent safety plans in place, Te Ahu a Turanga was one of the first major projects to resume construction in Level 3, and the site is fully operational in Level 2.	Closing Manufacturing
Foreign Affairs	08 Nov 2021	The Government has agreed to allow some <i>building product manufacturing in Auckland during COVID-19 lockdown</i> to support continued residential construction activity across New Zealand.	Short supply

Themes arising from news reports

The central theme of the news was extracted and classified into three primary inter-related issues: supply chain, delivery time, and workforce.

According to (scoop.co.nz, 2021), the supply chain shortages inside Auckland stem from the elimination of expenses, such as overseas travel, which increased the money New Zealanders had to spend and led to people investing in their homes. According to Chaston (2021), in January 2021, despite the pandemic interruptions, consents in Auckland City are up +55 percent from a year ago, leading to shortages of supply.

Since most building products manufactured domestically are manufactured in Auckland, construction projects all over the country face problems. To assist continuing home construction activity across New Zealand, the Government agreed to allow limited building products such as insulation, coated roofing steel, gypsum, and plasterboard manufactured in Auckland under COVID-19 lockdown (Harris, 2021; scoop.co.nz, 2021).

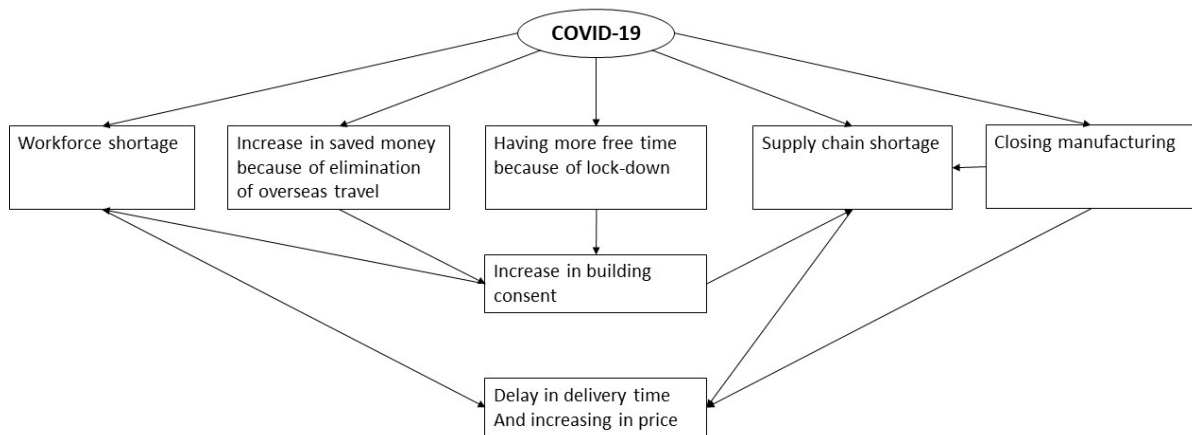


Figure 1: The impacts of COVID-19 on Auckland construction industry based on released news (Authors, 2022)

Figure 1 shows how inter-related issues were affected by COVID-19 and how COVID_19 influenced the construction industry in Auckland. Based on released news, Covid-19 caused workforce and supply shortages. (LOGIC)

People were locked down and could not spend their money. They could also not go overseas for holidays. There was money available for people to spend on other things.

Many people turned to their homes for renovation repairs or looked for new properties.

Demand for renovation, repairs, or new properties caused a surge in building consents and an increased need for construction professionals to do the work.

The increase in building consents meant that more building projects would also need more material, machinery, and resources.

7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM

Creating Capacity and Capability for the Future of the Built Environment

Some of the material came from overseas, but with global supply chains disrupted, and Auckland factories closed, shortages were observed even more. Low supply for resources (people and materials) pushed up prices.

Overall, the industry faced delays in delivery time and increases in prices.

RESEARCH SIGNIFICANCE

Auckland is the home to construction companies, including material suppliers, designers, and builders. It also provides a large construction workforce

Auckland's industry grew during COVID-19 and provided job opportunities but magnified workforce shortage. Auckland faced a lack of supply and workforce and increasing housing prices. According to the media studied for this paper, COVID-19 was considered the leading cause of the housing cost rise, the rise of construction material prices, and the lack of workers.

REFERENCES

- Chaston, D. (2021). Residential building consents jump in November, partly as COVID catchup, partly encouraged by very strong demand for housing where supply is very constrained. from interest.co.nz <https://www.interest.co.nz/property/108602/residential-building-consents-jump-november-partly-covid-catchup-partly-encouraged>
- Dodd, O., & Liao, S. (2020). Health or wealth? New Zealand response to the Covid-19 pandemic and stock market performance.
- Harris, C. (2021). Government lets factories return to unplug building supplies bottleneck [Press release]. Retrieved from Government lets factories return to unplug building supplies bottleneck scoop.co.nz. (2021). The Effect Of COVID-19 On New Zealand's Construction Industry.
- Shooshtarian, S., Maqsood, T., Wong, P. S., Khalfan, M., & Yang, R. J. (2021). Extended Producer Responsibility in the Australian Construction Industry. *Sustainability*, 13(2), 620.
- Statista. (2021). Construction industry in New Zealand - statistics & facts. Retrieved 14-11-2021 from <https://www.statista.com/topics/5725/construction-industry-in-new-zealand/#dossierKeyfigures>
- Vrijhoef, R., & Koskela, L. (2000). The four roles of supply chain management in construction. *European journal of purchasing & supply management*, 6(3-4), 169-178.

Evaluating Capacity and Capability of the Construction Sector: The Application of Big Data Tools

Azam Zavvari, Massey University, New Zealand.

Monty Sutrisna, Massey University, New Zealand.

Mostafa Babaeian Jelodar, Massey University, New Zealand.

SYNOPSIS

The capacity and capability of the Architecture, Engineering, and Construction (AEC) Industry is a broad topic. Capacity and capability can be applied in three different levels: the government, organisations, and projects. This research focuses on how big data tools can improve the planning quality in the future of capacity and capability, especially at the government decision making level. In recent years, the AEC industry has started to apply more modern technologies such as Robots, Internet of Things (IoT), Drones, Radio Frequency Identification (RFID), Cloud Computing and Building Information Modelling (BIM) platforms. These technologies have captured a large amount of data and have pushed the industry to enter the era of big data. With the use of modern technologies, companies now have the ability to collect more data and undertake the analysis of this information to generate more control and confidence over projects and their deliverables, thus reducing the project risk, increase the confidence in the overall project cost and reduce overall waste across the project's life. By collecting the data across the AEC industry, big data can be a tool of great importance across the whole construction industry. Therefore, big data analysis is a big game-changer for future projects. The challenges in front of big data within the ACE industry are the output inconsistency and the complexity that this places on analysing the data produced from the different technologies currently used. In this paper, we will explain how big data analysis can improve planning and technologies in AEC industry.

KEYWORDS: Big Data Analysis, Capacity, Capability, AEC Industry

INTRODUCTION

Construction is one of the industries that has slow movement to adopt the innovation and new technologies at the larger scale, because of the risks that are associated with new ideas or technologies (Meng & Brown, 2018; Wang, Gong, Xu, Liu, & Han, 2021). As the construction industry expands and modern technologies gradually move into it, massive databases continue to fill up with the information from designing work, building model, daily communications, and cost (Iliescu & Ciocan, 2017). Many data sources are available these days, and companies have started to collect the data for their future decision making. The construction data is divided into three categories. The categories are structured data like excel files or SQL databases, semi-structured data such as log files, and mainly unstructured data such as documents, pdf, web pages, text, image, etc. (Cauteruccio et al., 2020; Mao, Zhu, & Ahmad, 2007). The data gets collected in a different format, and it is challenging to access the correct information without the right tool. Big data analytics tools are able to transfer the semi-structured and unstructured data into a structured format to support the decision making of the companies. This paper aims to identify and review the challenges and the issues of big data analysis adoption in AEC industry within New Zealand, along with the recommendation of the potential tools and methods to assist the capacity and capability within the industry.

How big data can help AEC Industry

7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM

Creating Capacity and Capability for the Future of the Built Environment

Big data refers to the huge amount of complex and diversely formatted sets of data that require advanced analytics systems to process, manage, and extract meaningful data (Han & Wang, 2017). Data in construction is collected by various modern mechanisms, including robots, drones, cameras, sensors, smart applications, and platforms like BIM, etc. (Bourgault, Danjou, & Pellerin, 2020). By using this data the construction sector will be able to make predictions about:

- Materials estimation
- Labor and machinery needs
- Design support system
- Detecting the structural damages
- Manage the cost and risk
- Understand Feasibility of a project

Big data analysis tools, Artificial Intelligence, and Machine Learning Methods can predict any potential issues before actual construction gets started (Huang, Ninić, & Zhang, 2021). During the construction phase, contractors can use the benefit of big data analytical tools. For example, for capacity and capability prediction, these tools can be applied to track the employees' movements for health and safety. They also can have intelligent decision-making for material and equipment to save time and cost. In the absence of accurate and detailed data and information, planning for infrastructure face a huge obstacle in assessing weaknesses and strengths. The industry needs to know the gaps in advance to provide a basis for developing programs for their improvement.

Capacity and capability

Big data analysis also can hugely help predict capacity and capability. Capacity and capability as critical players for infrastructure planning and long-term decision-making progress, to modify the industry for future changes (Mouchili, Aljawarneh, & Tchouati, 2018). For example, it is possible to predict the workforce as one of the main indicators of capacity and capability with historical data. Based on workforce demand prediction, the industry can identify critical skill gaps in the future. Then the government can start to fill up the gap with policies for skilled worker emigrants and training for contractors, clients, and newbies.

CONCLUSION

It is extremely important within any industry to understand its capacity and capabilities from the past, present and future. With the help of big data analysis, this information enables the industry to undertake planning, reduce overall risks and costs to projects and improve the industry overall with time. Capacity and capability within an industry is not created by accident, and this includes the AEC industry. There has to be an intervention within the industry to standardise planning, design and management in a structured data format so this data can be utilised in the future. The first stage is collecting the available data and providing/transposing it into a standard structured format to be able to be used within an analysis. Movement forward in the future, the Government needs to assist in in standardisation of data by applying new policies and regulations regarding data collection throughout the industry. Every industry for its infrastructure planning needs to have a measure of its capacity and capabilities. With the help of big data analysis, this information enables the industry to create and operate and, in

7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM

Creating Capacity and Capability for the Future of the Built Environment

general, improve themselves over time. Capacity and capability do not happen with an accident, and the industry needs to make it with planning, design, and management. And the first stage is collecting data and giving the structure to the massive amount of data. Government can help with new policies and regulations regarding data collection.

REFERENCES

- Bourgault, M., Danjou, C., & Pellerin, R. (2020). CONSTRUCTION 4.0: A SURVEY OF RESEARCH TRENDS.
- Cauteruccio, F., Giudice, P. L., Musarella, L., Terracina, G., Ursino, D., & Virgili, L. (2020). A lightweight approach to extract interschema properties from structured, semi-structured and unstructured sources in a big data scenario. *International Journal of Information Technology & Decision Making*, 19(03), 849-889.
- Han, Z., & Wang, Y. (2017). The applied exploration of big data technology in prefabricated construction project management. In *ICCREM 2017* (pp. 71-78).
- Huang, M., Ninić, J., & Zhang, Q. (2021). BIM, machine learning and computer vision techniques in underground construction: Current status and future perspectives. *Tunnelling and Underground Space Technology*, 108, 103677.
- Iliescu, M., & Ciocan, R. (2017). Modern technologies innovation in use for quality control on construction site. *Procedia Engineering*, 181, 999-1004.
- Mao, W., Zhu, Y., & Ahmad, I. (2007). Applying metadata models to unstructured content of construction documents: A view-based approach. *Automation in construction*, 16(2), 242-252.
- Meng, X., & Brown, A. (2018). Innovation in construction firms of different sizes: drivers and strategies. *Engineering, Construction and Architectural Management*.
- Mouchili, M. N., Aljawarneh, S., & Tchouati, W. (2018). *Smart city data analysis*. Paper presented at the Proceedings of the First International Conference on Data Science, E-learning and Information Systems.
- Wang, N., Gong, Z., Xu, Z., Liu, Z., & Han, Y. (2021). A quantitative investigation of the technological innovation in large construction companies. *Technology in Society*, 65, 101533.

The Development of a Decision-Support System (DSS) for Selecting Best-Fit Zero-Carbon Building Materials; The Cases of Iran and New Zealand Building Industries

Ali Hashemi Araghi, School of Built Environment, Massey University, New Zealand.
Eziaku Rasheed, School of Built Environment, Massey University, New Zealand.
Priya Vishnu, School of Built Environment, Massey University, New Zealand.

SYNOPSIS

A zero-carbon building is a green and environmental-friendly structure designed and functioning with the primary objective of eliminating or reducing carbon dioxide, thereby positively impacting natural resources and climate change. The current worldwide focus on sustainability and decreasing carbon emissions have significant consequences for the construction sector.

The purpose of this qualitative study is to determine the factors that influence the decision making involved in material choice for zero-carbon buildings by senior construction professionals. In addition, this study seeks to provide mechanisms to overcome the barriers for stakeholders to meet the sustainability challenges in the industry. The research investigates decision-making changes between conventional and sustainable construction and provides a pathway for zero-carbon construction. It will be essential to develop insights into responsible sourcing as an area of growing industry relevance and compare the influence of these factors between New Zealand and Iran. Comparing these two countries with quite different building materials and construction practices could show some interesting emergent properties that both countries could benefit from. The culture of using these materials and the reasons behind their use can advance the body of knowledge in the construction sector. The scope of this proposal is sufficiently well-defined to make the project feasible in the time allocated.

The findings of this study will be beneficial to society, considering that zero-carbon buildings play an important role in the move to a more sustainable future. The greater demand for greenhouses for individuals and companies justifies more effective constructional approaches. Thus, government, businesses, and individuals that apply the recommended approach derived from the results of this study will be able to sustain the environment better. The New Zealand and Iranian construction industry stakeholders, will be guided on what materials should be used to improve resources efficiency. For researchers, the study provides insight into critical areas that have received limited attention in zero-carbon construction and renewable construction materials.

Keywords: Zero Carbon Building, Sustainability, renewable energy, construction materials

INTRODUCTION

Over the last few decades, the world's population has increased more rapidly than ever before. In Iran, the housing demand rises daily. Due to the lack of structural materials, houses are expensive as a significant part of society cannot afford to buy homes or apartments, especially in Tehran (Rouhani, 2019).

7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM

Creating Capacity and Capability for the Future of the Built Environment

According to the research published by United Nations (2009), more than 40% of the construction industry's global energy consumed leads to operational carbon emissions and one-third of worldwide greenhouse gas emissions (Pearce & Ahn, 2017). It is also estimated that more than 50 per cent of the water and energy that flows into buildings is wasted (U.S. Energy Information Administration, 2021).

The building and construction sector makes up approximately 20% of New Zealand's greenhouse gas emissions (Ministry of Business Innovation and Employment, 2020). In Iran, this sector is responsible for 24.1% of CO₂ emissions, which is more than household sectors, occupied by 23.4% (worldometers, 2020). Research indicates that until 2025, scientists forecast that buildings will be the largest consumers of energy, even more than transportation systems and industrial sectors (Li et al., 2018).

Adding to the issue is the traditional materials used in building construction which consumes 56% more energy in the long term. U.S. Energy Information Administration (2013) indicates that the increasing number of new building construction will consume a large amount of energy which adds a burden to the environment. Economically, this will cost residents a vast amount of money on utility, while simultaneously, environmentally, it will emit carbon dioxide. Buildings consume more than 40 per cent of energy usage and produce 24 per cent of greenhouse gas emissions (Riedy, 2012).

Reducing carbon emissions in structures will be crucial to achieving the Paris climate aims and net zero emissions by 2050 while simultaneously eliminating the negative impacts. However, green buildings alone may not completely solve the potential problems. One practical solution is exploiting local natural resources or materials from the origin to construct zero carbon buildings. In the long-term, these locally sourced zero carbon structures will contribute to both society and the environment; consequently, they will achieve economic, environmental, and social sustainability. In this research, the authors investigate which factors have the most influence when choosing zero-carbon building materials in Iran and New Zealand.

Green Building Materials used in Construction

Zero carbon building materials are different from traditional construction materials. Generally, raw materials are used to produce zero carbon structure materials using natural resources as minimum as possible. It mainly uses garbage, tailings, and further types of waste materials to decrease manufacturing costs the waste of natural resources. Zero carbon structures reduce energy production processes and pollution-free manufacturing technology, plummeting environmental risks and controlling costs. The strategy of zero-carbon building products is about improving the quality of human life as the main goal (Cai & Sun, 2014). A review of literature provides numerous Green building materials used in construction, such as those described below:

- **Low Carbon Brick:** In recent years' engineers and scientists discovered a new technology for making brick that does not need high-temperature fire and escapes the usage of high-energy materials like Portland cement. This knowledge solves the disposal issues associated with construction and demolition waste mitigation. (PTI, 2021).
- **Wood (Timber):** Timber is a renewable and natural material that reduces carbon dioxide emissions. There are different types of timber construction systems such as cross-laminated timber, and timber frame not only reduce carbon emissions but also bring the

positive aspects of up-to-date construction methods. Therefore, using this type of build system could reduce construction time, decrease waste, increase safety. (Wood for good, 2021).

- **Bamboo:** Considering bamboo as a green and sustainable material is still debated. Supporters believe that due to its sustainable harvesting, and similar properties to wood, bamboo could be a green alternative to other materials used in the construction and interior design. (Inbar, 2021). However, others argue that the environmental expenses of bamboo production and the fact that most bamboo jungles are far from western countries outweigh bamboo's green advantages (Inbar, 2021).
- **Raupo:** Raupo is from the same family as the bulrush, and it is counted as a sustainable material, mainly was common in New Zealand around the shallow edges of lakes. Collecting it is easy; moreover, it is dry to assemble into constructions quickly. Thatched into rows, the stems slow water penetration and provide a suitable thermal insulation level. Alsoraupo may have been used with a timber framework (Isaacs, 2005).
- **Fibreglass:** Fibreglass is one of the best choices when engineers and architectures look for energy-efficient, green, and sustainable materials because of its composition and low energy required to produce fibreglass from raw materials. Usually, fibreglass does not need extra materials to reinforce it, so decreasing the windows doors' weight and bulk could help cut the transportation budget. (ENERGY STAR, 2021) Furthermore, fibreglass has a long lifecycle, and even if it is broken, it could recycle and use again. (ENERGY STAR, 2021).
- **Structural Insulated Panels (SIPs):** Structural insulated panels (SIPs) are a kind of sandwich panel with an insulating foam core, widely used in the construction industry, including residential and light commercial. Oriented strand board (OSB) is one kind of board. Under factory-controlled conditions, SIPs can be manufactured and fabricated to fit almost all building designs. This kind of building system brings strong, energy-efficient and cost-effective (The Structural Insulated Panel Association, 2021).
- **Cordwood:** Cordwood construction is a versatile, economical, low-impact, and beautiful building technique. Instead of using standard long logs, short logs are used to build a wall. For cordwood construction, well-seasoned cedar is preferred to wood because it is naturally rot-resistant (McLeod, 2017). Cordwood building structures can last at least 150 years. This building method can use local construction materials at minimal cost and bring low material impact (Henstridge, 2021).
- **Straw Bale:** Its structural elements usually are oats, rice, wheat and rye straw that are usually covered by stucco, plaster, clay, or other treatment on the interior and exterior sides of a bale wall. This building method offers a sustainable, bio-based insulation material for structure resulting from cereal food crop production (Walker, et al., 2020).
- **Earthbags:** Earthbags are excellent material for zero carbon buildings due to their resistance to moisture damage. Installing and building houses with earthbags is easy, decreasing construction expenses. When filled with insulation such as perlite or scoria, earthbag walls and foundations enable you to grow plants year-round. (Geiger, 2009).
- **Steel:** One of the most popular construction materials is steel structure, which is often used with concrete to make extraordinary and lifelong buildings. Because of its versatility, sustainability, flexibility, and cost-effectiveness are often chosen as the main building material. (allplan, 2019).
- **Thatch:** It is a traditional but common roofing material. The building elements commonly use dry vegetation, such as straw, palm leaves, and water reeds that are

naturally sourced. Therefore, the building materials can be sourced locally and eco-friendly (Mohanram, 2018).

- **Composites:** A combination of two construction materials that have enhanced features when used together than they do apart is known as composite construction. The most common composite material used in construction is concrete. Other materials such as Fibre-reinforced polymer (FRP), Carbon-fibre-reinforced polymer (CFRP), and Glass-fibre-reinforced plastic (GFRP) are also used widely. Composites are generally used in the construction industry for architecture, bridges, infrastructure, refurbishment, etc. The features of composites include low maintenance, fire-resistant, superior durability, lightweight and short construction times (Ostrowski, et al., 2020).
- **Natural Fibre:** The use of natural fibres reinforces the strength properties of the composites. Some natural fibres include coconut fibres, sisal fibres, jute fibres, flax fibres, etc. To achieve eco-friendly composites, natural fibres are sustainable and renewable resources. Natural fibres have numerous advantages, such as renewability, lightweight, cost-effectiveness, biodegradability, and high specific properties (Girijappa, et al., 2019).
- **Polyurethane:** Polyurethane, a plastic material, is used in a wide variety of applications, including in building insulation, construction applications, cushioning for furniture, carpet, composite wood panels and so on. Polyurethane has several advantages, such as strength-to-weight ratio, insulation properties, durability and versatility. Polyurethane plays a vital role to support our daily lives to be more convenient and environmentally friendly (American Chemistry Council, 2021)
- **Cellulose:** Cellulose, a molecule, comprises carbon, hydrogen and oxygen atoms. The core element found in plant cell walls is cellulose. It is a superior insulation material with low embodied energy and can resist air infiltration. Newsprint and other wood fibre made paper are the source of cellulose building. Thus, it is a recycled material (Lea, 1996).
- **Cork** is probably one of the most sustainable and eco-friendly construction materials. It is chemical-free, non-toxic, waterproof, 100% recyclable, fire retardant, and soundproof (WILLIAMS, 2020).
- **Stone:** Stone counts as a green material for buildings because it is natural and durable. Also, the stone is recyclable and could last for years if it receives appropriate maintenance and care. (Vierra, 2016).

METHODOLOGY

This research assesses the impact of material sourcing for zero-carbon building. We will use a questionnaire and interviews with experts across the industry, such as civil engineers, architects, environmental engineers, project managers, construction managers, developers and major clients in New Zealand and Iran. This research intends to answer the following questions:

1. What factors influence construction professionals' decision-making when considering material choices for conventional and sustainable practices?
2. What are the similarities and differences between New Zealand and Iran?
3. What are the zero-carbon building effects on the environment?
4. What are the zero-carbon building effects on resource efficiency?
5. How does the usage of recycled and reusable materials compare between the New Zealand and Iran construction sectors?

7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM

Creating Capacity and Capability for the Future of the Built Environment

This research uses a mix of quantitative and qualitative methods to investigate the effects of green building materials on the environment and resource efficiency by using interviews and a Doodle survey, made using an online data gathering platform, will be used as the principal instruments of the survey. Target participants for this research are professionals working in construction companies in New Zealand and Iran.

CONCLUSION

The findings of this study will be beneficial to society, considering that zero-carbon buildings play an essential role in the move to a more sustainable future. The greater demand for zero carbon houses for individuals and companies justifies the need for more effective constructional approaches. Thus, governments, businesses, and individuals that apply the recommended approach derived from the results of this study will be able to sustain the environment better. It will help them reduce the building and maintain costs on structures. The New Zealand and Iranian construction industry stakeholders will be guided on what materials to use to improve resources. For researchers, the study provides insight into critical areas that have received limited attention in zero-carbon construction and renewable construction materials.

REFERENCES

- allplan, (2019). Steel for Construction, Austria: Nemetschek Group.
- American Chemistry Council, (2021). Polyurethane Applications, Washington D.C: ACC.
- Cai, j.-w. & Sun, J., (2014). Brief Discussion on Green Building Materials. Ningbo, China, IOP.
- ENERGY STAR, (2021). Fiberglass Green And Sustainability, Schaumburg, Illinois: FGIA.
- Geiger, O., (2009). Earthbag Greenhouses, USA: Natural Building Blog.
- Girijappa, Y. G. T., Rangappa, S. M., Parameswaranpillai, J. & Siengchin, S., (2019). Natural Fibers as Sustainable and Renewable Resource for Development of Eco-Friendly Composites: A Comprehensive Review, Lausanne: Frontiers.
- Henstridge, J., (2021). Durability of Cordwood Homes, Kansas: mother earth news.
- Inbar, (2021). How 'Green' Are Bamboo Products?, China: International Bamboo and Rattan Organisation.
- Isaacs, N., (2005). Going back in time raupo houses, New Zealand: Branz.
- Lea, D., (1996). Cellulose: Building Insulation with High Recovered Content, Low Embodied Energy, Gainesville, FL, USA: Green Building Materials.
- Li, J.-F., Ma, Z.-Y., Zhang, Y.-X. & Wen, Z.-C., (2018). Analysis on energy demand and CO₂ emissions in China following the Energy Production and Consumption Revolution Strategy and China Dream target. *Advances in Climate Change Research*, pp. 16-26.
- Marsh, J., (2021). How many solar panels do I need for my home? USA: Energy Sage.
- McLeod, B. R., (2017). Tricks of the Trade: Building With Cordwood, New Hampshire: northern wood lands.
- Ministry of Business Innovation and Employment, (2020). Building for Climate Change: Transforming operational efficiency and reducing whole-of-life embodied carbon, New Zealand: MBIE.
- Mohanram, A., (2018). Charming thatch, India: thehindu.
- Ostrowski, K. A., Kinasz, R. & Dybel, P., (2020). The Impact of Surface Preparation for Self-Compacting, High-Performance, Fiber-Reinforced Concrete Confined with CFRP Using a Cement Matrix, Basel, Switzerland: MDPI.
- Pearce, A. & Ahn, Y. H., (2017). Sustainable Buildings and Infrastructure: Paths to the Future, U.K.: routledge.
- PTI, (2021). Low-carbon bricks developed using C&D waste for energy-efficient walling envelopes. [Online]

7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM

Creating Capacity and Capability for the Future of the Built Environment

- Available at: <https://www.thehindu.com/sci-tech/science/low-carbon-bricks-developed-using-c-and-d-waste-for-energy-efficient-walling-envelopes/article36494316.ece>
- Riedy, C., (2012). What is a zero carbon building?, Ireland: Medium.
- Rouhani, H., (2019). Iranians struggle to afford housing as prices soar, Doha: Aljazeera.
- The Structural Insulated Panel Association, (2021). What are SIPs?, USA: SIPA.
- U.S. Energy Information Administration , (2013). International Energy Outlook 2013, Washington DC: EIA.
- U.S. Energy Information Administration, (2021). Energy use in homes, Washington DC : EIA.
- Vierra, S., (2016). Top Five Reasons Why Natural Stone is a Sustainable Choice for Your Home, Ohio: use natural stone.
- Walker, P., Thomson, A. & Maskell, D., (2020). Nonconventional and Vernacular Construction Materials , USA: Woodhead.
- Williams, . J., (2020). Why cork could be the sustainable building material of the future, u.k.: Elle Decoration.
- Wood for good, (2021). How Can Building With Timber Help Us To Achieve Our Net Zero Goals?. [Online]
Available at: <https://woodforgood.com/news-and-views/2021/05/28/the-environmental-and-sustainable-benefits-of-building-with-timber/>
- Worldometers, (2020). Iran CO2 Emissions. [Online]
Available at: <https://www.worldometers.info/co2-emissions/iran-co2-emissions/>

Poster Presentations

7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM

Creating Capacity and Capability for the Future of the Built Environment



Energy Efficient Building Design – Energy Audit – A Mini Research Project (BRANZ Funded): Building Capability to help the Construction Industry Transition to Zero Carbon

Student: Kris Wang

Supervisor: Eziaku Rasheed

Master of Construction - School of Built Environment - Massey University



1. Introduction

The audited property at 318 Sturges Road lies on the southern side of Sturges Road in a semi-rural area surrounded by trees in a gentle valley. The single-storey gable-roofed rectangle-shaped bungalow lies 200m below the main road. Thanks to the natural landscaping configuration, the building has a perfect northern/west orientation towards the sun and has a good shelter. An internal arrangement of the rooms is enormously efficient due to the aspect and use related to the direction towards the sun. Energy-efficient building design took place in 2016 until now. Extensive renovation with added Passive House Design features contributed enormously to reducing energy use and increasing lifestyle to the next level.

2. Aim and Objectives

1. Identify the importance of the building orientation and zoning concerning a passive home.
2. To recognize and understand the energy and water usage and what can be done to minimize it.
3. To examine and identify the current issues with a building and capability towards renewable energy in transition to zero carbon.
4. To evaluate possibilities and adoption of the new environmentally friendly insulation for the whole envelope of the house.
5. Low maintenance and a better lifestyle with clean and green solutions.

3. Methods and Limitations

- Background information on the property was obtained the Auckland Council database. Unfortunately, my research was limited due to lack of more information on the property. Some relevant characteristics about the property include:
- Extensive previous and recent renovations with placement windows and shading devices (external/internal).
- Retrofitting for insulation and thermal bridging performance. Unfortunately, the roof space is unfinished and needs to be transformed into a warm roof in the project's third stage.
- Passive ventilation limits only to the areas of the tilted windows during the summer, while HRV ventilation system is switched automatically off due to the temperature of the roof space.
- Installation of photovoltaic panels, storage power bank, and harvesting storm water system will be limited to the availability of the budget.

4. Data Collection and Analysis

The purpose of data collection was to analyze the energy efficiency of the building design project. Collected data from thermal and moisture non-invasive inspections was supported with thermographic imaging focused on roof ceiling insulation and window's thermal bridging.

The second method was conducting an energy audit for all the electrical devices and appliances (from 1 – most power absorbed to 20 – less management absorbed devices), analyzing Energy Star Rating, power rating and consumption per year.

The third method was dedicated to Water Rating Stars efficiency of all water devices, tapware and appliances.

5. Results

Power - water consumption and cost.

Twelve months of the power and water bill statement with a monthly view on consumption and the cost from October 2020 to September 2021. Graphic indication of power and water consumption with cost calculation. Lower price water charges are applied as the septic tank has been used on site.



Figure 1. 318 Sturges Road 12 months power consumption (kWh) and cost-consumption graphic.



Figure 2. 318 Sturges Road 12 months water consumption (kL) and cost-consumption graphic.

6. Conclusions

The fundamental commitment of my conclusion is to reveal the importance of this concept of conducting an energy audit for my house that will undoubtedly clarify and explain any questions and provide the energy and water consumption related to the behaviour and lifestyle of the whole family. Analysed and evaluated gathered data shows the current water and power energy consumption and possibilities for reducing the consumables and emission of carbon dioxide into the atmosphere. The entire audit assessment will help lower our power bills, giving us a better lifestyle and a reasonable opportunity to increase the property's value.

7. Key References

1. Abodo. (2020, November 10). *Comparing the carbon footprint of different timbers*. Abodo. <https://www.abodo.co.nz/stories/news/comparing-the-carbon-footprint-of-different-timbers-a-study>
2. BRANZ. (2021). Designing to beat the heat | BRANZ Build. [www.buildmagazine.org.nz/Build/164\(164\)](http://www.buildmagazine.org.nz/Build/164(164)). <https://www.buildmagazine.org.nz/index.php/articles/show/designing-to-beat-the-heat>
3. Mammoth modern insulation. (2021). *Ceiling insulation blanket application*. <https://www.mammoth.co.nz/pdf/?product=mammoth-ceiling-insulation>
4. Rangiwhehu, L., Pierse, N., Viggers, H., & Howden-Chapman, P. (2018). Cold New Zealand Council Housing getting an upgrade. *Policy Quarterly*, 14(2). <https://doi.org/10.26686/pq.v14i2.5096>

7TH NEW ZEALAND BUILT ENVIRONMENT RESEARCH SYMPOSIUM

Creating Capacity and Capability for the Future of the Built Environment



Energy Efficient Building Design – Energy Audit - B

Mini Research Project (BRANZ Funded): Building Capability to help the Construction Industry Transition to Zero Carbon

Student: Raphael Tobias Connell Hardy Beazley

Supervisor: Eziaku Rasheed

Master of Construction - School of Built Environment - Massey University



1. Introduction

Conducting on behalf of Massey University, 51 Spencer Road, Pakiri, Auckland was assessed and audited in conjunction with BRANZ Annual Loss Factor tool (ALF 4.0) throughout the months of July and August. The dwelling audited is in the temperate climate of the northern border of Auckland, New Zealand which is considered a Zone 1 Climate (NZS4218:2009). The original single-story property was re-constructed in 2007-2008 after the dwelling was removed from its footings and delivered to the current plot, the home was then built upon, elevated and presented with a ground floor with a separated residential area and a 36.46 sqm exposed slab garage, the entire home has increased to a Gross Floor Area of 84sqm.

2. Aim and Objectives

The aim of the audit was to analyze the Building Performance Index (BPI) through BRANZ ALF tool, this would then provide a baseline average and state whether the home was compliant with the H1 - Energy Efficiency Code under the New Zealand Building Code.

After collating the data, we are then able to provide recommendations on how to increase energy efficiency within the home by use of retrofitting materials in compliance with BRANZ, NZ Standards and alternative sources on energy efficient products.

Loss Comparisons			
	No Adjustment	Adjustment	Reduction
Suspended Floor Loss	744.38	445.17	299.21
Slab Floor Loss	1.42	1.4	0.02
Wall Loss	48.23	40.46	7.77
Window Loss	129.44	59.98	69.46
Roof Loss	26.70	23.07	3.63
Skylight Loss	0.00	0	0.00
TOTAL	950.17	570.08	380.09

Fig 1, Loss Comparison

3. Methods and Limitations

No previous research has been collated on 51 Spencer Road except for Site Drawings as provided by Auckland Council

Assessment Bias has been noted due to Auditor being an occupant of dwelling at time of audit.

Time constraints were established due to deadline requirements provided by Massey University

BRANZ ALF has restriction of input of data such as R-Value of insulation which reduced the ability to provide a definitive figure of kWh/year reduction for higher R-Value insulation installs

4. Data Collection and Analysis

Data was programmed in BRANZ ALF system after being collated in a walkthrough audit.

The information was then summarized and broken-down into key headings within the system and a baseline was established, refer to Fig 1.

The baseline was then altered through re-analysis and each key heading was worked on to best encourage reduction of kilowatt consumption and thermal loss.

Upon a significant reduction which was further analyzed to be achievable by retrofit, recommendations were established to best suit the design of the dwelling.

5. Results

The key takeaways from the audit as as listed:

Insulation & Thermal Bridging

- o **Increase wall R value** from 1.9 to 2.8 or more will decrease loss factor by 7.77kWh/year; by removal and reinstall of new insulation material, and/or retrofit upgrade to compound upon current insulation.
- o **Increase Roof/Ceiling R value** from 2.9 to 3.6 or more will decrease loss factor by 3.63 kWh/year; by removal and reinstall of new insulation material, and/or retrofit upgrade to compound upon current insulation.
- o **Insulate of suspended timber floor** which is included in the "Roof/Ceiling" analysis on ALF system, which will provide a 299.21 kWh/year saving on losses.
- o **Insulate perimeter of slab** with EPS saving .02 kWh/year loss.
- o **Removal of single glazed windows** and retrofitting Thermally Broken Aluminum Frame with Low-e Argon Double Glazing will reduces thermal loss by 69.46 kWh/year

Ventilation

- o **Draught Sealing** all window areas will provide a 36.39kWh/year savings, this would likely be remedy by installation of Aluminum windows, which would be a significant upgrade from timber framed windows and doors

Appliances & Energy

- o **Upgrade to energy efficient appliances and heating methods**, the current kWh/year consumption at 51 Spencer Road fails to meet the national median when analyzed by square metreage, which suggest that Spencer Road is overreaching in use of energy, this includes use of heating, along with general utility use of appliances.

6. Conclusions

Through the audit of 51 Spencer Road, we established that the dwelling BPI was 1.41, this is compliant with New Zealand Building Code, Energy Efficient Clause H1 which requires dwelling to be less than 1.55 BPI. However, despite being within the realms of acceptability, as stated in the aims, our audit was focused on producing a baseline and reducing the kWh/year losses. The establishment of a baseline lead to a fundamental reanalysis of each category of losses, we were then able to reduce each category significantly and altogether lead to the recommended reduction of 380.09kWh/year which is equal to a 40% reduction in losses. If the recommendations were applied to the dwelling the home would reduce its BPI to 0.89 from 1.41 which is a significant figure and present the home as a modern, energy efficient home.



Fig 2, 51 Spencer Road, Pakiri, Auckland

7. Key References

- ALF Branz. (2021). ALF 4.0. Retrieved from BRANZ: <https://alf.branz.co.nz/projects/project/6666/design/11217/enter/walls-windows/>
- CBM. (2007). *Proposed Dwelling 51 Spencer Road*. Snells Beach: CBM.
- Standards New Zealand. (1999). *NZS3604:1999*. Wellington: Standards New Zealand.

Surviving or thriving? The resilience lessons of New Zealand construction sector from COVID 19

Project contact: Dr Alice Chang-Richards
Email: yan.chang@auckland.ac.nz

Thomas Yang¹, Paarth Rajpal², Alice Chang-Richards³, Suzanne Wilkinson⁴
^{1,2,3} Department of Civil and Environmental Engineering, The University of Auckland
⁴ School of Built Environment, Massey University

Introduction

Covid-19 is a respiratory disease caused by SARS-CoV-2 which has caused millions of deaths across the globe and re-defined the way in which businesses operate. As of October 1st 2021, there have been 219 million cases and 4.5 million deaths globally due to Covid-19. However, throughout 2020/21, the New Zealand government has imposed some of the strictest lockdowns which has prevented wide-spread community transmission of the virus. These lockdowns have had serious adverse consequences on businesses in many different industries across the country.

This poster describes the impact of Covid-19 on the construction industry by collecting data from various companies operating in the different sectors of the construction industry. Data was collected through interviews in which the researchers asked various questions to get an in-depth understanding of how Covid-19 has impacted different businesses in the industry. The results were collected, summarized, analyzed and finally compared to previous shocks and stresses in the construction industry such as the 2008 GFC or the 2011 Christchurch Earthquakes.

Project Objectives

This research aims to examine and understand the impact of the pandemic on the New Zealand construction sector. It is hoped, this research can be used in the future to provide insights into how a construction project can be better managed against global shocks and stresses such as Covid-19.

Factors Considered in this project

Various factors were discussed during the interviews completed with companies operating in the sector. Regular mentions were made about the supply chain issues, project delays, and material and labour shortage. These are illustrated below.



Research Background

The Covid-19 global pandemic has had significant implications on construction industries across the world and the New Zealand construction sector is not immune to that. This research aims to understand the impact of the pandemic on the New Zealand construction sector at a project level and provide insights into how a construction project can be better managed to respond to any disruptions caused by shocks and stresses as such. By using a case study approach, a real commercial project in Auckland was selected and in-depth interviews were carried out with project stakeholders and participants. It was revealed that the pandemic and the repeated lockdowns had significantly affected the construction pipelines across the country due to project cancellations and delays, disrupted supply chain and skills shortages. The lessons derived from the case study are hoped to inform the cultural and practice change of the construction sector moving towards building resilience in their business model and operations.

Research Methodology

Between May and August 2021, the researchers organized and conducted various interviews with organizations in the construction sector. The main purpose of these interviews was to understand the impact Covid-19 has had on various aspects of the construction industry. The four key steps to implement the research experiment are outlined below:

- Creation of Questions
- Approaching organizations to arrange interviews.
- Completing these interviews to collect data
- Data Analysis

A total of 8 interviews were completed and covered a diverse range of contractors, subcontractors, consultants, and suppliers. Additionally, data was collected from organizations of varying sizes to obtain data representative of all businesses in the industry. The questions asked during these interviews ultimately answered the three main research questions outlined by the MBIE Endeavour Research Programme.

- How has Covid-19 impacted the construction sector?
- What practices have been adopted in construction projects after the initial level 4 lockdown?
- How can the construction industry become more resilient under future stresses and shocks?

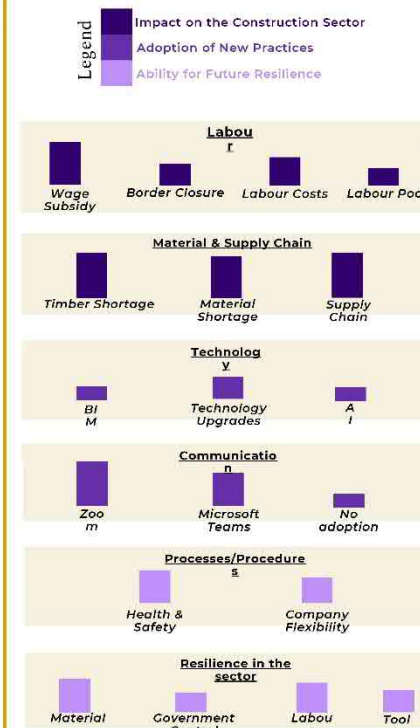
In order to conduct these interviews, an Ethics Approval was obtained by Massey University. Additionally, the researchers also issued an interview consent form and asked for each interviewee's consent to voice record the interview.



Results

The selected interviewees have outlined their opinions on the three main research questions shown under the research methodology section. The research questions were answered through analysis of six main topics, material & supply chain, labour, technology, communication, workplace procedures, and the resilience in the sector. Each main section then carries its own subsection for future analysis and classification.

The comparison of each topic helps determine the primary research questions by MBIE. To better understand the graphs, a legend is created to represent the y-axis of each graph.



Discussion

Covid-19 has had a significant impact on the construction industry and the NZ economy as a whole. Businesses have had to rapidly alter the manner in which they operate in order to adapt and comply with government regulations. This has led to extensive changes for businesses in the construction sector. These results are portrayed in the images below:



Conclusions

Covid-19 has been an extremely knowledgeable learning experience for all. There have been obvious setbacks such as project delays, extended lockdown periods and material shortages however there have also been some significant benefits. These include increased flexibility for employees, increased virtual collaboration and lastly uptake of modern communication methods such as MS Teams.

However, most importantly Covid-19 has shown businesses the importance of flexibility. Organizations have understood that in order to succeed in this uncertain environment, they need to rapidly adapt and adjust the methods in which they operate.

Various impacts of Covid-19 have been discovered and discussed in this research project. It is hoped, these learnings can be used in the future to provide insights into how businesses in the construction sector can cope with the global shocks and stresses.

Acknowledgements

This project is part of MBIE Endeavour Research Programme CANCONSTRUCT NZ (Ethics Notification Number: 4000023852) and WUN-BRIC Research on Building Resilience in Construction. We would also like to thank all interviewees for allowing us to collect data about their organization.