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TOWARDS ZERO CARBON REFURBISHMENT OF
EXISTING BUILDINGS IN AOTEAROA NEW ZEALAND:
A DECISION SUPPORT FRAMEWORK

A THESIS PRESENTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF
DOCTOR OF PHILOSOPHY
AT MASSEY UNIVERSITY, ALBANY,
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Abstract

Refurbishing the existing building stock is considered a fundamental element of reducing carbon emissions towards sustainable development. The renewal of the existing buildings is not only supposed to provide a better, healthier, more comfortable environment for people in which to live and work but also limit global warming, contributing to climate change mitigation. Due to existing buildings comprising the largest segment of New Zealand's building stock, encouraging the low-carbon performance of existing buildings will contribute to achieve the net-zero carbon target by 2050. As a result, it is crucial to ensure that existing buildings are well-refurbished to reduce whole-of-life carbon emissions. Strategic decision-making in building refurbishment can increase building adaptability, durability, and resiliency, as well as achieve zero-carbon goals. However, it is complex and challenging as the consideration of lifecycle carbon performance must be integrated with other requirements, such as building regulations, client's expectations, and stakeholders' values. Before this thesis, limited research has explored the main factors and actors that affect decision-making in reducing carbon emissions and how to better make decarbonisation decisions for building refurbishment comprehensively.

This thesis was undertaken to create a critical understanding of the decision-making process that incorporates carbon reduction initiatives in building refurbishment. This thesis aims to improve the decision-making towards zero carbon refurbishment of existing buildings in New Zealand. Following a sequence of multiple qualitative enquiry modes, a multi-method qualitative research design was applied to address the research aim, including literature review, preliminary study using semi-structured interviews, case studies and focus group discussions. Through examining the current practices of building refurbishment and the decision-making process for reducing whole-of-life carbon emissions in building refurbishment, a novel decision support framework towards zero carbon refurbishment of existing buildings in New Zealand was proposed as the main result of this thesis.

Findings from this research have revealed that New Zealand's building and construction industry is in the early stage of transiting to a net-zero carbon built environment, with many barriers to reducing carbon emissions in the design and construction of buildings, such as are financial issues, the shortage of knowledge, capacity and

capability, the lack of legislation, and organisational culture barriers. Moreover, stakeholders involved in building refurbishment have faced many challenges in integrating carbon reduction in their decision-making practices in different areas of the pre-design and design stages of the refurbishment process, including (1) inexplicit carbon goal setting, (2) ineffective building condition assessment, (3) deficient and incomprehensive relevant whole-of-life carbon information to support the decision-making, and (4) inconsistent and ambiguous carbon-calculation guidelines and benchmark. The results also emphasise that considering both embodied and operational carbon impacts is critical to maximising carbon reduction in a building throughout its life cycle. Especially, for building refurbishment, the priority should move from reducing operational to whole-of-life carbon emissions.

The results from this thesis also provide an in-depth understanding of the characteristics of the decision-making process in practice, lessons learnt for improved implementation of building refurbishment and the effectiveness of collaborative rationality among the diverse stakeholders. Based on theoretical propositions found in the literature and practical knowledge from empirical findings, a comprehensive decision support framework was developed that provides a detailed guideline to better-delivering building refurbishment towards zero carbon. The framework supports the stakeholders involved in building refurbishment to understand the refurbishment decision-making process and requirements for reducing carbon emissions in certain activities, identify areas for addressing carbon issues in the early stages of the refurbishment process, determine relevant information key factors and actors in driving carbon-reduction solutions, and promote stakeholder collaboration and integration in carbon-reduction building refurbishment.

This thesis updates both the practical and theoretical understanding of challenges and improvement measures to establish a greater way to support decarbonisation decisions for building refurbishment. The decision-support framework from this thesis offers building stakeholders a more holistic and streamlined interdisciplinary guide to recognise the decarbonisation decision with its required information, expertise, and mechanisms to reduce carbon emissions for the refurbished building throughout the decision-making process in practice. Findings from this thesis are also of relevance to the theoretical and practical knowledge of how the decisions are made to maximise carbon reduction in building refurbishment as a guide for other researchers who are pursuing closely related research topics to that of this thesis.

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“Xin bày tỏ lòng biết ơn gia đình, bạn bè, đồng nghiệp, những người đã giúp đỡ và bên cạnh tôi suốt thời gian qua, để tôi hoàn thành tốt luận văn này. Xin chân thành gửi lời cảm ơn đến tất cả mọi người.”

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Abbreviations

AC	Air Conditioning
AECB	Association for Environment Conscious Building
AHP	Analytical Hierarchy Process
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
AUTODESK	American Multinational Software Corporation
BIM	Building Information Modelling
BMS	Building Management System
BRANZ	Building Research Association of New Zealand
BREEAM	Building Research Establishment Environmental Assessment Method
BS EN	British Standard
BTO	United States Building Technologies Office
CCP-NZ	Climate Protection-New Zealand
CE	Concurrent Engineering
CHP	Combined Heat and Power
NZCIC	New Zealand Construction Industry Council
CLT	Cross-Laminated Timber
CNPS	Carbon Neutral Public Service
CO ₂	Carbon Emissions
COP	Conference of the Parties
CSIRO	Australia Commonwealth Scientific and Industrial Research Organisation
DCLG	The United Kingdom Department for Communities and Local Government
DOE	United States Department of Energy
ECI	Early Contractor Involvement
EECA	Energy Efficiency & Conservation Authority
EPB	Earthquake-Prone Building

EPBD	European Union Energy Performance of Building Directive
EPD	Environmental Product Declarations
ESD	Environmental Sustainability Design
EU	European Union
FEES	Fabric Energy Efficiency Standards
GC	Global Cost
GHG	Greenhouse Gas
GRS	Graduate Research School
GWP	Global Warming Potential
HVAC	Heating, Ventilation, and Air Conditioning
ID	Integrated Design
IDEF	Integrated Definition Method (Function Modeling Method)
IEA	International Energy Agency
ILFI	International Living Future Institute
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
ISO	International Organization for Standardisation
LCA	Life Cycle Assessment
LCANZ	Life Cycle Association of New Zealand
LCC	Life Cycle Costing
LCD	Life Cycle Design
LCI	Life Cycle Inventory
LEED	Leadership in Energy and Environmental Design
MBIE	Ministry of Business, Innovation and Employment
MEP	Mechanical, Electrical, and Plumbing
NABERSNZ	National Australian Built Environment Rating System - New Zealand
NASA	National Aeronautics and Space Administration

NDCs	Nationally Determined Contributions
NGO	Non-Governmental Organisation
NIWA	National Institute of Water and Atmospheric Research - New Zealand
NPV	Net Present Value
NREL	National Renewable Energy Laboratory - United States
NZ	Aotearoa New Zealand
NZEB	Net Zero Energy Building
NZGBC	New Zealand Green Building Council
PHPP	Passive House Planning Package
PIS	Participant Information Sheet
PV	Photovoltaic Panels
SBE	School of Built Environment, Massey University
SCI	Supply Chain Integration
SME	Small and Medium-sized Enterprises
TLS	Total Link Strength
UAE	United Arab Emirates
UK	United Kingdom
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
VFT	Value Focused Thinking
WGBC	World Green Building Council
ZCBs	Zero Carbon Buildings
ZCR	Zero Carbon Refurbishment
ZEB	Zero Energy Building

List of peer-reviewed publications

Publications within the thesis

1. Bui, T. T. P., Wilkinson, S., MacGregor, C., & Domingo, N. (2023). Decision making in reducing carbon emissions for building refurbishment: Case studies of university buildings in New Zealand. *Building and Environment*, 242, 110557.
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3. Bui, T. T. P., Domingo, N., MacGregor, C., & Wilkinson, S. (2022). Zero carbon refurbishment for existing buildings: A literature review. *IOP Conference Series: Earth and Environmental Science*, 1101(2), 022017.
4. Bui, T. T. P., MacGregor, C., Wilkinson, S., & Domingo, N. (2022). Towards zero carbon buildings: issues and challenges in the New Zealand construction sector. *International Journal of Construction Management*, 22(10), 1-8.
5. Bui, T. T. P., Domingo, N., Wilkinson, S., & MacGregor, C. (2022). Challenges to zero carbon refurbishment of existing buildings in New Zealand: An exploratory study. In: S. Perera & M. Hardie (Eds.), *Proceeding of 45th AUBEA conference 2022: Global Challenges in a Disrupted World: Smart, Sustainable and Resilient Approaches in the Built Environment*, Australia (pp. 522-542).
6. Bui, T. T. P., Wilkinson, S., Domingo, N., & Macgregor, C. (2021b). Towards Zero Carbon Building Refurbishment: A New Conceptual Framework for Decision Support Tools. In: L. Scott & C. J. Neilson (Eds.), *Proceedings of the 37th Annual ARCOM Conference*, 6-7 September 2021, UK (pp. 594-603), Association of Researchers in Construction Management.
7. Bui, T. T. P., Wilkinson, S., Domingo, N., & MacGregor, C. (2021c). Zero Carbon Building Practices in Aotearoa New Zealand. *Energies*, 14(15), 4455.

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3. He, P., Bui, T. T. P., Shahzad, W., Wilkinson, S., & Domingo, N. (2022). Towards Effective Implementation of Carbon Reduction Strategies in Construction Procurement: A Case Study of New Zealand. *Buildings*, 12(10), 1570.
4. Nidhin, B. K. S. N., Domingo, N., Bui, T. T. P., & Wilkinson, S. (2023). Construction stakeholders' knowledge on zero carbon initiatives in New Zealand. *International Journal of Building Pathology and Adaptation* (ahead-of-print). <https://doi.org/10.1108/IJBPA-08-2022-0119>

List of awards

1. Theme Highly Commended Paper Award, the 45th Australasian Universities Building Education Association (AUBEA) conference, Western Sydney University, Australia, 2022.
2. Best Paper Award for Durability and Climate Change, International Council for Research and Innovation in Building and Construction, World Building Congress, Australia, 2022.
3. Sebestyén Future Leaders Award, International Council for Research and Innovation in Building and Construction, 2022.
4. Research Achievement Award, Women in Construction Award, School of Built Environment, Massey University, New Zealand, 2022.
5. Best Paper Award for Conference Theme, Association of Researchers in Construction Management (ARCOM), ARCOM Conference, UK, 2021.
6. Research Achievement Award, Women in Construction Award, School of Built Environment, Massey University, New Zealand, 2021.

1 Chapter 1: Introduction

1.1 Research background

Climate change is one of the biggest challenges of our times, calling for a critical universal response from governments, communities, businesses, and individuals. Climate change is defined by the Intergovernmental Panel on Climate Change (IPCC) as: *“a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods”* (IPCC, 2014).

Climate change has been caused by a significant increase in human-induced greenhouse gas (GHG) emissions, which have increased since the pre-industrial era and are driven extensively by economic development and population growth. As a result, climate change increases existing risks and generates new ones, which may eventually be disseminated over natural and human systems (IPCC, 2014).

Responses to climate change can be categorised into mitigation and adaptation. Climate change mitigation means reducing emissions, which comprises reducing the flow of heat trapping GHG emissions into the atmosphere (NASA, 2022). Mitigation measures include reducing sources of GHG emissions (e.g., burning fossil fuels for electricity, heat, and transport) and enhancing the “sinks” that accumulate and store these gases, such as the oceans, forests, and soil. Whereas climate change adaptation is adapting to life in a changing climate, which encompasses adjusting to the actual or expected future environment. The goal is to mitigate risks from the harmful effects of climate change (e.g. sea-level rise, more intense extreme weather events, and food insecurity). It also includes making the most of any potential beneficial opportunities associated with climate change, for example, longer growing seasons and increased yields in some regions (NASA, 2022).

In light of climate change, global warming has reached approximately 1°C (likely between 0.8°C and 1.2°C) above pre-industrial levels in 2017 and increasing at 0.2°C (likely between 0.1°C and 0.3°C) per decade (IPCC, 2014). Thus, more attention has been paid to reduce emissions as a mean of climate change mitigation. The Paris Agreement – a legally binding international treaty on climate change was adopted by 196 Parties at COP21 in Paris on 12 December 2015 and entered into force on 4 November 2016, aimed to limit global warming to well below 2°C, preferably to 1.5°C, compared to pre-industrial levels. As a result, participating

countries aim to reach global peaking of GHG emissions as soon as possible to achieve a climate-neutral world by mid-century (2050) (COP21, 2015). The Paris Agreement is a landmark in the multilateral climate change process because, for the first time, a binding agreement brings all nations into a common cause to undertake ambitious efforts to combat climate change and adapt to its effects.

In line with the United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement signed in 2016, the New Zealand government released “Climate Change Response (Zero Carbon) Amendment Act 2019. In comparison to other countries such as the UK, New Zealand’s Climate Change Act was launched 10 years later, given that New Zealand’s net emissions have increased by 64% above 1990 levels while the figure for the UK witnessed a reduction by 38% below 1990 baseline levels (MacGregor et al., 2019). The Climate Change Act provides a framework by which New Zealand can develop and implement clear and stable climate change policies (Ministry of the Environment, 2019). The next steps will be getting the new provision up and running, particularly developing a provisional emissions budget for specific industry (e.g. the building and construction industry) towards net zero carbon by 2050.

The building and construction industry is fast becoming a key instrument in mitigating climate change. The sector accounted for 36% of final energy use and 39% of energy and process-related carbon emissions in 2018, 11% of which resulted from manufacturing building materials and products such as steel, cement, and glass (IEA, 2019). In New Zealand, the building and construction industry (including the construction, maintenance, and end-of-life of buildings, but excluding building energy use) contributes roughly 16% of the country’s GHG emissions (BRANZ, 2020). Therefore, decarbonising the buildings and construction industry is critical to achieve the Paris Agreement commitment. As part of their plans to limit GHG emissions, 184 countries have contributed Nationally Determined Contributions (NDCs) under the United Nations Framework Convention on Climate Change (UNFCCC). Although most countries (136) mention buildings in their NDCs, explicit actions to address emissions within the building and construction industry are lacking. In New Zealand, for example, the Ministry of Business, Innovation and Employment (MBIE) has launched the Building for Climate Change programme (MBIE, 2020), seeking to reduce emissions from buildings while also improving building resilience to climate change. However, the specific policy, regulation, and plan of actions for the building and construction industry to reduce emissions and contribute to New Zealand’s overall emissions reduction targets

is still under way. To maximise carbon reduction for the building and construction industry, measures to mitigate building emissions through switching to low-carbon and renewable energy sources should be further focused. Greater attention should be paid to low-carbon building materials, building envelope improvements, nature-based solutions, and equipment and system efficiency (UNEP, 2021).

Adopting zero carbon buildings (ZCBs) approach can reduce environmental impacts and contribute to climate change mitigation worldwide (Jones et al., 2015; Pan & Li, 2016; Li et al., 2022). The appearance of ZCBs can be due to carbon emissions released from the building and construction industry, which are projected to increase twice over the next 15 years in the continue business-as-usual scenario (UNEP, 2009). The Net Zero Carbon Buildings Commitment challenges businesses, organisations, cities, states, and regions to reach net zero carbon in operation for all assets under their direct control by 2030 and to advocate for all buildings to be net zero carbon in operation by 2050 (WGBC, 2019). However, it is also required to tackle embodied carbon emissions within the building and construction industry (Pomponi & Moncaster, 2016; Akbarnezhad & Xiao, 2017). As new construction is expected to double the world building stock by 2060, and many inefficient existing buildings remain (WGBC, 2019). Until now, actions have been taken to reduce energy consumption and GHG emissions worldwide in the building and construction industry. Many countries and regions, namely the UK, Europe, the US, Canada, etc., have encouraged adopting ZCBs as a government strategy for tackling anthropogenic climate change (Treasury, 2007; Crawley et al., 2009; Recast, 2010). In New Zealand, for instance, the government is working closely with the industry on a range of initiatives to reduce emissions in buildings, including reducing whole-of-life embodied carbon emissions and transforming operational efficiency (MBIE, 2020). This promotion has considerably driven the development of ZCBs, as many have been constructed and reported globally through several channels.

1.2 Research problem

In the international context, the environmental problems related to the new development of the current building stock can be solved by executing strict emission target requirements and adopting up-to-date building designs and technologies for new buildings. Whereas a challenging task is attaining the existing building stock's efficiency and carbon reduction goals. Refurbishment of the existing building stock is currently getting increased attention in many countries due to its great potential for improving environmental, social, and

economic aspects (Xing et al., 2011; Loli & Bertolin, 2018; Moran et al., 2020). In fact, building refurbishment projects make up only half the embodied impacts compared to new builds, and there is a 53%-75% emission reduction when the refurbishment is compared to a new construction scenario (Hasik et al., 2019; Moncaster et al., 2019). A major refurbishment of existing buildings, which, among other things, involves a significant improvement in energy and carbon performance (Jensen, Maslesa, & Brinkø Berg, 2018).

Reducing carbon emissions in building refurbishment can be achieved if effective decisions are made throughout the refurbishment process. Over the years, international scholars have attempted to design and develop decision-support mechanisms to aid in identifying the optimal refurbishment solutions (Juan et al., 2010; Xing et al., 2011; Jensen & Maslesa, 2015; Li & Froese, 2017; Gade et al., 2018; Serrano-Jiménez et al., 2021). However, fewer researchers have been able to draw on research into the comprehensive decision-making process for building refurbishment (Ma et al., 2012; Bhuiyan et al., 2015). Turban et al. (2005) argued that the decision-making process is pure art, acquired over a long period through experience and learning from trial and error. Nowadays, decision-making is even more complicated due to “more alternatives to choose from”, “large cost of making errors”, “more uncertainties”, and “the need for quick decisions”. Accordingly, making decisions incorporating zero-carbon targets for building refurbishment can be difficult as it is a multi-objective problem influenced by various constraints and limitations (i.e., project target, budget, building techniques) (Ma et al., 2012). Likewise, government policies and social factors, such as user comfort can also impact decision-making in the refurbishment process (Al-Ragom, 2003; Rose et al., 2019; Bui et al., 2021b). Critically, the decision-making in the early stages of the refurbishment process, including the pre-design and design phases, plays a crucial part since all other ones adapt to these strategic decisions in the overall process (Ferreira et al., 2013; Nielsen et al., 2016). The issues that might occur in the construction and post-occupancy evaluation stages are also considered in pre-design and design phases. However, decisions made in the early stages of the refurbishment process are complex because of the involvement of multiple stakeholders (Rey, 2004; Klotz & Horman, 2010). Therefore, there is a need to prioritise decision-making in the early stages of the refurbishment process considering zero-carbon targets.

In the New Zealand context, the refurbishment of existing building has not received considerable critical attention. There are only few studies which evaluate the environmental impacts of the energy-efficient

refurbishment of buildings (Ghose et al., 2017; Ghose et al., 2019; Ghose et al., 2020). These studies shed light on technical solutions such as refurbishment strategies for New Zealand's existing buildings considering life cycle impacts and their influence on the 2050 climate change mitigation target. However, a systematic understanding of how these refurbishment strategies is considered in the decision-making process where other factors such as economic, political, and social aspects integrated has been still lacking. Further studies, which take these variables into account, will need to be undertaken. In addition, a lot of attention has been devoted zero carbon refurbishment research on residential buildings. While New Zealand's public sector is required to be carbon neutral by 2025 (New Zealand Government, 2020). The contribution of the public sector to driving changes in the building and construction industry is important. Therefore, the focus of this research is on non-residential buildings, particularly those owned by the public sector.

Overall, there has been a lack of detailed investigation into the decision-making process to reducing carbon emissions in building refurbishment in international and New Zealand contexts. This research attempts to fill the knowledge gap by shedding new light on decision-making in building refurbishment towards zero carbon in a systematic way. The direction of the research project was influenced by reviewing the extensive literature from both international and local context, investigating New Zealand's government policy documents, attending relevant workshops and seminars held by professional institutions (e.g. New Zealand Green Building Council (NZGBC)), as well as discussing with policy makers from Ministry of Business, Innovation and Employment (MBIE) and senior scientists from Building Research Association of New Zealand (BRANZ). The identified research problem also aligns with BRANZ's current research programme, "Transition to a zero-carbon built environment" in New Zealand.

1.3 Research aim and objectives

Appraisal of the research background and problem statement indicates the necessity of addressing the knowledge gap in the early-stage decision-making process for building refurbishment towards zero carbon in the New Zealand context. This thesis pays particular attention to the contextual background and theoretical and practical concepts surrounding the decision-making process for building refurbishment towards zero carbon. It also attempts to provide recommendations that promote the uptake of zero-carbon initiatives for the New Zealand building and construction industry.

This thesis aims to recommend a best practice approach to the decision-making towards zero carbon refurbishment of existing buildings in New Zealand. The following research questions and objectives were formulated to achieve the research aim, as shown in Table 1-1.

Table 1-1: Research questions and objectives (Source: Authors)

Phases	Research questions	Research objectives
Stage 1	Q1: What are the current practices towards zero carbon buildings in the international context?	Objective 1: To explore the current practice of zero carbon buildings worldwide
	Q2: What is the current development and implementation of building refurbishment towards zero carbon in the international context?	Objective 2: To assess the global development and implementation of building refurbishment towards zero carbon
Stage 2	Q3: What is the current adoption of zero carbon buildings in New Zealand?	Objective 3: To examine the adoption of zero carbon buildings in New Zealand
	Q4: What is the current development and implementation of building refurbishment towards zero carbon in New Zealand?	Objective 4: To investigate the development and implementation of building refurbishment towards zero carbon in New Zealand
Stage 3	Q5: How and why are the decisions regarding whole-of-life carbon reduction made in the current refurbishment process in New Zealand?	Objective 5: To examine the current decision-making process for reducing whole-of-life carbon emissions of building refurbishment in New Zealand
Stage 4	Q6: What can be done to improve the decision-making process towards zero carbon refurbishment of existing buildings in New Zealand?	Objective 6: To develop and validate a novel decision support framework towards zero carbon refurbishment of existing buildings in New Zealand

1.4 Research methodology

1.4.1 Research philosophy

Research is a process that people undertake carefully and systematically to find out things, thereby increasing their knowledge (Saunders et al., 2016). This process aims to systematically investigate a problem and thoroughly interpret, describe, predict, and explain a phenomenon (Tan, 2002). In order to qualify as “research”, the process must be, as far as possible, controlled, rigorous, systematic, valid and verifiable,

empirical and critical (Kumar, 2018). Research begins by considering the philosophical underpinnings surrounding the study background and by understanding the focus of the study, aims and objectives, and the research design (Jackson, 2013; Saunders et al., 2016; Creswell & Creswell, 2017).

According to Guba and Lincoln (1994); Blanche et al. (2006), the research process has three major dimensions: ontology, epistemology, and methodology. It is suggested that a research inquiry should be based on the concepts of ontology (i.e. the way the investigator defines the truth and reality), epistemology (i.e. the process in which the investigator comes to know the truth and reality) and methodology (i.e. the method used in conducting the investigation). There is a closed relationship between ontology, epistemology, and methodology, and understanding these relationships helps achieve more relevant research findings (Rohrman, 1998; Hammond & Wellington, 2012). The relationship between the tripod stance underpinning any research is directional in a logical sequence. While ontology precedes epistemology, epistemology precedes methodology (Grix, 2018).

As a starting point in understanding and developing research, Crotty (1998); Jackson (2013) suggested addressing the following questions: (1) what existing theory surrounds the research (2) what methods are proposed (3) what methodology rules and guides the choice of method (4) what the theoretical rationale behinds the methodology (5) what the ontology and epistemology is underpinning in the research. The answer to questions regarding three dimensions provides an interpretative framework that guides the entire research process, including strategies, methods, and analysis.

Ontology refers to assumptions about the nature of reality (Saunders et al., 2016; Grix, 2018). Ontology is concerned with the existence of knowledge and the nature of knowledge and describes what knowledge is (Fellows & Liu, 2021). There are two broad contrasting positions: objectivism and constructivism. An objectivist believes that there is one objective reality experienced the same way by each of us, whilst a constructivist believes that reality is ‘constructed’ by each of us differently (Sutrisna, 2009).

Epistemology concerns assumptions about knowledge, what constitutes acceptable, valid, and legitimate knowledge, and how we can communicate knowledge to others (Burrell & Morgan, 2017). Epistemology concerns the nature of human knowledge and how researchers know reality. Epistemology poses the following questions: What is the relationship between the knower and what is known? How do we know what we know?

(Antwi & Hamza, 2015). Whereas ontology may initially seem rather abstract, the relevance of epistemology is more obvious (Saunders et al., 2016). There are two broad epistemological positions: positivism and interpretivism. While positivism strives to maintain an objective and independent stance by believing that only an observed and measured phenomenon would be regarded as valid knowledge, usually governed by a deductive approach. Interpretivism attempts to minimise the gap that may appear in various methods of participatory inquiry, usually governed by an inductive approach (Bryman, 2008). Table 1-2 presents a comparison between these two epistemological perspectives.

Table 1-2: Positivism versus interpretivism epistemological perspectives (Bryman, 2008)

Descriptive	Positivism	Interpretivism
Basis	Natural science	Human interactions
Approach to social science	Description and generalisation of human behaviour	Interpretive understanding and causal explanation of human behaviour
Subject matter	Nature	Social reality
Subject actions	Unmotivated and inanimate	Engaged and expressive
Data collection	Observation, classification, and measurement	Understanding the perspective of human subjects
Research and Theory	Majorly deductive	Strongly inductive

Methodology refers to the principles and procedures of the logical thought processes that can be applied to a scientific investigation (Fellows & Liu, 2021). It is a research strategy translating ontological and epistemological principles into guidelines. These guidelines show how research is conducted (Sarantakos, 2017) and the principles, procedures, and practices governing research (Healy & Perry, 2000; Marczyk et al., 2010). Saunders et al. (2016) claimed that methodology includes philosophy, approaches, strategies, methods, choices, time horizons, data collection and analysis techniques and procedures. Creswell and Creswell (2017) stated that three questions needed to be addressed when selecting the research methodology: (1) what knowledge claims are being made by the researcher? (2) what strategies of inquiry will inform the procedures? (3) what methods of data collection and analysis will be used? Thus, understanding the philosophical stances of the research is the first step in designing a research methodology.

Considering the relationship between ontology, epistemology and methodology helps researchers to achieve more holistic research findings (Rohrmann, 1998). On the one hand, if this research reflects the philosophy of positivism, the researcher may use existing theories to develop hypotheses and to create a research strategy to collect data. These hypotheses will be tested and confirmed, in whole or part, or refuted, leading to further development of theory, which may be tested by further research (Saunders et al., 2016; Creswell & Creswell, 2017). Bell et al. (2018) agreed that positivism describes social phenomena similar to the natural sciences. However, approaching the development of an artifact (i.e. a framework) from a positivist perspective assumes that objective knowledge already exists, and the focus is on what can be measured quantitatively. This approach may result in the development of an artifact that does not consider user involvement or the expectation that the user's behaviour can be automatically changed when using a new mechanism. On the other hand, the interpretivist advocates that, as humans, we play a part in the stage of human life. Within interpretivism, the researcher believes that reality is socially constructed, and the researcher is a social actor interacting with the world and the field of research (Tolley et al., 2016; Bell et al., 2018). However, following the interpretivism philosophy, the researchers must adopt an empathetic stance. The challenging task is to enter the social world of research subjects and understand the world from the researchers' viewpoint (Saunders et al., 2016). The inquiry aims to understand a particular phenomenon, not to generalise to a population (Farzanfar, 2005).

In the context of this research, the outcome should generalise a decision support framework to be used in the early stages of the refurbishment process incorporating carbon-reduction initiatives in the industry practice. It was believed that the decision-making process of building refurbishment towards zero carbon is affected by the interactions between relevant stakeholders involved in the process and various approaches, mechanisms, tools, and systems. The research also focused on a specific context, in which, although the decision-making process of building refurbishment may be seen as an objective reality, it is important to understand the insiders' (stakeholders, approaches, tools and systems) meaning and viewpoint. In addition, the researcher was not influenced by a predetermined view of adequate knowledge. Therefore, it is not initiated particularly with either a positivist or interpretivist view. Rather than considering the most suitable view, this research study gave priority to understanding the research problems and the most appropriate approaches and methods to

investigate knowledge about these problems. The literature identifies the philosophy of “pragmatism” (i.e., what works is what should be important in answering research questions) which is in line with the above (Murphy & Murphy, 1990; Saunders et al., 2016; Tashakkori & Teddlie, 2021). For a pragmatist, research starts with a problem and aims to contribute practical solutions that inform future practices (Saunders et al., 2016). In addition, Creswell and Creswell (2017) stated that regardless of method forms, researchers should emphasise the research problem and use all approaches needed to understand its problems and solutions. The philosophical stance of this research is more towards the pragmatic theoretical perspective due to several reasons identified by Cherryholmes (1992); Morgan (2007); Creswell and Creswell (2017) as below:

- Pragmatism is not committed to any one system of philosophy and reality.
- Individual researchers have the freedom to choose the methods, techniques and procedures of research that best meet their needs and purpose.
- The researcher using a pragmatic worldview has opportunities to use multiple/mixed research approaches to best answer the research question and address the research problem.
- Pragmatist research examines the questions “what” and “how” to research based on the intended consequences (i.e., where the researcher wants to go with it).
- Pragmatists agree that research always occurs in social, historical, political, and other contexts.

1.4.2 Research approach

The approach to theory development is fundamental to selecting the appropriate research design as it depends on the extent to which the researcher clarifies the theory at the beginning of the research project (Saunders et al., 2016). Regardless of what kind of study, theory – “an explanation of observed regularities” is central (Bryman, 2016). When conducting research, data are collected and analysed to generate knowledge. While much knowledge has practical applications, researchers are primarily interested in using data to inform theoretical understanding of the world (Bell et al., 2018). The relationship between theory and research has two major issues: (1) the link between theory and research depends on what form of theory is being referred to, (2) there is a question of whether data are collected and analysed to test an existing theory or to build new theory (Saunders et al., 2016; Bell et al., 2018; Gray, 2018).

Two contrasting approaches to the reasoning adopted in the research design are inductive and deductive. Deductive reasoning occurs when the conclusion is derived logically from a set of premises, the conclusion being true when all the premises are true. In contrast, in inductive reasoning, there is a gap in the logical argument between the determination and the beliefs observed, the conclusion being “judged” to be supported by the observation made (Ketokivi & Mantere, 2010). Inductive and deductive processes, however, are not mutually exclusive and can be combined within the research project (Saunders et al., 2016; Gray, 2018). This so-called “abductive approach” combination is often advantageous as it enables the researcher to gather benefits from both approaches (Johnson & Gill, 2010; Yin, 2014). Table 1-3 summarises the differences between the deductive, inductive, and abductive research approaches.

Table 1-3: Comparison between the deductive and inductive approaches (Saunders et al., 2016)

	Deduction	Induction	Abduction
Logic	In deductive inference, when the premises are true, the conclusion must also be true	In inductive inference, known premises are used to generate untested conclusions	In an abductive inference, known premises are used to generate testable conclusions
Generalisability	Generalising from the general to the specific	Generalising from the specific to the general	Generalising from interactions between specific and general
Use of data	Data collection is used to evaluate propositions or hypotheses related to an existing theory	Data collected is used to explore a phenomenon, identify themes and patterns, and create a conceptual framework	Data collection is used to explore a phenomenon, identify themes and patterns, locate these in a conceptual framework and test this through subsequent data collection and so forth
Theory	Theory falsification or verification	Theory generation and building	Theory generation or modification; incorporating existing theory where appropriate to build new theory or modify existing theory

This research started with the deductive reasoning approach with a problem definition and led to an inductive reasoning approach of theory building. In particular, the researcher investigated the decision-making process

of building refurbishment. Taking a selection of facts (building refurbishment in the context of zero carbon buildings, stakeholder involvement in the refurbishment process, refurbishment strategies, methods, approaches, and systems), the researcher formulated a conceptual framework (deductive approach) related to the decision-making process of building refurbishment towards zero carbon. The researcher then became interested in what and how others impact this framework in the working practices, particularly regarding zero-carbon initiatives. Empirical data were collected and analysed to subsequently test and modify the conceptual framework (inductive approach). This reasoning process is in line with that of Saunders et al.'s (2016); Gray's (2018) formulation of a modern problem. Where data are collected to explore a phenomenon, identify themes, and explain patterns, to generate a new or modify an existing theory which is subsequently tested through additional data collection (Saunders et al., 2016).

1.4.3 Methodological choice

Research design can be thought of as arriving at conclusions to a particular research question (Tan, 2002). It provides a framework including plans and procedures for research that span the steps from broad assumptions to detailed methods of data collection, analysis, and interpretation (Bryman, 2016; Creswell & Creswell, 2017). There are three advanced research design approaches: qualitative, quantitative, and mixed methods (Saunders et al., 2016; Creswell & Creswell, 2017; Bell et al., 2018; Gray, 2018). According to Newman et al. (1998), the qualitative and quantitative research design should not be viewed as rigid, distinct categories, opposites, or dichotomies. Instead, they represent different ends on a continuum. A study tends to be more qualitative than quantitative or vice versa. Mixed methods research design resides in the middle of this continuum because it incorporates elements of both qualitative and quantitative approaches (Creswell & Creswell, 2017).

One way of differentiating quantitative research from qualitative research is to distinguish between numeric data (numbers) and non-numeric data (words, images, video clips and other similar materials) (Saunders et al., 2016). A more complete way to view the differences is in the basic philosophical assumptions and the types of research strategies used in the research (e.g. quantitative experiments or qualitative case studies), and the specific methods employed in conducting these strategies (e.g. collecting data quantitatively on instruments versus collecting qualitative data through observing a setting) (Creswell & Creswell, 2017). Given how philosophical assumptions, research strategies and methods inform methodological choice, the initial

distinction drawn earlier between numeric and non-numeric data appears insufficient to design research (Saunders et al., 2016). Moreover, when selecting a research design, Yin (2014) suggested three factors to consider: (1) the type of research question, (2) the extent of control an investigator has over actual behavioural events, and (3) the degree of focus on contemporary, as opposed to historical events. Therefore, there is a need for an inclusive and pluralistic analysis of each research design to identify the most suitable to address the research problem in a given situation.

In the context of this research, very little research, practical knowledge, and background information regarding the refurbishment of existing buildings towards zero carbon, has been recognised in New Zealand. The researcher much concerned about the current decision-making practices, how and why things happen and what can be done to improve. Furthermore, developing a novel framework for industry practice requires real-life, highly contextual, and rich information. Therefore, a multi-method qualitative research design, which is intense, engaging, contextualised and highly variable (Gray, 2018) was considered appropriate for this study. It can adopt various theoretical stances and methods, including literature review, interviews, document analysis, observations, case studies and focus groups (Flick, 2018). Qualitative data can be a powerful source for analysis in this research as they are highly contextual, collected in a natural “real life” setting and often go beyond giving a mere snapshot or cross-section of events to show how and why things happen (Charmaz, 1995). Far from lacking scientific rigour, qualitative research, in certain circumstances, can even be used for testing hypotheses to see if theoretical propositions can be supported by the evidence (Strauss & Corbin, 1990), which was suitable for designing a novel decision support framework in this study.

In terms of philosophical stance, qualitative research is often associated with an interpretive philosophy (Denzin & Lincoln, 2011) because researchers need to make sense of the subjective and socially constructed meanings expressed about the phenomenon being studied. However, it is argued that qualitative research may also be used within pragmatist philosophy as for pragmatists, the nature of the research question, the research context and likely research consequences are driving forces determining the most appropriate methodological choice (Saunders et al., 2016; Creswell & Creswell, 2017; Tashakkori & Teddlie, 2021). Regarding theory development, many varieties of qualitative research commence with an inductive approach, where a naturalistic and emergent research design is used to build theory or to develop richer theoretical perspectives

than already exist in the literature (Saunders et al., 2016; Gray, 2018). However, some qualitative research strategies start with a deductive approach to test an existing theory using qualitative procedures (Yin, 2014). In practice, much qualitative research uses an abductive approach to theory development, where inductive inferences are developed, and deductive ones are tested iteratively throughout the study or vice versa (Saunders et al., 2016; Bell et al., 2018; Gray, 2018). This is the case of this research, where the combination of inductive and deductive reasoning was applied for problem-addressing and theory-building.

1.4.4 Overview of research methods

As mentioned above, this thesis adopted a multi-method qualitative research design that includes literature review, preliminary study, case study and focus groups (see Figure 1-1). These methods were carefully selected based on the research problems, aim, questions and objectives. This section demonstrates an overview of research methods, while the details on how these research methods were implemented to achieve research objectives can be found in each following chapter.

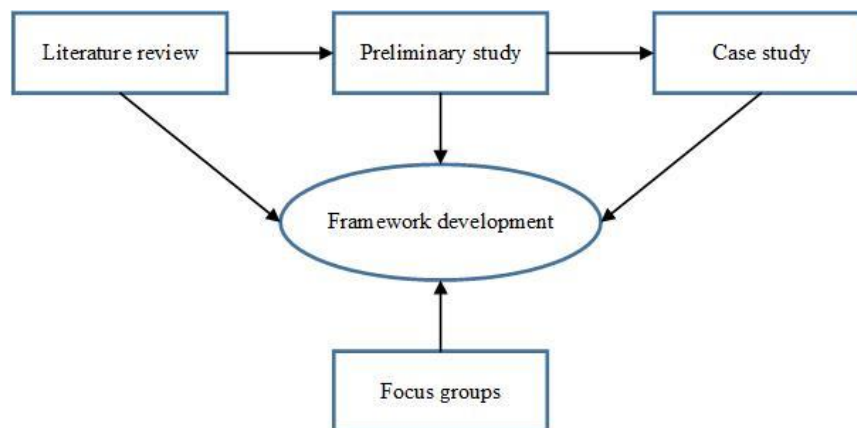


Figure 1-1: Research design (Source: Authors)

The term “research method” refers to the techniques or procedures used to gather and analyse data related to some research questions or hypotheses (Blaikie, 1993; Fellows & Liu, 2021). This section briefly introduces the research methods used in this thesis, while their detailed descriptions, including data collection and analysis techniques and procedures, are further addressed in the following chapters. Figure 1-2 demonstrates the research process and inter-relationships between research objectives, methods, outcomes, and publications.

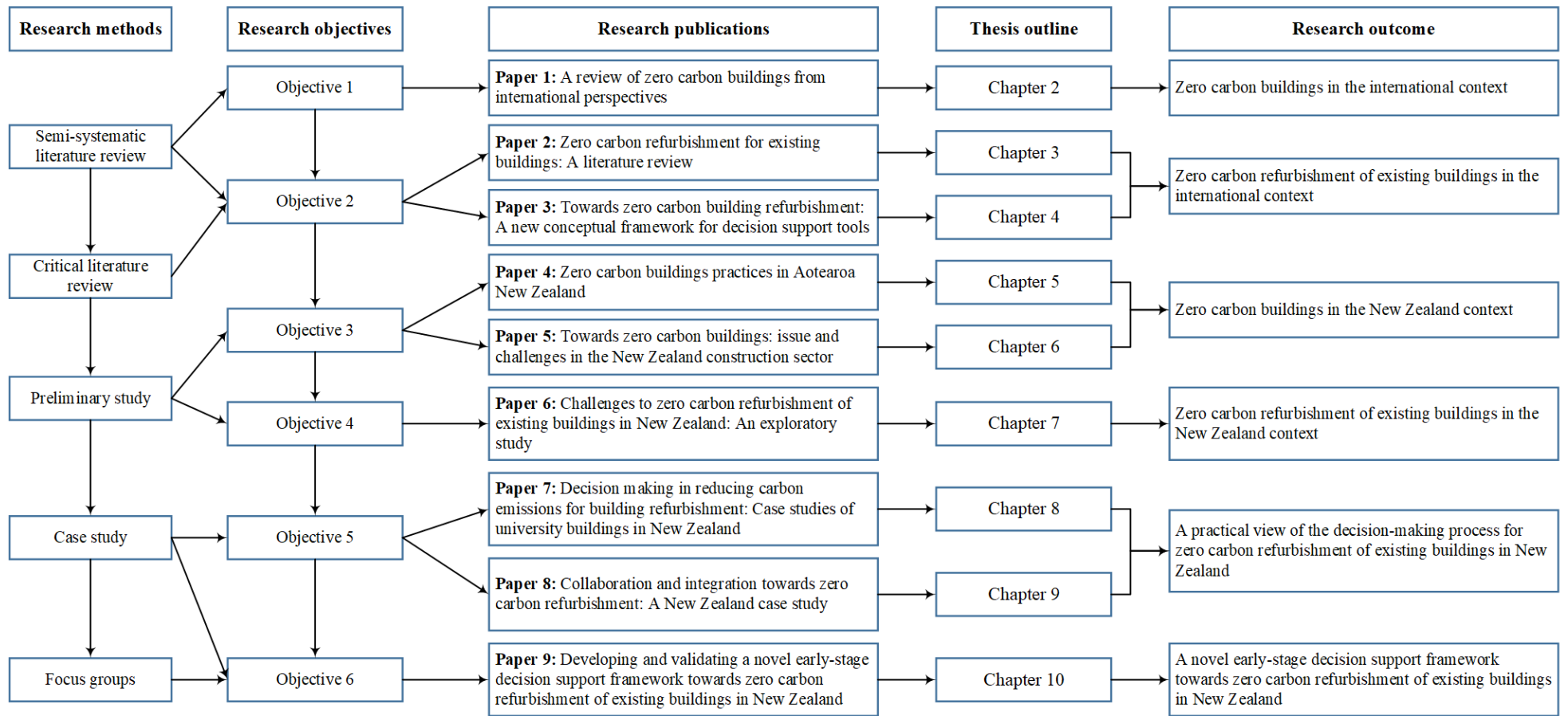


Figure 1-2: The inter-relationships between research objectives, methods, outcome, and publications (Source: Authors)

1.4.4.1 Literature review

A literature review can broadly be described as a more or less systematic way of collecting and synthesising previous research (Baumeister & Leary, 1997; Tranfield et al., 2003). An effective and well-conducted review as a research method creates a firm foundation for advancing knowledge and facilitating theory development (Webster & Watson, 2002). Three broad types of techniques commonly used are systematic literature review, semi-systematic (narrative) literature review and integrative (critical) literature review (Snyder, 2019). Two types of literature review methods were adopted in this research, including semi-systematic and critical literature reviews.

1.4.4.1.1 Semi-systematic literature review

A semi-systematic literature review can be seen as a comprehensive way to critically examine existing knowledge on a research topic, usually done to establish a theoretical focus or context for the topic (Green et al., 2006; Onwuegbuzie & Frels, 2016). Besides the aim of overviewing a topic, a semi-systematic review often looks at how research within a selected field has progressed over time or how a topic has developed across research traditions. In general, the review seeks to identify and understand all potentially relevant research traditions that have implications for the studied topic and to synthesise these using meta-narratives instead of measuring effect size (Wong et al., 2013, Davis et al., 2014). A semi-systematic literature review is useful for detecting themes, theoretical perspectives, or common issues within a specific research discipline or methodology or identifying a theoretical concept's components (Ward et al., 2009).

In this research, the semi-systematic literature review technique was used within the thesis to summarise the literature in the research field. In particular, the review was conducted to address Objective 1 and Objective 2 by drawing conclusions about the zero-carbon research topic and identifying gaps or inconsistencies in the growing body of knowledge on zero carbon refurbishment of existing buildings. The knowledge gaps identified from the semi-systematic literature review facilitate the research direction and the formation of parameters applicable to the development of the novel decision support framework.

1.4.4.1.2 Critical literature review

In comparison to a semi-systematic review, a critical review usually has a different purpose, intending to review, critique, and integrate representative literature on a topic in a synthesised manner that enables new knowledge, perspectives, understanding and theoretical frameworks to emerge (Torraco, 2005; Cronin & George, 2020). According to Snyder (2019), there are two types of critical literature review; one aims to address mature topics, while the other intends to deal with new or emerging topics. A potential contribution of a critical literature review is that it offers the advancement of knowledge and theoretical frameworks rather than a simple overview or description of a research area. Thus, it should not be descriptive or historical but should preferably generate a new conceptual framework or theory. However, the critical review presents a unique challenge in integrating knowledge from different communities of practice and synthesising different perspectives can be problematic (Carlile, 2004; Cronin & Weingart, 2007). Therefore, a careful and systematic approach to organising a critical literature review could produce a comprehensive understanding of the topic of interest and reduce any possible drawbacks in the process (Whittemore & Knafl, 2005).

Accordingly, the critical literature review was applied within the thesis to assess, critique, and synthesise the literature on zero carbon building refurbishment. Specifically, the technique was used to critically review decision support mechanisms for building refurbishment to facilitate a new conceptual framework for a new conceptual decision support framework for zero carbon refurbishment (Objective 2). This is the case of mature topics, where the purpose of using the critical review is to overview the knowledge base, critically review and potentially re-conceptualise, and expand on the theoretical foundation of the specific topic as it develops (Snyder, 2019). The critical review provides a new understanding of decision support mechanisms for building refurbishment towards zero carbon in the research field. These findings were later used to develop a novel decision support framework for zero carbon refurbishment of existing buildings to be used in New Zealand.

1.4.4.2 Preliminary study

Preliminary studies are useful when exploring or searching through a problem or situation to provide insights and ideas. They are particularly helpful in breaking broad, vague problem statements into smaller, more precise sub-problem statements (Naoum, 2012; Zikmund et al., 2013). Especially when the researcher has a limited amount of data or experience, or knowledge about a research issue, a preliminary study is required as an initial

exploratory step to identify key features of the research. It also helps examine the feasibility of further investigation by indicating what might be relevant to study in more depth (Harvey, 2004; Hart, 2018). The principal benefit of conducting a pilot study is that it provides researchers with an opportunity to adjust and revise the main study, and the decisions taken at this stage determine the direction of the research project (Kim, 2011; Kuster et al., 2015). In addition, exploratory studies allow the researcher to define the problem more precisely, identify relevant courses of action, or gain additional insights before confirming further findings. Exploratory research can be based on a single investigation or a series of informal studies to provide the background information needed to form the foundation of a good research study through triangulation (Zikmund et al., 2013; Hart, 2018).

In this research, a considerable amount of literature has been published on zero-carbon research over the past few years, particularly in refurbishing existing buildings to achieve zero carbon goals by 2050. However, little is known about the concept of zero carbon buildings in New Zealand and the understanding of zero carbon refurbishment of existing buildings remains unclear. Consequently, a preliminary study was conducted using semi-structured interviews with building experts to explore the zero carbon buildings practices (Objective 3) and zero carbon refurbishment of existing buildings in New Zealand (Objective 4). This study is beneficial to the thesis in terms of (1) clarifying findings from the literature and formulating research problems more precisely, (2) establishing a clear focus for the main study and enhancing methods triangulation, (3) improving the researcher's familiarity with the research problems and the practical difficulties of carrying out the research.

1.4.4.3 Case study

According to the theoretical definition by Yin (2014), the case study method is “an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not evident”. A case study strategy can generate insights from intensive and in-depth research into the study of a phenomenon (e.g. the decision-making process of building refurbishment) in its real-life context, leading to detailed, empirical descriptions and the development of the theory (e.g. a new decision support framework) (Dubois & Gadde, 2002; Eisenhardt & Graebner, 2007; Ridder, 2017).

The case study method can be used for various issues, including the evaluation of training programmes, organisational performance, project design and implementation, policy analysis, and relationships between different sectors of an organisation or between organisations (Gray, 2018). It can be invaluable in understanding, extending the experience and increasing conviction about a subject (Dooley, 2002; Stake, 2008). Moreover, conducting multiple cases of the same problem or phenomenon is more beneficial compared to a specific case as it increases the reliability, objectivity, legitimacy, and generalisation of the research (Yin, 2014).

The case study method allows the use of multiple sources of evidence, including archives, interviews, surveys, visual methods, and participant observation (data triangulation) when developing theoretical grounds (Dooley, 2002; Yin, 2014). It is also ideal when a “how” and “why” question is being asked about a contemporary set of events over which the researcher has no control (Yin, 2014; Saunders et al., 2016; Gray, 2018). In this research, the researcher wanted to know “how” and “why” the decision in carbon-reduction initiatives was made in the real-life refurbishment process. In other words, how building stakeholders involved in the refurbishment process influenced and made carbon-reduction decisions. Thus, a case study would be able to deal with this more explanatory issue and to illuminate key features enabling the theory building or modification compared to other approaches, such as a survey that intends to address ‘what’, ‘who’, and ‘where’ questions (Bell et al., 2018; Gray, 2018).

The findings from the case study approach provide an in-depth understanding of the real-life decision-making process of building refurbishment, its key actors, and factors (Objective 5). These findings were later combined with the results from the literature review and preliminary study to develop the new decision support framework (Objective 6).

1.4.4.4 Focus group

The focus group is a qualitative data collection approach that allows data to be gathered from a small number of participants through group discussions focused on a specific topic usually defined by the researcher (Morgan, 2002). The focus group allows the researcher to study how individuals collectively make sense of a phenomenon and construct meanings around it. This approach enables a shift from focusing predominantly on individuals’ thoughts and perceptions towards more contextualised understandings (Tadajewski, 2016). Group

settings may be better at generating discussion around shared and unshared attitudes and experiences compared to interviews which are used to identify the range and depth of individual values and beliefs (Bell et al., 2018).

The focus group method is ideal for exploring people's opinions, beliefs and perceptions about products, services, ideas, and concepts (Gibbs, 1997; Krueger, 2014; Wilkinson, 2015). In particular, focus groups can validate the development of products, services, ideas and concepts based on data collected using other methods or sources, enabling data triangulation (Gray, 2018; Bell et al., 2022).

In this research, a focus group was conducted with a panel of building experts to validate the proposed decision support framework (Objective 6). This is because of the opportunity it provides to test and refine the developed framework based on industry experts' beliefs and opinions and verify the generalisation of the potential implementation of the developed framework in the industry practice. The findings from the focus group workshop corroborate the development of the decision support framework based on the literature review, preliminary study, and case study, allowing methodological triangulation in this research, where the researcher employs varieties of data-gathering techniques (Gray, 2018).

1.5 Validity and reliability

Much attention is paid to reliability and validity in all research methods because, without rigour, research is worthless, becomes fiction, and loses its utility (Morse et al., 2002). Guba and Lincoln (1981) stated that all research must have "truth value", "applicability", "consistency", and "neutrality" to be considered worthwhile. However, the nature of knowledge within the rationalistic (or quantitative) paradigm differs from that of the naturalistic (qualitative) paradigm. Unlike quantitative researchers, who apply statistical methods to establish the validity and reliability of research findings, qualitative researchers aim to design and incorporate methodological strategies to ensure the 'trustworthiness' of the results (Noble & Smith, 2015).

Qualitative validity means that the researcher checks for the accuracy of the findings by employing certain procedures. In contrast, qualitative reliability indicates that the researcher's approach is consistent across different researchers and projects (Gibbs, 2018). Validity is one of the strengths of qualitative research. It is based on determining whether the findings are accurate from the standpoint of the researcher, the participants,

or the readers of an account (Creswell & Miller, 2000). Whereas the goal of establishing qualitative reliability is to minimise errors and biases in a research study (Yin, 2014; Saunders et al., 2016).

Instrumentation rigour and bias management are major challenges for qualitative researchers. Researcher bias can be occurred during every step of a research process, including the initial planning stage, theory development and modification, data collection and analysis (Chenail, 2011). It is argued that the nature of qualitative research is so personal to the researcher that another researcher might use the same data to come to radically different conclusions (Mays & Pope, 1995). Moreover, a few authors highlighted that the participant bias due to their comments, post-hoc evaluation, tone and verbal behaviour during the interviews adversely affect the reliability of the data findings (Yin, 2014; Saunders et al., 2016).

However, these contentions are countered by qualitative researchers who seek to show, through various strategies, how qualitative research can demonstrate rigour (Gray, 2018). Qualitative researchers can reclaim responsibility for reliability and validity by implementing verification strategies integral and self-correcting during the conduct of inquiry itself. Verification strategies can be adopted that ensure both reliability and validity of data are activities such as ensuring methodological coherence, sampling sufficiency, developing a dynamic relationship between sampling, data collection and analysis, thinking theoretically, and theory development (Morse, 2002). It is also important to note that the researchers carrying out qualitative research are an integral part of the process and final product. Therefore, as long as the researcher has been transparent and reflexive (i.e. critically self-reflective about their own preconceptions, relationship dynamics, and analytic focus) about the processes by which data have been collected, analysed, and presented, the potential bias can be minimised (Polit & Beck 2014; Galdas, 2017).

A procedural perspective recommended for research proposals is to identify and discuss one or more validity and reliability strategies available to check the accuracy and establish the truth of the findings. This research took many initiatives throughout the study to establish the reliability and validity of the research outcomes. Table 1-4 shows the measures taken in this research to ensure validity and reliability.

Table 1-4: Validity and reliability improvement measures

Improvement strategies	Actions taken in this research
Validity	<p>Data triangulation: data were gathered using multiple sampling strategies.</p> <p>Investigator triangulation: data were checked by senior colleagues/supervisors (even participants) to validate the findings by checking the final report, specific transcripts/descriptions, themes, and the proposed and refined versions of the framework.</p> <p>Multiple triangulation: multiple methods, data types, observers and theories were combined in the same investigation to interpret the findings.</p> <p>Methodological triangulation: Various research methods were employed within the research design (i.e. literature review, preliminary study, case study, focus groups).</p>
Reliability	<p>Comprehensive data collection and analysis procedure</p> <p>Established preliminary and case study protocols, including the case study overview, data collection procedures, research objectives and questions, and a tentative outline for the report.</p> <p>Audio recorded and transcribed interviews during the preliminary study and case study, as well as focus groups, to ensure that all the important information provided by the participants was captured correctly.</p> <p>Checked transcripts several times to avoid mistakes and errors that occurred during transcription.</p> <p>Used database represented all sources of evidence using the computer-aid qualitative data analysis software NVivo12, Excel and word-processing tools.</p>

Sources: Whitemore et al. (2001); Morse et al. (2002); Noble & Smith (2015); Creswell & Creswell (2017); Gray (2018)

1.6 Ethical consideration

This research was evaluated by peer review and assessed to be at low risk by the Massey University Human Ethics Committee. The ethics approval with Notification Number 4000023526 was given in 2020 for three years. Before making an ethics approval application to the Massey University Human Ethics Committee, the researcher read and complied with the Code of Ethical Conduct for Research. Throughout the research, the

researcher adhered to an excellent ethical standard in the entire data collection process (i.e. semi-systematic literature review, critical literature review, preliminary study, case study and focus groups). The respondents were advised to complete the confidentiality agreement contained in the participant information sheet (PIS) and sign the consent forms before commencing each data collection process (see Appendix 4). All collected data were stored on Massey University's premises. The supervisors and researcher were the only authorised people granted access to these data. Participants' identities were not revealed in the transcripts, and analysis, except with participants' permission. Based on the analysis, written reports were prepared, which might be published in various formats as study findings. The data collected will be destroyed within five years after the completion of this research project.

1.7 Research significance

The findings of this thesis play a significant part in the existing knowledge of climate change mitigation, sustainable built environment, facilities management, and construction management. The research is aligned with United Nations Sustainable Development Goal, including Goal 9 – Industry, Innovation and Infrastructure, Goal 11 – Sustainable Cities and Communities and Goal 13 – Climate Action. Specifically, the research results contribute to improve decision-making in building refurbishment towards zero carbon. At the international level, the findings from this research addresses a lack of detailed investigation on the decision-making process for building refurbishment considering whole-of-life carbon reduction in the industry practice. More importantly, the findings provoke the discussion about how building stakeholders collaborate and integrate available techniques, methods, approaches, and tools in the decision-making process to reduce carbon emissions in building refurbishment, which has not been treated in much detail in previous studies. At the national level, before this research, no previous study has investigated the zero carbon building practices and very little attention has been paid to the role of building refurbishment in the transition to a net-zero carbon built environment. This research has successfully addressed the knowledge gap by offering building professionals and practitioners a more holistic and streamlined interdisciplinary guide to better deliver building projects towards zero carbon. The study sheds new insight into the current industry practice, barriers, and opportunities, as well as policy implications for the uptake of zero carbon refurbishment in New Zealand. Especially, this research has potential forwards to enhancing the understanding of how the decisions are made

to maximise carbon reduction in building refurbishment. It provides improvement measures and recommendations to enhance the industry practice in reducing whole-of-life carbon emissions for building refurbishment.

The significant result of this thesis is a novel decision support framework for zero carbon refurbishment. The developed framework, integrating international and local best practices, provides a valuable contribution to the body of knowledge by presenting challenges and improvement measures to establish a greater way to support decarbonisation decisions in building refurbishment. The framework could be adapted to suit other types of buildings in New Zealand and other countries, aligning with the country-specific plan of work, regulations and guidelines, the maturity of the building and construction industry and building-specific issues regarding implementing carbon-reduction initiatives. At a certain level, several activities and characteristics could also be used in the process of designing new buildings, for example, the generation, performance estimation and evaluation of the design alternatives.

The outcomes from this study also built on existing literature in multi-method qualitative research design in the sustainable built environment field. The findings from triangulated data collection, analysis and interpretation prove the strength of using the qualitative approach in identifying and solving the research problems. Therefore, other researchers could apply this research design and results as references for future research in this area.

1.8 Thesis outline

The thesis is organised following Massey University Graduate Research School's Doctoral Thesis with Publications guidelines, which comprises eleven chapters. Apart from Chapter 1 – an overall introductory chapter and Chapter 11 – a coherent synthesis and overall conclusions of the work, the remaining chapters have been written as papers for peer-reviewed publication. For the chapters comprising articles, opening sentences linking with the preceding chapter is included in the abstract and closing sentences linking to the next chapter is encompassed in the conclusion in which the overall fit of the article is set clearly within the body of the thesis and repetitive writing is avoided.

Chapter 1 introduces the research background, problems, aim, and objectives. It also offers an overview of the research methodology, and ethical considerations. This chapter also sets out the structure of the study, with a summary of objectives, methods, activities, and brief results of the next chapters.

Chapter 2 aims to examine the application of zero carbon buildings worldwide through conducting a semi-systematic literature review. The chapter's findings clearly establish the concept of zero carbon buildings and the life cycle carbon impact of buildings with the classifications of operational and embodied carbon emissions. The results also reveal strategies for reducing carbon emissions in buildings, of which refurbishing existing buildings offers the greatest opportunity for life cycle carbon mitigation.

Chapter 3 investigates the global development, knowledge structure and gaps in the zero carbon refurbishment research field by conducting a semi-systematic literature review with mixed-method data analysis, including quantitative (science mapping) and qualitative (thematic) analysis. The findings from this chapter provide an insight into practices, methods, approaches, and tools that have been used to deliver building refurbishment towards zero carbon, identify knowledge structure and gaps in the research field, as well as propose future research directions.

Chapter 4 examines the existing decision support tools for building refurbishment and their applications to zero carbon refurbishment in the early design stages using a critical literature review. The chapter provides perspectives on the lessons-learned for the future development of zero carbon refurbishment decision support tools. Based on existing evidence, a conceptual framework is proposed for new decision support tools for building refurbishment towards zero carbon.

Chapter 5 aims to probe zero carbon buildings practices in the New Zealand context using a preliminary semi-structured interview with building experts in New Zealand. The chapter's findings reveal the current practice in which the New Zealand building and construction industry plans and implements buildings towards zero carbon. The results provide a deeper insight into the concept of zero carbon buildings in the New Zealand context, government initiatives, industry engagement and assessment methods and tools to reduce carbon emissions in buildings.

Chapter 6 inspects the challenges and issues to implement zero carbon initiatives in New Zealand's building and construction industry by undertaking an exploratory study using semi-structured interviews with New Zealand's building experts. The results illustrate significant challenges, including financial problems, the shortage of knowledge, capacity and capability, the insufficiency of legislation, and organisational culture barriers. The chapter's findings shed new insight into barriers to achieve whole-of-life building carbon reduction.

Chapter 7 investigates the implementation of building refurbishment towards zero carbon in New Zealand. The findings present opportunities and challenges to reducing carbon emissions in building refurbishment in New Zealand, resulted from the preliminary semi-structured interview with building experts in New Zealand. The findings call for a comprehensive decision support framework that provides detailed guidelines on incorporating whole-of-life carbon-reduction practices, methods, approaches, and tools for building refurbishment in New Zealand.

Chapter 8 examines decision making in reducing carbon emissions in the early stages of the refurbishment process by investigating three real-life case studies that incorporate carbon-reduction decisions. The results demonstrate the decision-making process, decision-making practices, the application of available methods, approaches, and tools to reduce whole-of-life carbon emissions in the early stages of the refurbishment process and lessons learnt for future work.

Chapter 9 explores the collaboration and integration in the decision-making process towards zero carbon refurbishment through the investigation of three real-life case studies in New Zealand. The chapter's findings divulge building stakeholders involved in each stage of the refurbishment process, their responsibilities, relationship and timely involvement, and key attributes required in an ideal process of collaboration and integration towards zero carbon refurbishment of existing buildings.

Chapter 10 presents the development and validation processes of a novel early-stage decision support framework towards zero carbon refurbishment of existing buildings in New Zealand. The development of the framework was based on the critical analysis and interpretation of the literature review, preliminary study, and case study. The developed framework was validated and refined using a focus group workshop with New

Zealand's building experts. The new framework provides a detailed guideline to use in the early stages of the refurbishment process with a focus on maximising whole-of-life carbon reduction.

Chapter 11 features a synthesis of the work that demonstrates the overall contribution to knowledge provided by the body of research within the thesis. The chapter first draw on final overall conclusions revisiting the research objectives. Then, theoretical, and practical implications, contribution to knowledge, and limitations are highlighted before suggestions and opportunities for future research are provided.

Appendices show documents used for data collection and analysis, including schedules, participant information sheets and consent forms. The DRC 16 “Statement of Contribution – Doctorate with Publications/Manuscripts” for each publication is also provided in the Appendices.

2 Chapter 2: A review of zero carbon buildings from international perspectives

This chapter is based on the following manuscript. It is intended that the manuscript will be published, but it has not yet been submitted to a Journal/Conference.

Bui, T. T. P., Wilkinson, S., MacGregor, C., & Domingo, N. (2024). A review of zero carbon buildings from international perspectives.

Abstract

There is a strong consensus that carbon emissions attributed to buildings are a major contributor to global warming. In addressing anthropogenic climate change, many buildings worldwide have been designed and constructed towards zero carbon. Chapter 2 aims to examine the current practices of zero carbon buildings (ZCBs) worldwide. The research questions are (1) What is the concept of ZCBs? (2) What are strategies for reducing carbon emissions in buildings? and (3) What is a key aspect for maximising carbon reduction in buildings? A semi-systematic literature review was conducted to gain insights into the current practices of zero carbon buildings from international perspectives. The findings reveal that there is terminological confusion in the literature as the definitions of ZCBs vary in different countries. It is suggested that the design and construction of buildings towards zero carbon should aim to achieve the highest level of whole-of-life carbon reduction and align with the carbon budget, which is the carbon benchmark based on the climate target in different nations. Strategies for reducing carbon emissions in buildings are (1) implementing passive design, energy efficiency, and renewable energy technologies, (2) reducing the use of new materials throughout the entire life cycle of buildings, (3) using alternatives with lower environmental impacts, and (4) improving construction and operation processes. The results also highlight the importance of refurbishing existing building, which is acknowledged as one of the key aspects for maximising carbon reduction. The study contributes to existing knowledge by providing a better understanding of ZCB practices in the international context.

2.1 Introduction

Carbon emissions emitted from the construction and operation of buildings are alleged as a major contributor to anthropogenic climate change. Reducing carbon emissions of buildings, thus, is a matter of urgency and importance. Apart from operational carbon emissions released during building operation and maintenance processes, buildings also demand a large amount of embodied and operational carbon emissions for their associated intensive procurement and on-site construction processes, contributing 33% of the total carbon emissions worldwide (UNEP, 2009). Therefore, measures to mitigate building emissions through switching to low-carbon and renewable energy sources should be further focused. Greater attention should pay to low-carbon building materials, building envelope improvements, nature-based solutions, and equipment and system efficiency (UNEP, 2021).

The ZCBs approach has been promoted in many countries and regions as a government strategy for addressing anthropogenic climate change. Until now, actions have been taken to reduce energy consumption and GHG emissions worldwide in the building and construction industry. Many countries and regions, namely the UK, Europe, the US, Canada, etc., have encouraged the adoption of ZCBs to tackle anthropogenic climate change (Treasury, 2007; Crawley et al., 2009; Recast, 2010). This promotion has considerably driven the development of ZCBs, as many have been constructed and reported globally through several channels. Markedly, the International Energy Agency's (IEA) Solar Heating & Cooling (SHC) Program Task 40 “Net Zero Energy Solar Buildings” has analysed and reported the conceptual approaches of several hundreds of “net zero-energy and energy-plus buildings” worldwide (Musall, 2015). The Zero Carbon Hub’s (ZCH) Building Profiles showcase “zero carbon homes” at national level (Zero Carbon Hub, 2015). Various researchers reported on individual or groups of projects of “zero carbon buildings” (Zuo et al., 2012; Pan, 2014). From the worldwide promotion and reporting, more “zero carbon buildings” can be expected to be developed for future years. Thus, cross-context learning of the past and existing practices is important, however largely constrained.

This chapter aims to provide a literature review of ZCBs from international perspectives, thus, to achieve a better understanding of the concept, implementation strategy and performance of buildings towards zero carbon worldwide. There are three research objectives: (1) to reveal the concept of buildings towards zero carbon; (2) to examine the strategies for reducing carbon emissions in buildings; and (3) to explore the key

aspect for maximising carbon reduction in buildings. Following this introduction, the paper reports on the findings and discussion before conclusions are drawn.

2.2 The concept of zero carbon buildings

2.2.1 Life cycle carbon emissions of buildings

Before introducing the concept of ZCBs, it is important to understand the carbon impact across the life cycle of the building. Life Cycle Assessment (LCA) method is often used to calculate life cycle carbon emissions. ISO 14040: 2006 defined LCA as the “compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system through its life cycle”. The framework for LCA studies prescribes four phases in the process, as shown in Figure 2-1.

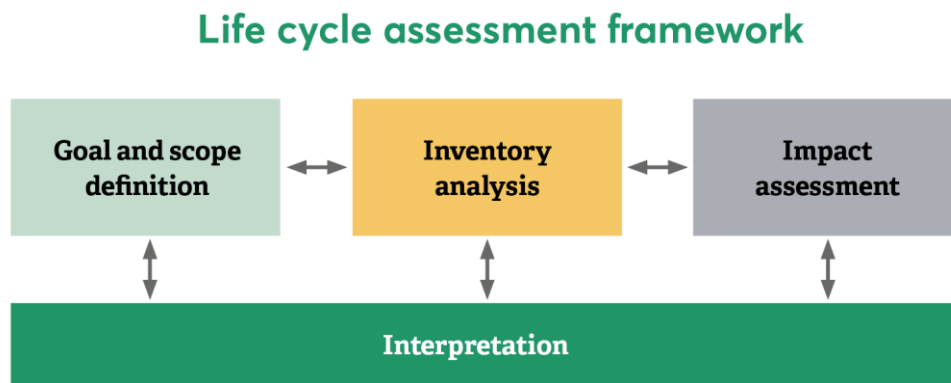


Figure 2-1: ISO 14040 framework for life cycle assessment (ISO 14040, 2006)

For buildings, LCA considers all the carbon-equivalent emissions output from a building over different phases of its lifetime, including raw materials extraction, manufacturing, construction, operation, maintenance, repairs, replacement, and demolition. The BS EN 15978:2011 standard – *Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method* sets out the methodology for calculating the life cycle carbon emissions of buildings (See Figure 2-2).

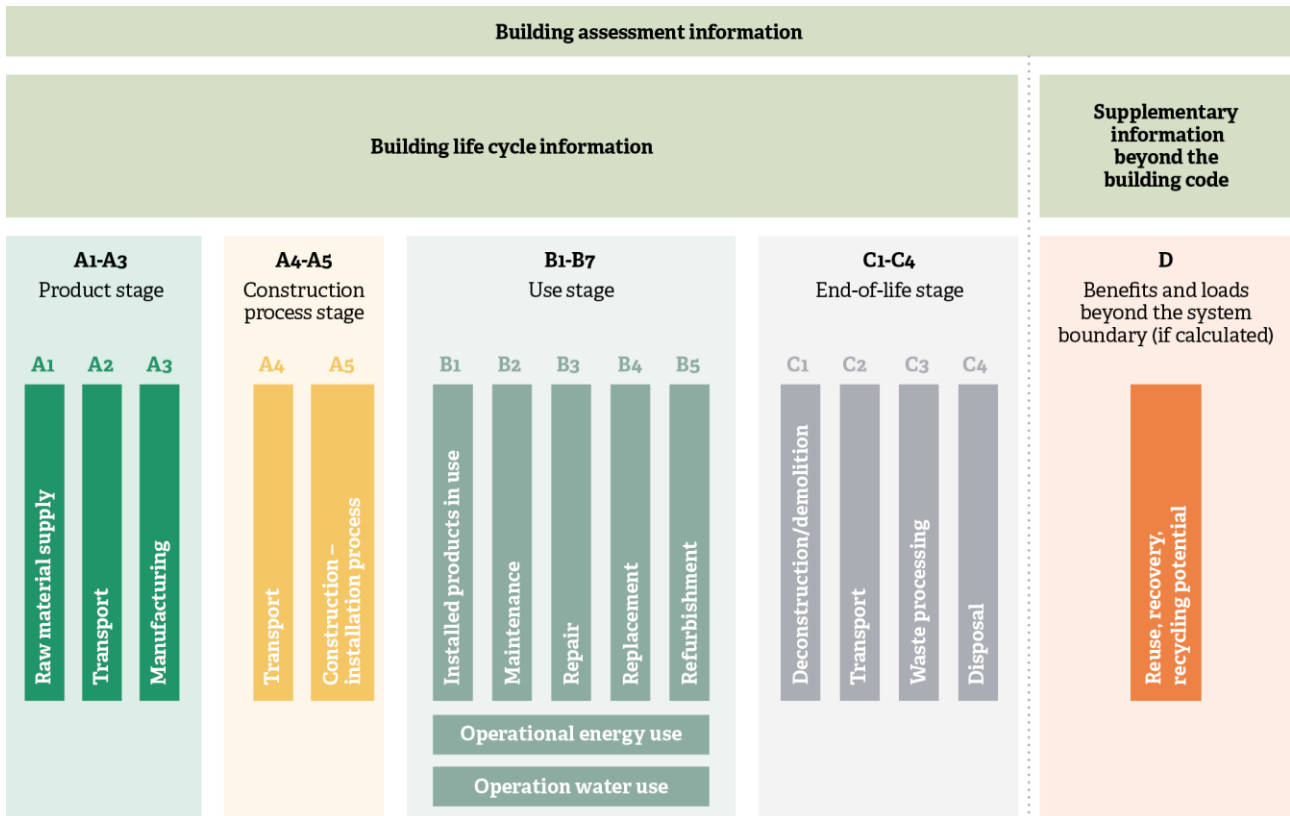


Figure 2-2: Building life cycle stages and modules (BS EN 15978:2011)

The system boundary of LCA determines the processes encompassed in the LCA, which should be consistent with the objectives of an LCA study. Typical examples of life cycles adopted in previous studies include cradle-to-gate, cradle-to-site, cradle-to-end of construction, cradle-to-end of use, cradle-to-grave, and cradle-to-cradle (see Figure 2-3). It is important to note that system boundaries of LCA may vary in many aspects, such as life cycle stage, scope, and method. Modules for LCA of buildings can be included and excluded depending on the scope of work and data availability (Balouktsi & Lützkendorf, 2016; Pan et al., 2018; Moncaster et al., 2019). To complete a holistic LCA study, at least a whole-of-life, which is ‘cradle-to-grave’ approach of assessing environmental impact should be considered.

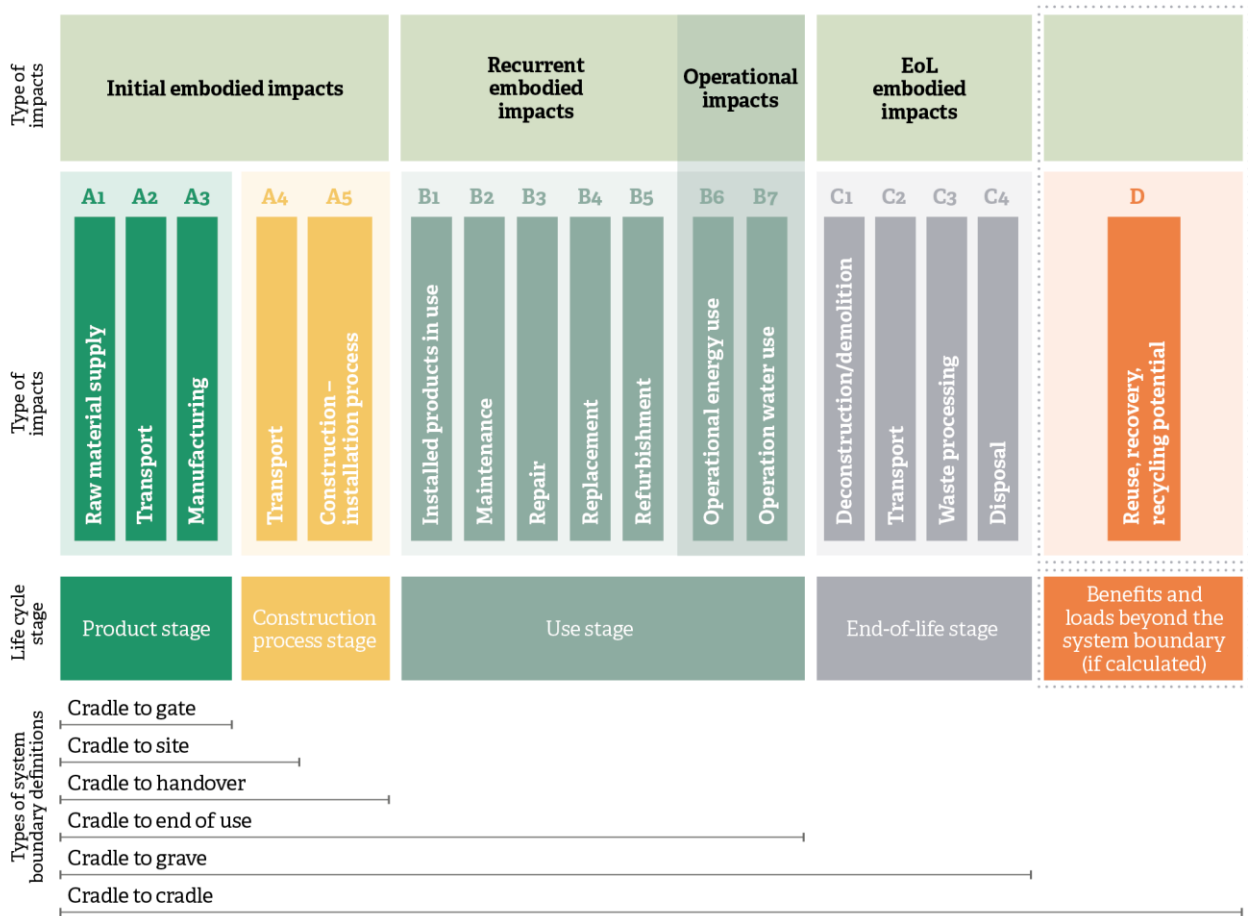


Figure 2-3: System boundaries definitions in relation to the life cycle stages of a building (Balouktsi & Lützkendorf, 2016; Moncaster et al., 2019).

Historically, operational carbon emissions – the carbon emissions associated with the use stage of a building, such as operational energy use (B6) and operational water use (B7) are the main contributor to its life cycle carbon emissions, responsible for approximately 80-90% of the total emissions in residential and office buildings, according to 73 case studies in 13 different countries (Ramesh et al., 2010). While operational carbon emissions have gradually decreased due to the implementation of energy efficiency systems and technologies, embodied carbon emissions have increased as a proportion of the life cycle carbon emissions (Opher et al., 2021). In 2018, 11% of global energy-related carbon emissions were attributed to manufacturing building materials and components. A building’s life cycle embodied carbon is the sum of emissions released throughout supply chains. These include raw material extraction and transportation, manufacturing (A1-A3); construction site activities and material losses (A4-A5); repair, maintenance, and replacement (B1-B5), and

end-of-life processing (C1-C4, D) (Chau et al., 2015; Schwartz et al., 2018; Opher et al., 2021). A review of 238 LCA studies revealed that relative contributions to buildings' embodied carbon emissions are around 64%, 22%, and 14% from production, construction, and maintenance during the use and end-of-life phases, respectively (Röck et al., 2020). Therefore, the central focus on minimising embodied carbon emissions from materials and products is critical.

2.2.2 The concept of zero carbon buildings within the context of countries

There is terminological confusion in the ZCBs literature as the definitions of ZCBs vary in different countries (Hernandez, 2010; Marszal et al., 2011; Pan, 2016). Many terms describe ZCBs in terms of their aspects and context, for example, zero carbon homes, zero energy buildings, nearly zero energy buildings, low carbon buildings, low energy buildings, etc. The concept of ZCBs within the context of countries leading the policies and practices of implementing ZCBs was examined in this section.

The United Kingdom (UK) was the first country to set a target for delivering ZCBs. The development of the ZCBs definitions in the UK has contributed significantly to the global understanding of ZCBs. The UK government first introduced the concept of ZCBs in the national standard named “Code for Sustainable Homes” in 2006, which takes a step further in housing practice. The definition of a zero-carbon home became one where carbon emissions from regulated energy use were limited or mitigated by a combination of three factors (the first two of which are known as carbon compliance standards):

- Achieving minimum Fabric Energy Efficiency Standards (FEES) based on space heating and cooling:
 - 39 kWh/m²/year for apartments and mid-terraced houses
 - 46 kWh/m²/year for terrace, semi-detached and detached houses.
- Using low and zero carbon technologies and connected heat networks to limit on-site built emissions:
 - 10 kg CO₂eq/m²/year for detached houses
 - 11 kg CO₂eq/m²/year for attached houses
 - 14 kg CO₂eq/m²/year for low-rise apartments.

- Where it is not possible to reduce the regulated carbon emissions to zero using these on-site measures, the remaining carbon emissions could be mitigated through allowable offsite solutions (Department for Communities and Local Government, 2010).

However, the allowable solutions measure has been criticised as it is a form of indirect carbon offsetting (offset carbon by purchasing carbon credits), which may not lead to the effort to reduce carbon emissions during the design and construction processes (Bullock et al., 2009). The Code of Sustainable Homes was operational from 2007 to 2015. The code was mandatory if it was a requirement of a local authority. Although this policy became voluntary in 2015, it well signposted the start of governments' promotion of ZCBs worldwide (MacGregor et al., 2019).

European Union (EU) policies encourage energy efficiency and renewable production to achieve a climate-neutral continent by 2050. The recast Energy Performance of Building Directive (EPBD), a central policy document, introduced Nearly Zero Energy Buildings (NZEBs) in 2010 and established that new buildings occupied by public authorities and properties must be NZEBs by December 31, 2018, and all new buildings by December 31, 2020. A nearly zero energy building is a building with very high energy performance, where the nearly zero or very low amount of energy required should be covered as much as possible by renewable energy sources produced on-site or nearby. This definition addresses energy rather than carbon but offers flexibility in achieving the “nearly zero” target. A uniform approach for implementing NZEBs is not established in the EPBD. Member States must develop NZEBs definitions in line with national, regional, or local conditions and include a numerical indicator of primary energy use (in kWh/m²y) (D’Agostino et al., 2021).

The Norwegian Research Centre on Zero Emission Buildings defined ZCBs based on different goal levels, regarding which life cycle stages are comprised, in line with BS EN 15978:2011. The term “ZEB-O-EQ” indicates the lowest level at which the on-site renewable energy generation compensates for the emissions related to all energy use during operation (O), minus the energy use for equipment/appliances (EQ). The term “ZEB-COMPLETE” is the highest level where all life cycle stages are considered. To achieve the highest zero-emission level, the GHG emissions of locally generated energy from renewable sources, such as photovoltaic

(PV) panels, solar thermal, heat pump or combined heat and power (CHP) technologies, must counterbalance the embodied emissions from materials (Moschetti et al., 2019).

In Australia, Sustainability Victoria, on behalf of the Australian Sustainable Built Environment Council, has provided ZCBs definition for Australia. A zero-carbon building has no net annual Scope 1 and 2 emissions from the operation of building-incorporated services (Riedy, 2011).

- Building-incorporated services include all energy demands or sources that are part of the building fabric at delivery, such as the thermal envelope (and associated heating and cooling demand), water heater, built-in cooking appliances, fixed lighting, shared infrastructure and installed renewable energy generation.
- Zero carbon buildings must meet specified standards for energy efficiency and on-site generation.
- Compliance is based on modelling or monitoring greenhouse gas emissions in kg CO₂e/m²/yr.

Scope 1 emissions is direct greenhouse gas emissions from sources owned or controlled by the occupant, such as emissions from burning natural gas in the home. Scope 2 emissions are those from the electricity generation used in the building. Scope 3 emissions are other indirect sources of emissions. These scopes are based on a reporting standard for GHG emissions established by the World Business Council on Sustainable Development and World Resources Institute in 2004 (Riedy et al., 2011).

In the United States of America, a zero-energy building (ZEB) can be defined in several ways, depending on the boundary and the metric. Torcellini et al. (2006) proposed a few ZEB definitions as follows:

- Net Zero Site Energy: A site ZEB produces at least as much energy as it uses in a year, when accounted for at the site.
- Net Zero Source Energy: A source ZEB produces at least as much energy as it uses in a year, when accounted for at the source. Source energy refers to the primary energy used to generate and deliver the energy to the site. Imported and exported energy is multiplied by the appropriate site-to-source conversion multipliers to calculate a building's total source energy.

- Net Zero Energy Costs: In a cost ZEB, the amount of money the utility pays the building owner for the energy the building exports to the grid is at least equal to the amount the owner pays the utility for the energy services and energy used over the year.
- Net Zero Energy Emissions: A net-zero emissions building produces at least as much emissions-free renewable energy as it uses from emissions-producing energy sources.

There are operational carbon-based and whole-of-life carbon-based concepts in defining ZCBs. These concepts are considered in a specific context (operational carbon released in the operation stage of the building) or general (embodied and operational carbon radiated throughout the life cycle of the building). From an academic standpoint, Pan (2014) proposed a model using two fundamental dimensions, including the aspect being described and the context under discussion, to reduce the complexity of ZCBs definitions (see Figure 2-4). It is important to note that the term “zero carbon building” is often conflated with “zero energy building” and “nearly zero energy building”, notwithstanding the difference between these concepts. Efforts on energy-related measures and a holistic focus on reducing and compensating for the embodied emissions of the materials during the entire life cycle are required to transition from a zero-energy building to a zero-carbon building (Moschetti et al., 2019).

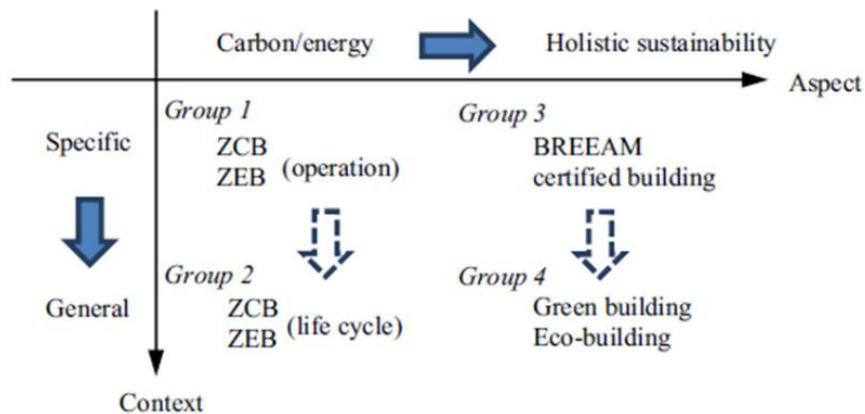


Figure 2-4: ZCBs' concepts by categories (Pan, 2014)

Without policy and regulation, measuring and reducing embodied carbon impacts may still be on the fringes since the building and construction industry traditionally focuses on improving energy and operational carbon performance (Ramesh et al., 2010; Moncaster et al., 2019). However, the inclusion of embodied carbon impacts into building regulations is starting to happen. There is increasing coverage of Environmental Product

Declarations (EPD) at the component level and their development within the A2 version of BS EN 15804 (Passer et al., 2015; Lützkendorf, 2018). In 2022, the EN 15804 + A2 standard became mandatory for all new EPDs. The Netherlands is the first country to introduce a requirement into its building regulations to measure the embodied impact of materials. Several other countries are taking the first steps towards this end, including France, Sweden, Norway, Denmark, and Finland (Moncaster et al., 2019).

2.2.3 The carbon budgets

Implementing ZCBs means maximising carbon reduction throughout a building's life cycle to meet Paris agreement's emissions reduction targets. However, the critics question the carbon benchmark required for a building and how much carbon reduction should be targeted for a building's design and construction. It is believed that the carbon budget can provide information about the building's performance in terms of global climate targets. The carbon budget represents "allowable" emissions between now and 2050 based on the Intergovernmental Panel on Climate Change (IPCC) estimates (IPCC, 2018). These estimates are the total amount of carbon that humankind can emit in the period 2018–2050 that will not result in exceeding specified temperature rises (usually specified as 1.5 or 2.0°C). Therefore, the budget is an allowance between now and 2050 – a transition period before we need to be net-zero carbon. A top-down approach, which targets to cascade global climate targets down to sub-global levels, quantifying the individual building target value (Zimmermann et al., 2005; Hollberg et al., 2019), can be used to develop carbon benchmarks.

Global efforts have been made to calculate climate change targets for residential and non-residential buildings. For example, Hollberg et al. (2019) used the grandfathering sharing principle, which assigned a carbon budget share to the residential industry based on its relative contribution to national GHG emissions. According to this approach, the climate target of a Swiss single-family house was 360 kg carbon dioxide equivalent per capita per year ($\text{kgCO}_2\text{eq.cap}^{-1} \cdot \text{yr}^{-1}$). In another study, Russell-Smith et al. (2015) estimated a target of 2.29 tonne per square metre floor area ($\text{tCO}_2\text{eq. m}^2$) for the whole life cycle of a commercial building in the USA, considering a 50-year lifetime. The target was based on the GHG emissions projections in the IPCC Fourth Assessment Report (IPCC, 2007), which recommended a 70-80% GHG emissions reduction below 1990 levels by 2050 for buildings to operate within the 2°C climate target. Recently, similar approach has been taken by other researchers (Chandrakumar, 2020; Bullen et al., 2021), who subsequently updated and extended to

include an assessment of residential and office buildings against a 1.5°C climate target set in the Paris Agreement. For example, it was found that the carbon footprint of the New Zealand office building sector for 2018–2050 (8566 ktCO₂eq) exceeded the carbon budget (2140 ktCO₂eq) by a factor of 4.0 (Bullen et al., 2021) Although many studies defining carbon targets for buildings exist, these targets are different from one country to another, given the large variations in the construction materials, climate conditions and energy mix in other parts of the world.

In summary, the design and construction of a zero-carbon building should aim to reduce operational and embodied carbon emissions throughout the whole life cycle of the building. The concept of ZCBs considered in this research is to achieve the highest level of carbon reduction and align with the carbon budget, which is the carbon benchmark based on the climate target in different nations.

2.3 Strategies for reducing carbon emissions in buildings

2.3.1 Reducing operational carbon emissions

Improving building energy performance may be the most effective and available measure to reduce operational carbon emissions in buildings (Y. Wang et al., 2016; Azzouz et al., 2017; Luo et al., 2019). It can be achieved mostly via integrating design strategies, including passive design, energy efficiency, and renewable energy technologies (Pan & Li, 2016). Low energy design should consider the passive design attributes that can be used to modify the external climate to the benefit of improving the energy performance of the building, including orientation, solar control, daylight, and use of thermal mass. Even in mechanically cooled and ventilated spaces, passive building envelope design (e.g. walls) for cooling and heating can significantly reduce energy consumption. The building envelope is a major part of the passive design approach. For modern office design, the use of ‘smart’ layered facades can provide good thermal insulation and control solar heat gains and daylight (Zhu et al., 2013; Jones et al., 2015). Besides passive design, integrating energy-efficient ventilation, heating, cooling, and lighting systems can improve comfort and energy use (Pan & Li, 2016).

Renewable energy technology is one of the most effective solutions to reduce fossil fuel energy usage, for example, solar power generation technology (Xydis, 2009; D'Agostino et al., 2017). Most renewable energy sources are derived from solar radiation, including the direct use of solar energy for heating or electricity

generation; indirect forms such as energy from wind, running water, and plants and wood wastes. Another renewable energy resource is geothermal energy, which can be found in geysers, boiling pools, and hot springs (Nakata et al., 2011). Renewable energy resources are abundant and can offer stabilisation and reduced future prices (Jäger-Waldau, 2019). However, the mainstream deployment of renewable technologies will continue to improve. The concern is also expressed regarding the increased embodied carbon impacts due to using immature technology in the manufacturing process of renewable technologies (Vares et al., 2019). Furthermore, the performance gap related to evaluation standards, installation issues, or installer/user behaviours remains overlooked (McElroy & Rosenow, 2019).

2.3.2 Reducing embodied carbon emissions

In response to a growing proportion of embodied carbon (sequestered in building materials) in whole-life carbon emissions, recent studies have developed guidance on embodied impact assessment. According to the literature (Lupíšek et al., 2015; Moncaster et al., 2019; Opher et al., 2021), three strategies for reducing embodied carbon emissions in a building's design and construction are:

- Reduction of the number of needed materials throughout the entire life cycle
- Substitution of carbon-intensive materials for alternatives with lower environmental impacts
- Reduction of construction stage impact

The strategy for reducing the number of needed materials is further broken into the five sub-strategies:

- Optimisation of layout plan
- Optimisation of structural system
- Low-maintenance design
- Flexible and adaptable design
- Components' service life optimisation

The strategy of substitution of the carbon-intensive materials with alternatives includes the six sub-strategies:

- Reuse of building parts and elements
- Utilisation of recycled materials
- Substitution for bio-based and raw materials

- Use of innovative materials with lower environmental impacts
- Design for deconstruction
- Use of recyclable materials

It is believed that the key mitigation strategy is to increase the use of alternative materials with lower embodied carbon (Giesekam et al., 2014; Giesekam et al., 2016). Examples include low-carbon concrete and bricks (Cabeza et al., 2013) and bio-based materials (Gross & Walker, 2014; Baduge et al., 2019). Although concrete used to construct buildings generates the high embodied carbon level, this building material is likely dominant in the building and construction industry. Alternative concretes, which produce low carbon emissions, such as concrete containing industrial wastes (e.g. steel slag, sewage sludge ash, silica fume), can be routinely considered for use on a project than natural or unconventional materials (Giesekam et al., 2016). With the innovations of engineered timber products and processes, the benefits of using timber as a construction material are performant durability, less energy used in its production, and long-term carbon sequestration. Meanwhile, using recycled materials (e.g. timber waste) can help reduce carbon emissions produced by new materials (Qu et al., 2012; L. Wang et al., 2016).

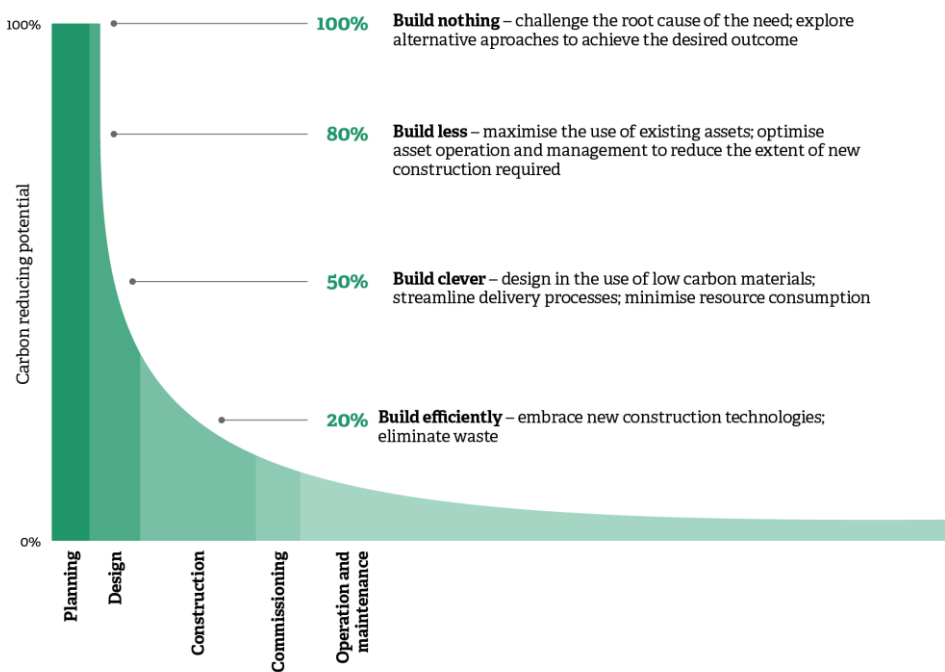


Figure 2-5: Carbon reduction potential over time and illustrative relative savings of decisions to build (New Zealand Government Procurement, 2021)

Reusing existing building elements and utilising recycled materials is also critical. The retention of existing buildings, where feasible, offers a better opportunity to maximise embodied carbon reduction (Pomponi & Moncaster, 2016; Moncaster et al., 2019). The greatest opportunities to reduce whole-of-life embodied and operational carbon are at a project's planning and design phases as shown in Figure 2-5. At the beginning phase of identifying a business need, significant carbon emissions can be reduced by considering other options that do not result in a new building. For example, consider other options at the business case stage, such as improving the use of existing space and refurbishing to enhance the building's usability. The following sections elaborate on the greatest opportunity for life cycle carbon mitigation, which lies with the upkeep of existing buildings.

2.4 Zero carbon building refurbishment: A key aspect for maximising carbon reduction

2.4.1 Refurbishment in the context of zero carbon buildings

The terms retrofit, refurbishment, renovation, and reuse of buildings are often used interchangeably. Retrofit means addition of features for the improvement of performance in a particular area (e.g. energy efficiency and structural integrity). Refurbishment and renovation both represent a “modification and improvement to an existing building in order to bring it up to an acceptable condition”. The International Organisation for Standardisation ISO 21931:2010, British Standards BS EN 15978:2011 and Building Research Establishment Environmental Assessment Method (BREEAM) use the term “refurbishment”, while the term “renovation” is more prevalent in the North America region throughout the Leadership in Energy and Environmental Design (LEED) and European Union member countries such as Denmark and Sweden (Vilches, 2017; Hasik et al., 2019). Following the international standards, the term “refurbishment” is used throughout this research. As mentioned earlier in this research, the concept of ZCBs considers the highest level of carbon reduction and aligns with the carbon budget, which is the carbon benchmark based on the climate target in different nations. The refurbishment of existing buildings consistent with the context of ZCBs is called “zero carbon refurbishment (ZCR)”.

It is important to identify the refurbishment boundaries in LCA, which indicate how to calculate the life cycle carbon impact of refurbished buildings. As shown in Figure 2-2, refurbishment in LCA is expressed as a module (B5). The scope of this module is different from that of the B2 (maintenance), B3 (repair) and B4 (replacement) modules. According to BS EN 15978:2011, the system boundaries of the B5 module (refurbishment) are as follows:

- Production of new components of the building
- Transport of new components (including the production of materials lost during transport)
- Construction as part of the refurbishment process (including the production of materials lost during the refurbishment)
- Waste management of the refurbishment process, and
- End-of-life of the substituted building components

However, there is a lack of clarity on what constitutes the waste management of the refurbishment process and end of life of substituted building components. It is not specified whether the waste management of refurbishment processes should include only the waste from the production and installation of newly added components, or it should also consider the waste resulting from the demolition of existing components. In addition, whether the end-of-life of the substituted building components should consist of only the end-of-life of the newly added components, or it should also include the end-of-life of the demolished components. Therefore, substituted materials (end-of-life stage, C1-C4) and remaining existing building materials (end-of-life stage C1-C4) are possible boundary extensions that should be considered when undertaking LCA for refurbished buildings (Vilches et al., 2017; Hasik et al., 2019). Figure 2-6 shows the building refurbishment boundaries considered in this research. The refurbishment boundaries consist of new embodied carbon (product stage A1-A5), operational use (use stage B1-B7) and new embodied materials (end-of-life stage C1-C4). Substituted materials (end-of-life stage, C1-C4) and remaining existing building materials (end-of-life stage C1-C4) are considered as possible boundary extension. Depending on the scope of LCA in each building, the refurbishment boundaries can be extended.

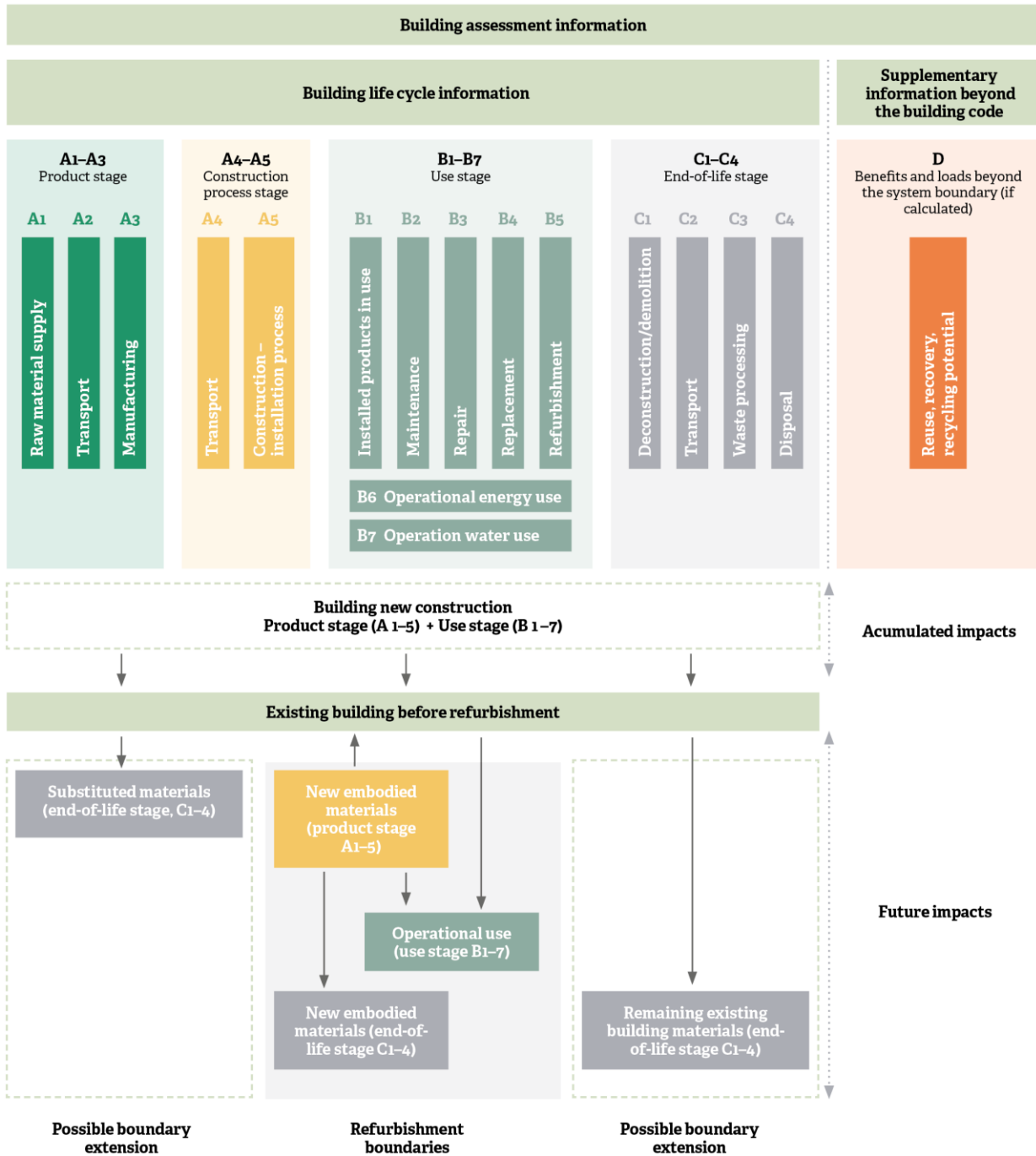


Figure 2-6: Building refurbishment boundaries (Vilches et al., 2017)

2.4.2 Why refurbish? The importance of building refurbishment in reducing carbon emissions

The refurbishment of existing buildings is an important component in climate change mitigation and plays a key role towards a net-zero carbon future. It is argued that refurbishing existing buildings offers a greater opportunity to reduce carbon emissions than constructing new buildings. This appears to be especially true in

advanced economies where the existing building stock forms the vast majority of the built environment. Of the European buildings that will be occupied by 2050, up to 80% have already been built (King, 2010). In some countries such as the UK, Hong Kong and Australia, the ratio of new to old buildings is lower than 4% each year, and the replacement rate of existing buildings by new buildings is only around 1-3% (Ma et al., 2012; Li et al., 2017).

Many studies have shown the carbon benefits of building refurbishment versus new build from operational and embodied carbon perspectives. Early examples of research into this area include Power (2008) and Power (2010), which strongly support the refurbishment case. It was concluded that the demolition case is greatly weakened when considering embodied and operational carbon emissions. Gaspar and Santos (2015) provide further support evidence from previous work, demonstrating that the refurbishment of a detached house in Portugal built in the late 1960s would be 22% more carbon saving than demolition and rebuild. In the same vein, one of the International Energy Agency research projects recently investigated the reduction of embodied carbon emissions over the whole life ('cradle to grave') of buildings (Annex 57) by collating and analysing over 80 detailed quantitative and qualitative building case studies from the participating nations around the world. The results show that the median carbon emissions in the product stage of refurbishment projects was 125 kgCO₂e/m², just under half the median value for the new build projects of 254 kgCO₂e/m² (Moncaster et al., 2019). The refurbishment of a two-story stand-alone building in Philadelphia, the USA, was found to help reduce environmental impacts associated with the life cycle of building components by 53–75% (Hasik et al., 2019). The importance of building refurbishment in reducing carbon emissions has been widely acknowledged. Therefore, the question is not whether to refurbish existing buildings but how to refurbish existing buildings to reduce carbon emissions.

2.5 Conclusion

This chapter set out to investigate the current zero-carbon building practices in the international context. The findings provide a clear understanding of the life cycle carbon impact of buildings with the classifications of operational and embodied carbon emissions and support effective cross-context learning of the practices worldwide. Although the concepts of ZCBs are acknowledged differently across the globe, the design and construction of buildings towards zero carbon should aim to achieve the highest level of carbon reduction and

align with the carbon budget, which is the carbon benchmark based on the climate target in different nations. To reduce whole-of-life carbon emissions in buildings, the following strategies identified in the literature should be considered (1) implementing passive design, energy efficiency, and renewable energy technologies, (2) reducing the use of new materials throughout the entire life cycle of buildings, (3) using alternatives with lower environmental impacts, and improving construction operation processes. One of the most important strategies is retaining existing buildings to maximise embodied carbon reduction. Refurbishing existing buildings offers the greatest opportunity for life cycle carbon mitigation than constructing new buildings. Thus, approaches for reducing carbon emissions in building refurbishment would be a fruitful area for further work.

3 Chapter 3: Zero carbon refurbishment for existing buildings: A literature review

This chapter is based on the following Journal article, which has been published in final form. The paper was also presented and accomplished Best Paper Award for Durability and Climate Change at World Building Congress, International Council for Research and Innovation in Building and Construction, Australia, 2022.

Bui, T. T. P., Domingo, N., MacGregor, C., & Wilkinson, S. (2022). Zero carbon refurbishment for existing buildings: A literature review. *IOP Conference Series: Earth and Environmental Science*, 1101(2), 022017. <https://doi.org/10.1088/1755-1315/1101/2/022017>

Abstract

As indicated in Chapter 2, encouraging the refurbishment of existing building will enable the significant reduction of life cycle carbon emissions. To meet zero carbon emissions targets for buildings by 2050, the building and construction industry needs to implement zero carbon strategies for the refurbishment of the existing building stock rather than demolishing and rebuilding. Zero carbon refurbishment (ZCR) of existing buildings, therefore, is a significant research area of interest. This chapter investigates the global development, knowledge structure and gaps in the ZCR research field by conducting a semi-systematic literature review. The final selection of 147 up-to-date journal articles was analysed using mixed-method data analysis, including quantitative (science mapping) and qualitative (thematic) analysis. Quantitative results reveal evolving research topics such as energy performance and efficiency, life cycle environmental impacts, energy resources and policy, and decision-making. Research in ZCR is well-established in European countries and there is much interest and activity around the world. ZCR research on residential and office buildings provokes much consideration compared to other building types. The qualitative discussion demonstrates the mainstream research areas (e.g. decision-making with multi-objective optimisation), determines research gaps (e.g. carbon impact), and recommends the future research agenda (e.g. a holistic multi-objective methodology considering whole-of-life carbon, economic factors, co-benefits, and other impacts). The chapter's findings offer academics a comprehensive understanding of ZCR research to link current research areas into future trends

while also provide construction professionals with current practices and an interdisciplinary guide to better deliver ZCR projects.

3.1 Introduction

Over the last few decades, climate change has presented many challenges (Seneviratne et al., 2016). The global carbon emissions have continuously increased, from 22.5 billion tons in 1998 to 34.04 billion tons in 2018 (The World Bank, 2018). The Paris agreement in 2016 sought to limit the temperature increase from 2°C to 1.5°C above pre-industrial levels by 2050 (Rogelj et al., 2015). Due to one-third of global GHG emissions, the building and construction industry is critical in alleviating carbon emissions. Compared to new buildings, refurbishing existing buildings offers a favourable opportunity to maximise carbon benefits. For example, Hasik et al. (2019) compared the whole-building life cycle assessment (LCA) of refurbishment and new construction in the USA. The case study demonstrates 53–75% environmental impact reductions when refurbishing rather than constructing a new building. Due to a large volume of literature describing the role of ZCR, several reviews exist in the ZCR research area to discover uncovered knowledge structures. Loli and Bertolin (2018) presented a literature review towards ZCR of historic buildings, determining research gaps in the field and highlighting the inconsistency in the Scandinavian countries. Hashempour et al. (2020)'s review paper focuses on energy performance optimisation of existing buildings, while Lu and Lai (2020)'s study predominantly pays attention to the carbon emissions of commercial buildings. However, the generalisability of published reviews on this issue is problematic as they mostly concentrate on specific building types, locations, and aspects. These results are also based upon data published until 2017-2018. Given the latest Paris agreement in 2016, the research interest in the global decarbonisation for the existing building stock is expected to increase. Thus, there is a need for an up-to-date evaluation of critical areas and emerging trends.

This chapter aims to provide the latest comprehensive literature review in ZCR for existing buildings. The novelty of this research is performing mixed-method data analysis, including science mapping and thematic analysis, in reviewing the ZCR research area. The following objectives are (1) analysing the main research topics within ZCR; (2) identifying the current research gaps; and (3) proposing future research directions. The remaining part proceeds as follows: (1) describe the methodology used in the study; (2) report results from the

science mapping approach; (3) discuss the main research topics with the research gaps and future research directions.

3.2 Research method

A semi-systematic review was undertaken to examine the state-of-the-art research on ZCR due to its organised, transparent, and reproducible way to synthesise research findings and discover future studies (Snyder, 2019). The chapter adopted a mixed-method data analysis technique, including quantitative (science mapping) and qualitative (thematic) analysis. This approach has been extensively used in construction engineering and management to present knowledge domains and research topics (Luo et al., 2019; Ren et al., 2020). Science mapping was employed to analyse and visualise bibliometric networks (Chen, 2017), while thematic analysis was applied to describe data in rich detail, summarise and interpret various aspects of the research topic (Braun & Clarke, 2022).

The research process consists of three stages. In stage 1, the bibliometric search strategy used the keywords: “zero carbon” OR “net zero carbon” OR “zero emission” OR “zero energy” OR “nearly zero energy” AND “refurbishment” OR “retrofit” OR “renovation” via Scopus to determine the relevant ZCR literature. Scopus was selected for document search because of its influential and all-inclusive database, covering more recent publications than other digital sources such as Web of Science (Falagas et al., 2007). To narrow the scope of the review, a set of selection criteria were considered, including (1) English journal articles published at the final stage in the last five years (2017-2021), (2) Relevant subjects in the construction research field, (3) Paper published in top-ranking journals in the construction field ranked by Scimago Journal and Country Rank (e.g. Energy and Building), publishing the largest number of papers in the research context. The final selection includes 147 up-to-date journal articles. In stage 2, VOSViewer – a comprehensive science mapping tool based on Visualisation of Similarities (VOS) technology was adopted. It has unique advantages in clustering fragmented knowledge from different domains according to their similarity and relatedness. Compared with other options, the viewing capabilities of VOSViewer are beneficial for maps containing at least a moderately large number of items (e.g., at least 100 items) and the tool displays such maps in a satisfactory way (Van Eck & Waltman, 2010). VOSViewer was employed in this research to visualise and analyse three scientometric tests: (1) keywords/clusters co-occurrence analysis, (2) country-specific analysis, (3) document co-citation

analysis. According to Van Eck and Waltman (2014), a node indicates a specific bibliographic item in the visualised networks, namely keyword, country, reference, etc. The node size signifies the counting of the appraised item, such as citation and occurrence. Link represents the co-citation and co-occurrence. The software automatically accomplishes the total link strength (TLS) to reflect the correlation between any two nodes in the created networks. The average normalised citation symbolises the normalised number of journal source, article, scholar, country, or organisation citations. The normalisation corrects the misinterpretation that older documents gain more time to receive citations than recent publications. In stage 3, a qualitative discussion was presented with a hierarchical knowledge structure of recent ZCR research. Ongoing main research topics were summarised while the research gaps and future research directions were determined.

3.3 Findings

3.3.1 Keywords co-occurrence analysis

A network of keywords was produced to exhibit the knowledge and rational organisation of the research themes. The options “All Keyword” and “Full Counting” in VOSViewer analysis were chosen to acquire a holistic academic knowledge of ZCR research. The minimum occurrence of a keyword was set at 4. Initially, 144 out of 1448 keywords met the threshold. After removing duplicates and general items such as “construction”, “retrofitting”, “building”, etc., 69 keywords with 1212 links were selected for final consideration. In addition, using VOSViewer, the whole network could be automatically divided into clusters labelled with terms from keywords. Studies within the same cluster might be more similar than those from other clusters. Three clusters were identified in different colours, demonstrating latent semantic themes within the textual data, where the research patterns were perceived to uncover knowledge (Luo et al., 2019). Cluster #1 (30 items) focused on energy performance, energy efficiency, and life-cycle environmental impacts. Cluster #2 contained 21 items centring on energy use, resources, and policy, whereas Cluster #3 (18 items) emphasised decision-making with multi-objective optimisation, including economic trade-offs and renewable energy compensation.

This network represented the boundaries and central tendency in the ZCR research area. The nodes sizes and the connection lines among keywords showed the most frequently studied and highly concerned terms, such

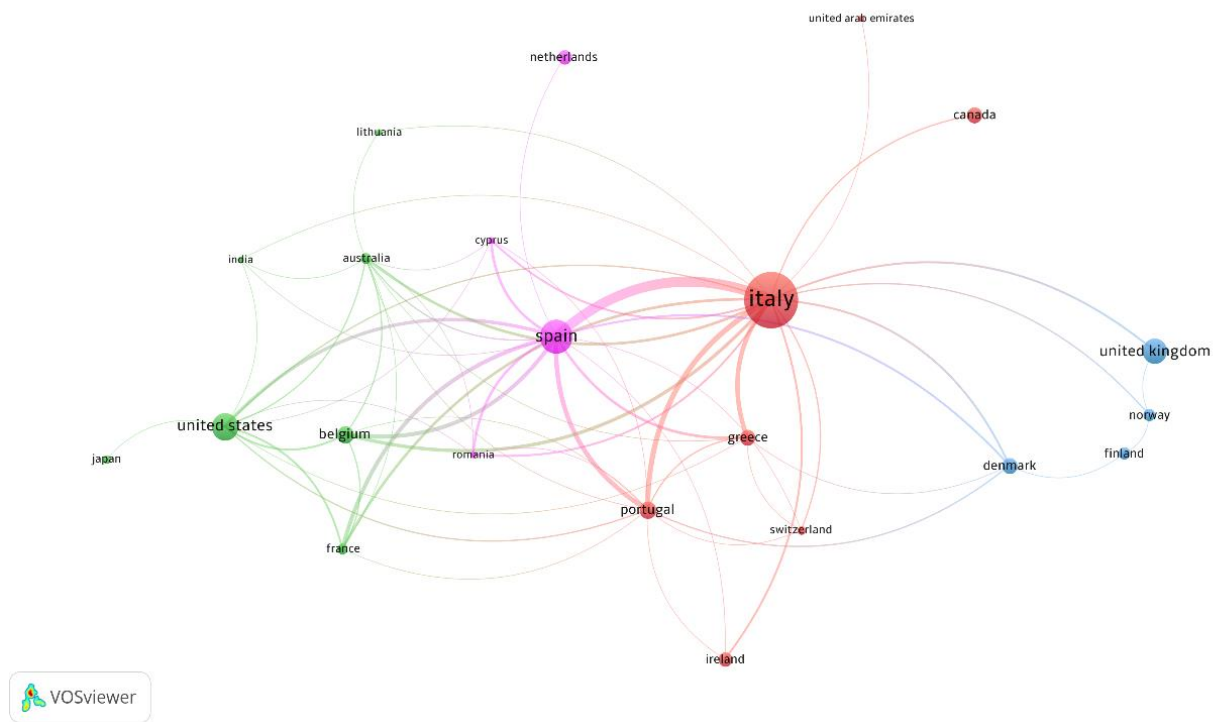


Figure 3-2: Mapping of countries contributing to ZCR research (Source: Authors)

According to the node sizes and connection lines, the following countries have contributed significantly to the global research: Italy, Spain, the US, the UK, Belgium, Portugal, Canada. Other countries such as France and Norway offered fewer publications but strongly expressed their significant influence through the high average citation. Scholars from Europe took the lead in ZCR research, ranking the top in terms of the number of publications and total citations, followed by North America. This result might be explained that European nations have started implementing a long-term renovation strategy set out in the Energy Performance of Buildings Directive (2010/31/EU) over a decade. Research on ZCR has also been attentive in other parts of the world, e.g., Oceania (Australia) and Asia (India, Japan and UAE). Table 3-1 present the findings of the top-ten countries influencing ZCR research in the last five years.

Table 3-1: Summaries of country-specific leadership in ZCR research (Source: Authors)

Countries	Numbers of publications	Number of citations	Average Norm. Citation	Countries	Number of publications	Number of citations	Average Norm. Citation
Italy	46	868	1.13	Belgium	8	216	1.98
Spain	22	296	1.06	Greece	7	162	0.97
United States	16	159	0.70	Canada	7	136	1.01
United Kingdom	14	144	0.66	Denmark	7	64	0.94
Portugal	8	226	1.81	Netherlands	6	52	0.49

3.3.3 Document co-citation analysis

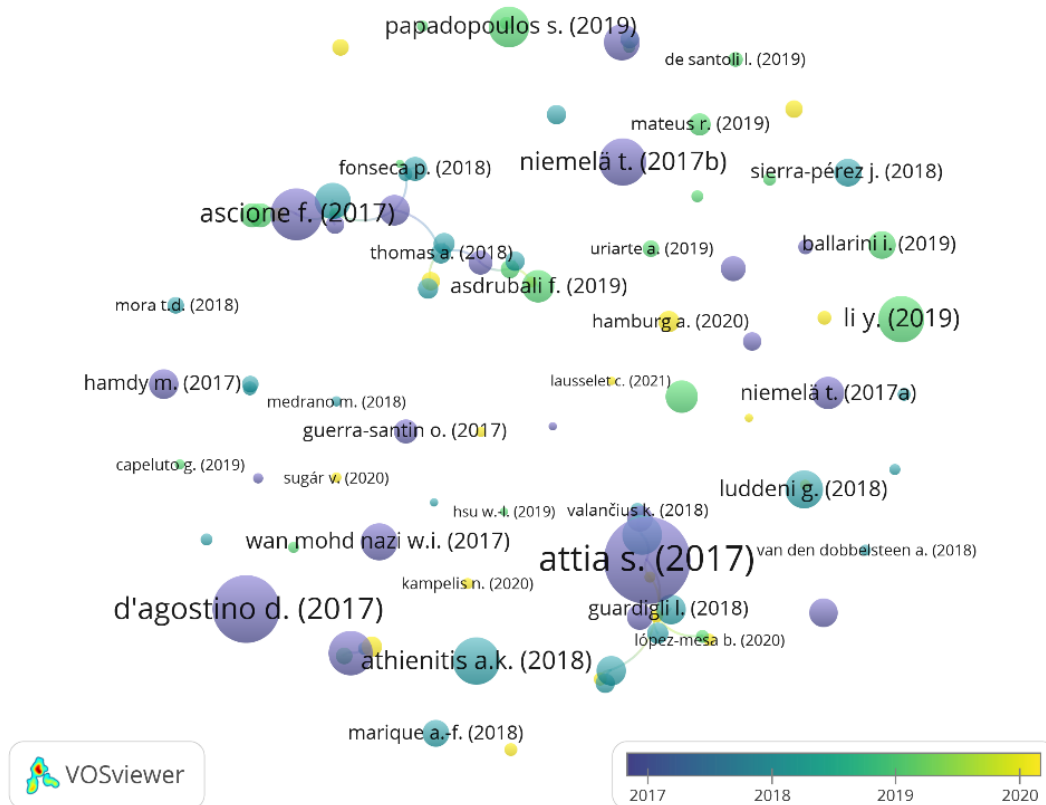


Figure 3-3: Mapping of co-citation analysis (Source: Authors)

A document co-citation analysis could divulge the underlying intellectual structure of a knowledge domain (Luo et al., 2019). Therefore, the most influential journal publications in the last five years were assessed with

the co-citation network generated in VOSViewer. The minimum number of citations was set to 5. Of the 147 documents, 92 meet the threshold, resulting in a co-cited visual network map, as shown in Figure 3-3. The most extensive set of connected items consisted of 20 items. The nodes in the map denoted the documents, identified by the first author's name and the publication year. The time of publication signified the colours of the nodes and the links.

The co-citation network showed an overall distribution, with only two large sets of connected items. This result indicated that the recent ZCR research directions went beyond common ideas and results. 2017 was a landmark year for ZCR research as the majority of high-citation papers were released. The latest ZCR research in the 2020s was expected to spread faster and more comprehensively. More details on the top-five most cited articles are demonstrated in Table 3-2.

Table 3-2: List of high-impact publications in ZCR (Source: Authors)

Scholars	Year	Title	Citations	Average Norm. Citation	Related topics
Attia et al. (2017)	2017	Overview and future challenges of nearly zero energy buildings (NZEB) design in Southern Europe	138	3.803	Operation and management research
D'agostino et al. (2017)	2017	Towards Nearly Zero Energy Buildings in Europe: A Focus on Retrofit in Non-Residential Buildings	95	2.618	Systematic evaluation
Ascione et al. (2017)	2017	Energy retrofit of educational buildings: Transient energy simulations, model calibration and multi-objective optimisation towards nearly zero-energy performance	64	1.764	Multi-objective optimisation
Athienitis et al. (2018)	2018	Assessing active and passive effects of façade building-integrated photovoltaic/thermal systems: Dynamic modelling and simulation	57	3.213	Environmental aspect
Niemelä et al. (2017)	2017	Cost-effectiveness of energy performance renovation measures in Finnish brick apartment buildings	56	1.543	Environmental and economic aspects

3.4 Discussion

Following the science mapping analysis, a qualitative discussion was carried out to summarise the growing research trend, identify research gaps and future work. An up-to-date ZCR knowledge map was developed, resulting from scientometric and thematic analysis (see Figure 3-4).

Existing research recognises the critical role of ZCR delivery methodology at the building level. The most highlighted finding is a continuous interest in using multi-objective optimisation processes, which support decision-making in selecting the best fit-for-purpose refurbishment options. Most studies adopt at least two sustainability objectives focusing on environmental and economic factors (Bui et al., 2021b). However, carbon impact is not a common investigation focus compared to energy. Contemporary research Asdrubali et al. (2019) has preliminarily incorporated whole-of-life carbon consideration with energy and economy aspects. Mainly being overlooked in the past, the social objective (“co-benefits”) has been recently well-established in multi-objective optimisation processes. An all-inclusive refurbishment to achieve the performance required by laws such as seismic regulations must also be considered. For instance, the methodology for comparing cost-optimality in building refurbishment developed in IEA Annex 56 project has been extended with: (1) an LCA including embodied primary energy and carbon emissions in the calculations (Almeida et al., 2018), (2) an approach to integrate co-benefits in the evaluation of the refurbishment scenarios (Ferreira et al., 2017), and (3) a method for energy and structural upgrade (Mora et al., 2018). These observations suggest that a holistic multi-objective methodology considering whole-of-life carbon, economic factors, co-benefits, and other impacts is necessary for the global ZCR development. Furthermore, multi-objective optimisation processes often incorporate various methods, tools, and systems to support decision-making. Hu (2018) proposed a novel building information model (BIM) – building performance model (BPM) – building environmental model (BEM) framework to identify the most energy-efficient and cost-effective refurbishment strategies. Rabani et al. (2021) integrated an Indoor climate and energy simulation software (IDA-ICE) and a generic optimisation tool (GenOpt) through a Graphical Script interface to find the best combination of refurbishment measures. Nevertheless, empirical research reporting on how these methods, tools and systems are adopted to support decision-making in the current industry practice is of interest for future work.

Another significant issue for upcoming research is relevant to the methodology for carbon quantification. Most LCA studies emphasise embodied carbon emissions of construction materials and rarely assess the carbon impacts of mechanical, electrical, and plumbing (MEP). The refurbishment often improves energy efficiency by upgrading building services, accounting for a considerable amount of embodied carbon emissions. To date, Rodriguez et al. (2020) established a preliminary range of material quantities and embodied carbon impacts for MEP and tenant improvement (TI) components, focusing on commercial office buildings in the Pacific Northwest. Further work is required to establish the availability of embodied carbon quantities worldwide.

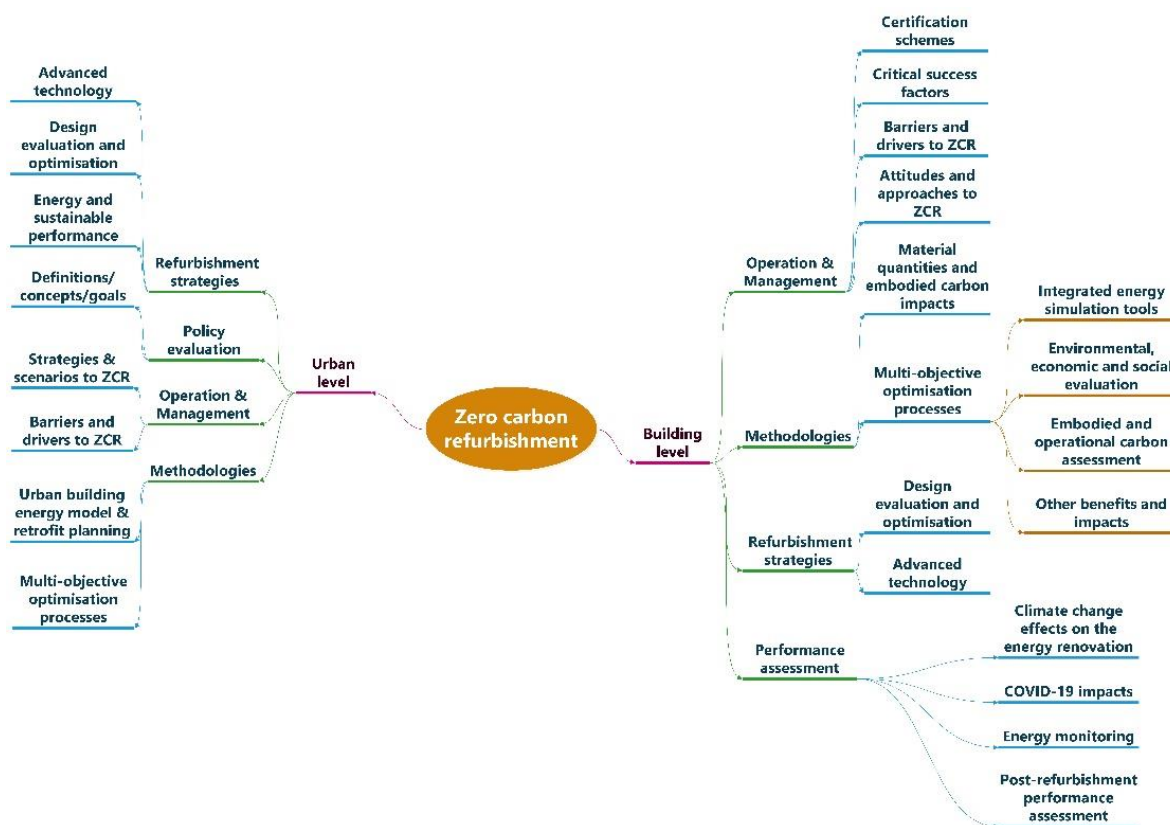


Figure 3-4: A mind map of ZCR research themes (Source: Authors)

There is a large and growing body of literature regarding refurbishment strategies in advanced technologies, design evaluation and optimisation for ZCR. Examples include multi-disciplinary analysis of light shelves application (Ruggiero et al., 2021), the evolution of double-skin and responsive façade (Ascione et al., 2021), PV optimisation (Gremmelspacher et al., 2021). This finding shows that investigations on refurbishment technologies and strategies have been widely studied. Turning to performance assessment, many attempts have been made to evaluate the energy performance before and after refurbishment and the impacts of occupant behaviours (Guerra-Santin et al., 2017; Teni et al., 2019). The current research trend evolves towards assessing

the effects of long-term climate change and global pandemics such as the COVID-19 crisis on refurbishment actions (Baglivo, 2021; Monzón-Chavarrías et al., 2021).

In terms of operation and management, understanding critical success factors, barriers and drivers to implement ZCR within the building and construction industry and the construction professionals' knowledge and attitudes towards ZCR are essential for a wide range of ZCR uptake (Aloise-Young et al., 2021; Butt et al., 2021). For example, Alam et al. (2021) argue that reducing embodied carbon emissions in the construction materials for refurbishment projects is less important than improving energy efficiency from Finnish stakeholders' viewpoints. However, the transition to a 100% renewable energy system in many countries such as Denmark and New Zealand by 2050 may leave behind the primary focus on energy efficiency. This result, while preliminary, informs the formulation of policies to drive the whole-of-life carbon consideration for ZCR. So far, there has been little discussion about the stakeholder collaboration in the decision-making process towards delivering ZCR projects. Regarding energy and carbon performance certificate schemes, which often calculate energy savings and operational carbon reduction (Y. Li et al., 2019), the current schemes create a demand-driven market for energy efficiency, rather than looking at the carbon challenge holistically, such as the whole-of-life carbon performance assessment.

Due to a call for massive decarbonisation by 2050, the current research trend shifts from an individual building level to an urban level. As same as the building level, various studies have assessed the efficacy of refurbishment strategies, operation and management and methodologies at the metropolitan level. The issue of ZCR-related policy has lately received considerable concentration. Cerezo-Narváez et al. (2021) examined the energy, emissions, and economic impact of the new NZEB regulatory framework and accomplished that the energy savings and carbon reduction objectives were greatly exceeded. Whereas Approved Document L for existing British buildings was underperforming but could feasibly be revised to encompass contemporary sustainable design solutions (Williamson & Finnegan, 2021). Nonetheless, most studies are conducted in Europe, where research into building refurbishment has a long history. The challenges and opportunities to ZCR policy implementation in Europe indicate lessons learnt for other countries.

3.5 Conclusion

This chapter set out to provide an updated systematic literature review in ZCR of existing buildings and new insights into the future ZCR research directions. The science mapping analysis reveals main clusters of research around energy performance and efficiency, life-cycle environmental impacts, energy use, resources and policy, multi-objective decision-making. European nations take the lead, but other countries also actively contribute to the ZCR research. To specify the contribution from every country, future research should analyse the case studies and their implementation. Meticulous attention has been devoted to ZCR research on residential and office buildings. The recent ZCR research directions exceed common ideas and results. The most cited publications are relevant to operations and management, systematic evaluation, multi-objective optimisation, environmental and economic aspects. The follow-up qualitative analysis's results considerably align with the science mapping analysis. The most critical suggestions for future work are as follows: (1) a holistic multi-objective methodology considering whole-of-life carbon, economic factors, co-benefits and other impacts; (2) empirical research on how available methods, tools and systems regarding multi-objective optimisation processes are adopted to support decision-making process in the current industry practice; (3) the investigation on stakeholder collaboration in the decision-making process towards delivering ZCR projects, (4) the availability of embodied carbon quantities; (5) whole-of-life carbon performance assessment.

4 Chapter 4: Towards zero carbon building refurbishment: A new conceptual framework for decision support tools

This chapter is based on the following conference paper, which has been published in final form. The paper was accomplished Best Paper Award for Conference Theme.

Bui, T. T. P., Wilkinson, S., Domingo, N., & Macgregor, C. (2021). Towards Zero Carbon Building Refurbishment: A New Conceptual Framework for Decision Support Tools. In: L. Scott & C. J. Neilson (Eds.), Proceedings of the 37th Annual ARCOM Conference, 6-7 September 2021, UK (pp. 594-603), Association of Researchers in Construction Management.

Abstract

As revealed in Chapter 3, there is a growing research interest in decision-making in reducing carbon emissions in building refurbishment. Reducing carbon emissions in building refurbishment can be achieved if effective decisions are made throughout the refurbishment process. To gain a deeper understanding in this research area, this chapter set out to examine the current decision support tools for building refurbishment and their applications to zero carbon refurbishment of existing buildings in the early design stages. A critical review was conducted with the final selection of 15 state-of-the-art decision-making tools for building refurbishment, which might be suitable for merging or modification into zero carbon refurbishment decision support tools. Based on existing evidence, a conceptual framework is proposed for future development of zero carbon refurbishment decision support tools. The study provides perspectives on the lessons-learnt for the future development of zero carbon refurbishment decision support tools such as the application of the carbon budget and Value-Focused Thinking in the goal-setting stage, the inclusion of refurbishment strategies, the involvement of project stakeholders and end-users throughout the refurbishment process and the potential integration of incentive schemes to take up zero carbon approaches. The insights gained from this chapter better support the building and construction industry to develop and deliver zero carbon refurbishment projects.

4.1 Introduction

In the light of climate change, the world wrestles with reducing global warming to no more than 1.5 degree and achieve net-zero greenhouse gas emissions by 2050. Having responsibility for more than 40% of international energy use and one-third of global greenhouse gas emissions (Lucon et al., 2014), the building and building and construction industry can significantly contribute to reducing climate change impacts. To decrease carbon emissions, one response is zero carbon buildings (Xing et al., 2011; W. Pan & M. Pan, 2020). However, the description of zero carbon buildings is confused. At present, the term encompasses several categories, such as “low energy”, “low emissions”, “sustainable” and even “green” buildings, leading to the problematic process of adoption and implementation. Thus far, (Pan, 2014) proposed a model using two fundamental dimensions of zero carbon buildings’ concept: (1) specific to general, and (2) carbon/energy to holistic sustainability. The concept of zero carbon building should be considered as the reduction of operational and embodied carbon emissions throughout the whole life cycle of the building.

To achieve net-zero carbon target by 2050, many existing buildings will need to be upgraded, refurbished, or renewed as much of the current existing building stock will still be in use in 2050. This research focuses on refurbishing buildings to reduce the highest level of whole-of-life carbon emissions. The term “refurbishment”, which represents a “modification and improvement to an existing building to bring it up to an acceptable condition” (ISO, 2010; British Standards Institution, 2011). Vilches et al., 2017 defined the building refurbishment boundaries according to BS EN 15978: 2011 and BS EN 15804:2012. These boundaries are the production of new components, transport of new components, construction as part of the refurbishment process, waste management and end-of-life of the substituted and remaining existing building components. Building refurbishment in the context of zero carbon buildings defined above is called “zero carbon refurbishment”.

Successful zero carbon refurbishment for existing buildings can be attained if effective decisions are made throughout the refurbishment process. Over the years, researchers have paid attention to the design and development of decision support tools to aid the optimal refurbishment solutions (Jensen & Maslesa, 2015; Li & Froese, 2017; Gade et al., 2018; Serrano-Jiménez et al., 2021). Several systematic reviews of decision support tools have been undertaken in academic studies (Thuvander et al., 2012; Ferreira et al., 2013). The

latest review was conducted by (Nielsen et al., 2016), which provided a state-of-the-art overview of the development of decision support tools in the pre-design and design phases. The authors have identified 43 decision support tools that are applicable in the pre-design and design phases of refurbishment projects. This view has shown a constant improvement of decision support tools for building refurbishment from the mid-1990s until 2015. However, most of them were designed for sustainable building refurbishment. The review was also limited to refurbishment strategies, which characterised distinctive levels of building refurbishment, depending on each urban and socio-economic context from different countries (J. Li et al., 2018; Penna et al., 2019). Apart from a hierarchical process towards zero carbon refurbishment for buildings established by Xing et al. (2011), there is a limited number of simple and holistic decision support tools that can address zero carbon problems for existing buildings. Making decisions about the refurbishment of buildings and the incorporation of net-zero carbon target are more difficult as decision-makers must deal with a combination of zero carbon problems and constraints and limitations. This chapter examines the present decision support tools for building refurbishment in the early design stages and determines lessons-learnt for developing zero carbon refurbishment decision support tools.

4.2 Research method

A critical literature review has been undertaken to assess, critique, and synthesise the literature on decision support for building refurbishment in a way that facilitates a new conceptual framework for future zero carbon refurbishment decision support tools. The critical literature review search strategy used the keywords: “building refurbishment” OR “building renovation” OR “building retrofit” AND “decision making” OR “decision support” in the title, keywords, and abstract fields via Scopus database to ascertain the relevant literature within the scope of the review. Scopus was chosen for the document search because it is the most present, influential, all-inclusive, and broadly used by academic researchers for peer-reviewed literature (Falagas et al., 2007). Initially, 160 papers including articles, review, book chapters, conference papers published in English from 2016 to 2021 were found. Then, the mainstream chosen for reviewing included top-ranking journals and conferences in the construction field ranked by Scimago Journal & Country Rank (e.g. Building and Environment), publishing the largest number of papers in the research context. 80 papers were examined and evaluated by reading abstracts to confirm that they were relevant to the research scope, which

was limited to the decision making in the early design stages including pre-design and design phases. The final selection included 15 state-of-the-art decision-making tools. The reviewed decision support tools were analysed according to six themes: country, target users, types of buildings, functionality, assessment methods and methodology.

4.3 Findings

The decision support tools are defined as mechanisms or approaches that can assist decision-makers, such as building clients and other building stakeholders, to make informed decisions related to building projects (Nielsen et al., 2016; Jensen, Maslesa, & Brinkø Berg, 2018). Literature shows that there is a continuous development of decision support tools in the last five years. The reduced version of the up-to-date decision support tools review, categorised according to target users, types of buildings, and functionality is illustrated in Table 4-1.

Table 4-1: Summary of key findings from the review of up-to-date decision-making tools (Source: Authors)

Tools/ Citation	Types of buildings	Target users	Functionality
BECEREN Olsson et al. (2016)	Residential buildings	Multi- decision makers	Provide alternative improvement options and renovation measures, evaluate different improvement options
Seddiki et al. (2016)	Masonry buildings	Multi- decision makers	Rank different thermal renovation solutions
Jafari & Valentin (2017)	Residential buildings	Homeowners	Calculate the economic benefits of energy retrofitting, determine the optimum retrofitting budget, select the optimum energy retrofitting strategy
Kamari et al. (2017)	All types of buildings	Relevant stakeholders	Audit, develop and assess building renovation performance. Support decision-making during the project's life cycle
SWAHO Li & Froese (2017)	Residential buildings	Homeowners	Enable trade-offs among renovation actions based on the homeowner's perception of sustainability

REDIS Gade et al. (2018)	School buildings	Danish municipality	Support the building owners in choosing which buildings to renovate within a building portfolio, or which renovation actions to initiate across multiple buildings
Li et al. (2018)	Multi-story residential buildings	Relevant stakeholders	Select low-carbon refurbishment solutions for multi-story residential buildings in high-density subtropical cities
Guardigli et al. (2018)	Public housing stocks	Investors	Assess different renovation strategies, evaluate the economic sustainability of various design alternatives
He et al. (2019)	Multi- buildings	Investors	Optimise energy efficiency retrofit investment in numerous buildings under financing budgetary restraint
NovaDM Kamari et al. (2019)	Large-scale residential buildings and social housing	Designers	A constraint-based renovation design support
Klimakit model Penna et al. (2019)	Social housings	Multi- decision makers	A tool for promoting the energy refurbishment of social housing
Napoli et al. (2020)	Public buildings	Multi- decision makers	Support the decision process of regional or local authorities in the context of a large number of energy retrofitting actions of public buildings
PARADIS Kamari et al. (2021)	Residential buildings	Designers	Support informed decision making for optimal renovation scenario design
Serrano- Jiménez et al. (2021)	Residential buildings	Housing managers	Select feasible and sustainable housing renovation strategies
PrioritEE toolbox Salvia et al. (2021)	Public buildings	Local decision- makers	A web-application Decision Support Tool for comparing and ranking a portfolio of energy interventions

Aside from those designed in the US, Canada and China, many decision support tools were developed in Europe. European policies have advocated the refurbishment of the existing building stock towards the sustainable development, as demonstrated in the Directive (EU) 2018/844 (European Commissions, 2011).

There were no decision support tools for building refurbishment in Oceania found in this review. The majority of tools (about 70%) were designed to support the decision-making for residential buildings rather than other building types. In the past, most of decision support tools were targeted at decisions and evaluation on individual refurbishment projects whilst the current trend moved from individual buildings into multi-buildings (Gade et al., 2018; He et al., 2019; Salvia et al., 2021). The tools were primarily generating and ranking refurbishment solutions and evaluating the economic benefits during the design stage, targeting a group of building professional users who had experience in building energy and cost modelling. Whereas Kamari et al. (2017) developed a new simplified holistic sustainability decision-making support framework, which could be used by non-professional building users in any stages throughout the refurbishment project life cycle.

In view of assessment methods and methodology, many of the designed tools were focused on sustainability, with at least one or two sustainable dimensions such as environment, economy, and social. A combination of Life Cycle Costing and Life Cycle Assessment methods was proposed for measuring two sustainability aspects including economy and environment. Considering the environmental dimension, both operational and embodied carbon emissions had been assessed in the process of choosing improvement options (Olsson et al., 2016). Whereas Net Present Value and the Global Cost calculated by analysis were predominantly used to appraise the economic sustainability of various design alternatives (Guardigli et al., 2018; He et al., 2019; Penna et al., 2019). Nonetheless, most of the tools have taken environmental and economic aspects as the main concerns, the social aspect has mostly been overlooked. In fact, Serrano-Jiménez et al. (2021) considered both impacts and benefits of the refurbishment applications through a procedure of quantifying and weighting multiple social, technical, and economic variables, whilst Kamari et al. (2017) engaged the involvement of multi-stakeholders and end-users through the application of Soft Systems Methodologies with Value-Focused Thinking. Although scholars have attempted to deal with the social issue by setting social criteria and additional parameters, social issues have remained on the fringe of mainstream practice (Jensen, Maslesa, & Brinkø Berg, 2018). These findings suggest that refurbishment project goals should be based on construction stakeholders and end-users' perspectives and consider wider aspects such as benefits and impacts of refurbishment projects, aside with sustainable aspects. Table 4-2 demonstrates details of the methodology used for the development of existing decision support tools.

Table 4-2: Summary of methodology used in developing up-to-date decision-making tools (Source: Authors)

Tools	Methodology
BECEREN Olsson et al. (2016)	Case studies. LCC and LCA approaches
Seddiki et al. (2016)	Delphi, Swing and PROMETHEE methods, and Graphical Analysis for Interactive Aid (GAIA)
Jafari & Valentin (2017)	Building energy simulation: eQuest. LCC formulation
Kamari et al. (2017)	Literature review, individual and focus group interviews, and application of Soft Systems Methodologies (SSM) with Value Focused Thinking (VFT)
SWAHO Li & Froese (2017)	A design science method
REDIS Gade et al. (2018)	A design science method
Li et al. (2018)	Identify sustainable refurbishment solutions, assess emission reductions. develop system process, validate with industry experts
Guardigli et al. (2018)	Evaluate the economic sustainability of various design alternatives with the net present value (NPV) and the global cost (GC)
He et al. (2019)	Use a multi-objective optimization model. Validate the model with 27 buildings of non-governmental organisations
NovaDM Kamari et al. (2019)	The IDEF5 methodology for knowledge engineering and ontology development
Klimakit model Penna et al. (2019)	Literature review, workshops, economic analysis based on Net Present Value (NPV)
Napoli et al. (2020)	Collect database of the building stock, develop of the multi-criteria model, apply ELECTRE TRI-nC method, sort the energy retrofitting actions into categories
PARADIS Kamari et al. (2021)	Building Information Modelling (BIM) based decision support system
Serrano-Jiménez et al. (2021)	Apply an iterative design process based on data and experiences from two case studies
PrioritEE toolbox Salvia et al. (2021)	Literature review, using national database, develop a web-based application, test in five local pilots

The review has demonstrated new decision support tools, which had additional parameters such as impacts and benefits of the refurbishment suggestions, and/or apply for a specific situation in different nations. This

might be because these tools were designed for definite purposes and practical cases. Some tools were not available for use online or with local languages and databases. Thus, even though there were many tools developed in the past with the same functionalities, researchers have intended to create new tools based on existing theoretical foundations, making them more suitable in different contexts. The literature has showed that there is a lack of tools to support decision-making processes in the early stages for building refurbishment specifically towards zero carbon target.

4.4 Discussion

The development of decision support tools for zero carbon refurbishment was critically examined. Overall, the development of the conceptual framework for zero carbon refurbishment is based on the theoretical framework of the refurbishment process in the early stages, including five main parts: (a) Goal setting; (b) Building condition assessment; (c) Refurbishment strategies; (d) Generation of refurbishment alternatives; (e) Performance estimation and evaluation. For zero carbon refurbishment projects, there is a need to examine the carbon measurement and performance, employ the refurbishment strategies towards zero carbon, engage with construction stakeholders and end-users, and consider the incentive schemes in a way that enable maximum the carbon reduction. A new conceptual framework for the future development of zero carbon refurbishment tools is recommended based upon the analysis (see Figure 4-1).

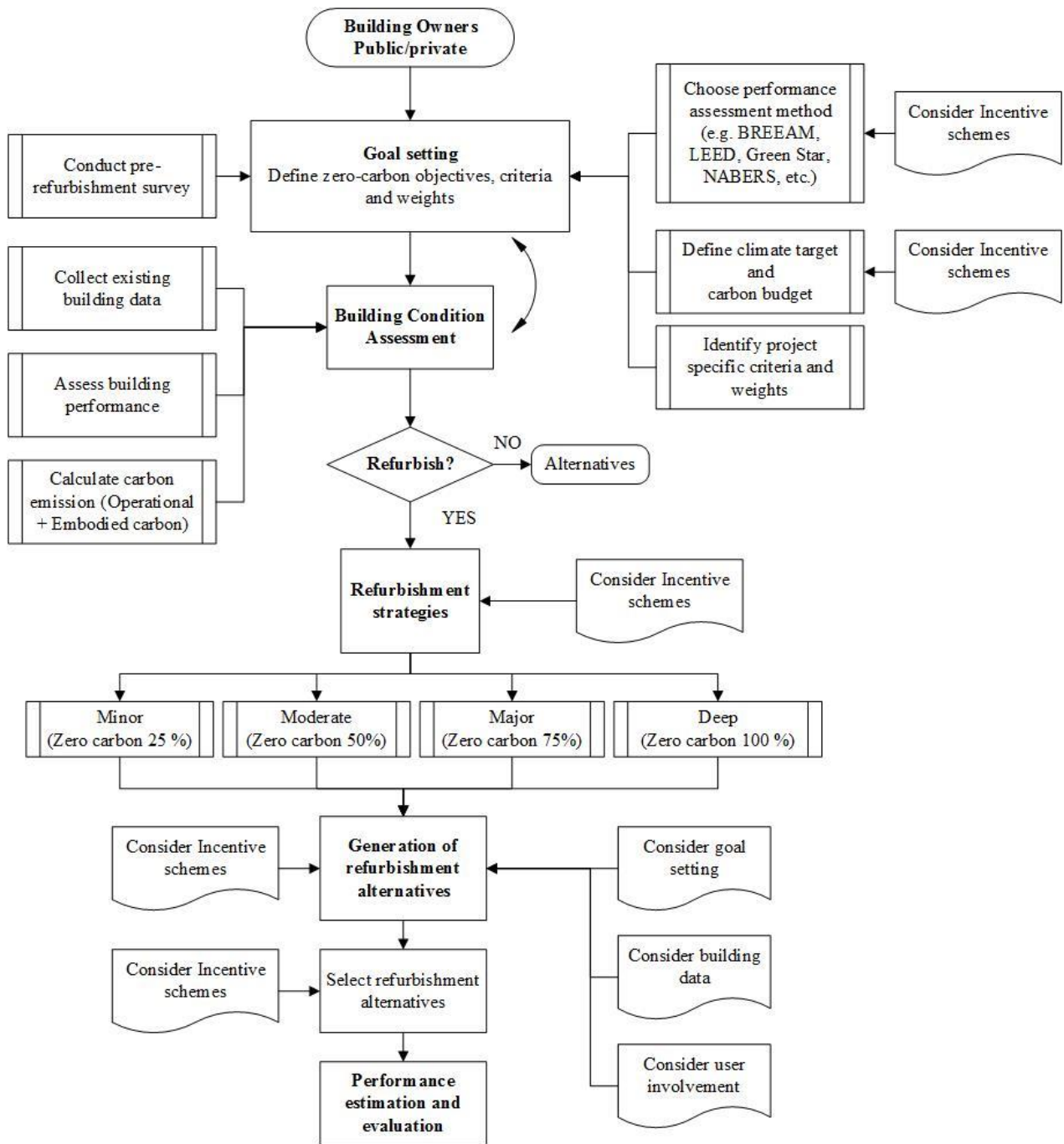


Figure 4-1: A conceptual framework for future zero carbon decision support tools (Source: Authors)

4.4.1 Setting the right goal

Setting the right goals is often the first and important step in the refurbishment process (Ferreira et al., 2013; Nielsen et al., 2016). For zero carbon refurbishment project to be successful, a building's life cycle carbon performance must be integrated with other project criteria, particularly clients' requirements and stakeholders' values. The concept of Value-Focused Thinking introduced by Keeney (1996), with the emphasis on the goal-

setting aspect of the decision-making process, has been applied in a few recent decision support tools because it promotes the uptake of sustainable building refurbishment while satisfying the client's preferences and requirements (Olsson et al., 2016; Kamari et al., 2017; Gade et al., 2018). As such, an implication for the future development of new decision support tools for zero carbon refurbishment projects is using Value-Focused Thinking as a fundamental basis to identify project criteria and weights. Moreover, there is potential for the use of carbon budgets for individual buildings suggested by several researchers (e.g. Chandrakumar et al. (2020)) to help define the carbon performance goal in decision support tools for zero carbon refurbishment. A meaningful zero carbon refurbishment decision support tool should consider the carbon impact of its building in order to achieve net-zero carbon target by 2050.

4.4.2 Refurbishment strategies

Research on zero carbon strategies for building refurbishment is limited. In the UK, Xing et al. (2011) established a hierarchical process towards zero carbon building refurbishment. Nevertheless, this concept may not be applicable in all building types as Dotzler et al. (2018) argue that it might be more efficient to refurbish the building services in the first place. Different countries may adopt different renovation strategies, for example, the UK has committed with decarbonising British electricity, and as a result, carbon emissions from electricity have fallen 46% in the three years to June 2016 (Staffell, 2017). Recently, partial or over-time refurbishment strategies seem to be a trend in some nations towards sustainable refurbishment (Jensen, Maslesa, & Brinkø Berg, 2018). For zero carbon refurbishment, long-term strategies also need to be established with regard to partial refurbishment, particularly the carbon budget can be established (e.g. 25%, 50%, 75%, 100% carbon reduction) in the early stages and achieved over time.

4.4.3 User-centred refurbishment process

User-involvement in the decision-making process is critical for bridging the “energy performance gap” and improving occupant well-being (Ma et al., 2012). However, in the early phases of a refurbishment project, the involvement of end-users is often ignored before making final decisions (Jensen & Maslesa, 2015). Prior to the work of J. Li et al. (2018), which reflected user-habits and methods of assessing emission reduction in the process of selecting refurbishment solutions, the role of end-users was largely unknown. Users should be involved in both goal setting and generation of refurbishment alternatives stages, aiming to generate

appropriate refurbishment solutions. For example, a biomass boiler can be a good selection in the case of low levels of user dependency (Kesidou & Sorrell, 2018). Future decision-making tools must be able to consider user-involvement throughout the refurbishment process.

4.4.4 The potential of integrating incentive schemes in future decision support tools

One criticism of the literature is that there are many decision-support approaches and tools available while the uptake of high-performance building refurbishment is very low. For example, despite much of the previous research has aimed at developing more sophisticated Life Cycle Costing models and tools, Gluch et al. (2018) claimed that managers' interest in these refinements seems limited. Government incentives, rewards, and tax policies could potentially drive consumer's and developer's decisions towards low carbon building interventions. Penna et al. (2019) has encompassed the public incentives in the decision support tool to reduce the payback period and increase the cost effectiveness of the refurbishment solutions. A robust energy intervention selection framework could be used to integrate set of government policies and practices (Perera et al., 2018). Such interventions should be integrated in decision support tools to drive users to make zero carbon decisions for refurbishment projects.

4.5 Conclusion

This chapter examines the current application of decision support tools for zero carbon refurbishment of existing buildings. The literature review has demonstrated how future zero carbon refurbishment decision-making tools can be developed to better support building stakeholders in the refurbishment process. The findings provide a new understanding of decision support tools for zero carbon refurbishment projects. The analysis of the climate change target and carbon budget undertaken here, has extended our knowledge of setting the right goal for zero carbon refurbishment projects. The involvement of project stakeholders and end-users in the building refurbishment process is also supported by the current findings. When zero carbon targets are considered in the project goal and criteria, there is a need for a balance among stakeholder's values, end-users' interaction and benefits, and other project requirements. Developing acceptable specific refurbishment strategies for the zero carbon refurbishment project is required, especially partial refurbishment strategies that can be established and achieved over time. The integration of incentives schemes is possible to take up zero

carbon approaches. Tools are created to not only support decision-makers but also encourage them to lead the uptake of zero carbon refurbishment projects. Overall, this research provides implications for the future development of zero carbon refurbishment decision support tools, better assisting the building and construction industry to develop and deliver zero carbon refurbishment projects. However, being limited to empirical data, the research lacks practical implications for specific building situations. Further experimental investigations are needed to evaluate the proposed conceptual framework in real-life case studies.

5 Chapter 5: Zero carbon buildings practices in Aotearoa New Zealand

This chapter is based on the following Journal article, which has been published in final form.

Bui, T. T. P., Wilkinson, S., Domingo, N., & MacGregor, C. (2021). Zero Carbon Building Practices in Aotearoa New Zealand. *Energies*, 14(15), 4455. <https://www.mdpi.com/1996-1073/14/15/4455>

Abstract

Previous chapters have presented the international perspectives on zero carbon building practices, with the particular focus on zero carbon refurbishment of existing buildings. Within New Zealand, research on climate change mitigation and environmental impacts of buildings has received renewed attention. However, there has been little detailed investigation of zero carbon buildings practices in general and zero carbon refurbishment of existing buildings in particular. Before examining the current development and implementation of zero carbon refurbishment of existing buildings in New Zealand, it is better to understand the perception of zero carbon initiatives and practices within the building and construction industry. This chapter undertakes an exploratory study using semi-structured interviews with government representatives and building experts to examine how the New Zealand building and construction industry plans and implements buildings towards zero carbon. The results show that New Zealand's building and construction industry is in the early stage of transiting to a net-zero carbon built environment. Key actions to date are focused on devising a way for the industry to develop and deliver building projects towards zero carbon. Central and local governments play a leading role in driving zero carbon initiatives. Leading construction firms intend to maximise the carbon reduction in building projects by developing a roadmap to achieve the carbon target by 2050 and rethinking the way of designing and constructing buildings. The research results provide an insight into the initial practices and policy implications for the uptake of zero carbon buildings practices in Aotearoa New Zealand.

5.1 Introduction

Climate change is one of the biggest environmental challenges facing the world. As instigated by the United Nations Framework Convention on Climate Change, the Paris Agreement, signed in 2016, attempts to limit

global warming to no more than 1.5 °C above pre-industrial levels (Niamir et al., 2020). The greater carbon reduction needs to be achieved to ensure that global warming does not exceed the 1.5 °C threshold (Rogelj et al., 2015). In the New Zealand context, the Aotearoa New Zealand Government passed the Climate Change Response (zero carbon) Amendment Act in 2019, which ratify the Paris Agreement and set carbon budgets to enable the country to transition to net-zero carbon by 2050 (Ministry of the Environment, 2019).

The building and construction industry offers potential for reducing GHG emissions (IPCC, 2014; Ahmad & Afzal, 2020). The building and construction industry makes up more than 40% of the global energy use, which contributes to operational carbon emissions, and one-third of worldwide GHG emissions (Pearce & Ahn, 2017; Ahmad & Afzal, 2020). In New Zealand, the building and building and construction industry accounts for around 20% of New Zealand's GHG emissions, considering all the materials used by the industry (MBIE, 2020). As the building and construction industry contributes significantly to tackle climate change impacts, Ministry of Business Innovation and Employment (MBIE) has launched the Building for Climate Change Programme in 2020, seeking to reduce building emissions while improving building resilience to climate change. The programme aims to reduce emissions within the building and construction industry by making changes to the building code and enhance the system operation (MBIE, 2020). The application of zero carbon buildings (ZCBs) is, therefore, fast becoming a key requirement (Jones, 2018; M. Pan & W. Pan, 2020). This research applies the concept of ZCBs that aims to achieve the highest level of carbon reduction including operational and embodied carbon emissions throughout the whole life cycle of the building.

There is a growing body of international literature that recognises the significance of ZCBs in many aspects. On the one hand, Jones et al. (2015) explored zero carbon design for non-domestic buildings in Europe, concluding that integrating smart facades, ventilation, and surface heating and cooling is possible for achieving low to zero energy buildings. However, Moschetti et al. (2019) argue that it is challenging to achieve a full compensation of the life cycle GHG emissions from materials by offsetting through renewable energy, even with extensive use of PV panels, especially in a low-carbon grid situation as in Norway. On the other hand, system boundaries, clusters, and exemplars of ZCBs in Hong Kong are introduced in the studies (Pan, 2014; Pan & Li, 2016). In the same vein, M. Pan and W. Pan (2020) investigate stakeholder knowledge, attitude, and practice for ZCBs in a systems manner. One conclusion is the distinction existing between different stakeholder

groups regarding their knowledge. This result underlines that explicit ZCBs knowledge plays a crucial role in generating a knowledge-induced attitude that advocates changes in ZCBs practice. In the case of business model, Zhao et al. (2018) developed a typology of business model innovations for implementing ZCBs from developers' and clients' perspectives by theoretically analysing five ZCBs projects in Australia, Japan, Hong Kong, Singapore, and the UK. The research findings support business solutions for successfully achieving ZCBs projects.

Despite the increased global interest in ZCBs, there is a lack of research published in this field in New Zealand. Based on the Scopus and Web of Science database, only four journal papers focusing on climate change mitigation and the environmental impacts of buildings in New Zealand were available when searching with the keywords (“climate change mitigation” AND “building” OR “construction” AND “New Zealand”). Whereas no papers mention the application of ZCBs in New Zealand with key words (“zero carbon” OR “low carbon” AND “building” OR “construction” AND “New Zealand”). Although no previous study has investigated the adoption of ZCBs in detail, the current research on climate change and buildings within New Zealand provide the knowledge foundation, contributing to the future development of ZCBs. For example, Chandrakumar et al. (2020) applied a science-based approach to determine a building carbon budget based on the global climate target of limiting global warming to below 1.5 °C. The results may help to define the boundaries for ZCBs in New Zealand. Ghose et al. (2017) are much more concerned with the feasible environmental impacts associated with the deep energy refurbishment of New Zealand's pre-existing office building stock. The main finding offers practical implications for reducing carbon emissions in building refurbishment. It is suggested that adopting efficient resource use and waste management solutions decreases carbon emissions without increasing environmental impacts. In a study reported to the government, MacGregor et al. (2019) identify financial constraints, skills and knowledge shortage, lack of legislation and slow innovation as the main industry barriers to ZCBs in New Zealand. However, due to the use of a literature review, the study is limited to the knowledge and experience of the building professionals and practitioners on developing and delivering buildings towards zero carbon. Therefore, there is a need for further in-depth research on the ZCBs practices in the New Zealand context.

This chapter aims to investigate the current ZCBs practices within the New Zealand building and construction industry from the government and building experts' perspectives. In the following sections, the chapter describes the methodology applied in the research, then reports the research results and analysis according to four main themes: (1) the concept of zero carbon building in New Zealand; (2) government initiatives; (3) industry engagement; (4) assessment methods and tools. Finally, the paper further discusses the significant influence of the government and policy implications for the uptake of ZCBs practices in New Zealand.

5.2 Research method

A qualitative approach utilising semi-structured interviews with government representatives and building experts were carried out to understand the implementation of ZCBs in New Zealand. This approach was chosen as it allowed probing of views and opinions, and participants were encouraged to expand their answers (Saunders et al., 2016; Gray, 2018), leading to interesting or unexpected participants' viewpoints about the issue of climate change and the building and construction industry in New Zealand. Multi-purposive sampling techniques including sampling to achieve representativeness and sequential sampling were used to select participants (Teddlie & Yu, 2007; Robinson, 2014). The expert sampling was used to ensure the desirable criteria while the snowball sampling approach was applied due to the shortage of building experts who had knowledge and experience in sustainable construction. Participants were required to work within the New Zealand building and construction industry for at least 5 years and have expertise on sustainable construction and carbon reduction for buildings. Initial interviewees were identified through professional references and LinkedIn—a professional networking tool that offered a large-scale database of business professionals (Albrecht, 2011), then these interviewees provided suggestions to locate further participants.

Between December 2020 and February 2021, 11 interviews were undertaken, including 4 in-person and 7 online interviews, ranging from 30 min to 1 h. The interviewees came from the three biggest New Zealand local governments, one national housing association, one non-profit building organisation, three large construction firms and three small-to-medium construction enterprises. An overview of the participants' profiles is illustrated in Table 5-1, including the codes used later in the paper to report the findings. This study was an exploratory and/or phenomenological research to offer an insight into the problem rather than grounded theory research. According to Creswell and Poth (2016), a grounded theory requires interviews with 20–30

participants, while there is a need for up to 10 people in phenomenological research. Francis et al. (2010) also recommended that the initial analysis sample is usually 10 interviews; after that, one or two further interviews can be conducted to confirm no new themes emerging. Thus, the sample size in this research was considered sufficient when achieving the saturation point of the data, which was reached after interviewing 9 participants.

Table 5-1: Participants' demographics (Source: Authors)

Participants	Position	Type of Organisation	Organisation Code
LG1	Sustainable Design Advisor	Local government	A
LG2	Asset Sustainability Specialist	Local government	B
LG3	Zero Carbon Advisor	Local government	C
AD1	Sustainability Manager	Architecture & Design	D
AD2	Senior Architect	Architecture & Design	E
AD3	Senior Architect	Architecture & Design	F
AD4	Senior Architect	Architecture & Design	G
PM1	Senior Project Manager	Project Management	H
EC1	Technical Director	Engineering & Consulting	I
NGO1	Senior Manager in Building and Communities	Non-profit building organisation	J
HA1	Zero Carbon Housing Manager	Housing Association	K

The interviews were digitally recorded subject to the participant's permission. Data collected from interviews were analysed using thematic analysis, which is known as a foundational method for qualitative analysis. It not only organises and describes data in rich detail but also interpret various aspects of the research topic (Flick, 2018; Braun & Clarke, 2022). Following step-by-step guidance demonstrated by (Braun & Clarke, 2022), the digitally recorded interviews were transcribed then analysed using NVivo 12. NVivo software is highly recommended by international researchers because it opens new ways of determining the missing data when managing the information without software, and generates efficient, multiple, and transparent data analysis (Hoover & Koerber, 2009; Bazeley & Jackson, 2013). Overall, four broad themes emerged from the data analysis: (1) the concept of zero carbon building in New Zealand, (2) government initiatives, (3) industry engagement, and (4) assessment methods and tools.

5.3 Findings

5.3.1 The concept of zero carbon buildings in New Zealand

Several concepts of ZCBs were proposed globally, examples included near-zero energy, zero energy, zero carbon, net-zero carbon Riedy et al. (2011). Since the meaning of ZCBs defined in building regulations and policies might be different among countries, critics has questioned what is the highest level of carbon reduction, and what are carbon performance benchmarks for ZCBs in New Zealand?

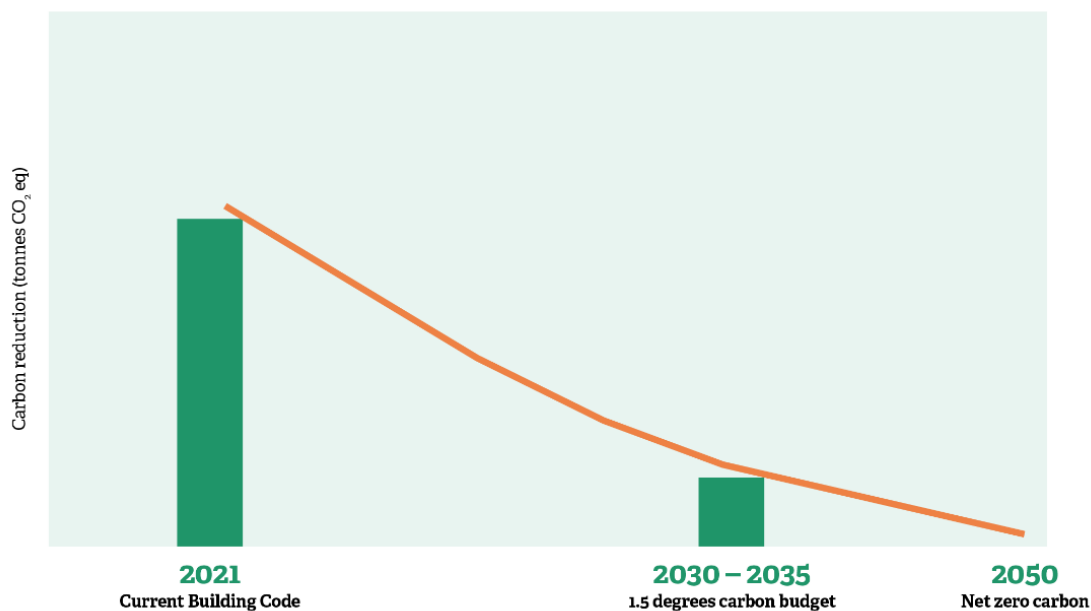


Figure 5-1: A proposed roadmap towards ZCBs in the New Zealand building and construction industry

(Source: Authors)

As mentioned above in (Chandrakumar et al., 2020), there is potential for the use of carbon budgets for individual buildings to help define the carbon performance goal for ZCBs. The global climate target is limiting global warming to below 1.5°C or 2°C and the global carbon budget is subsequently translated from the global climate target for the period of 2018–2050 (Rogelj et al., 2015). For instance, a New Zealand detached house has a carbon budget of 55,280 kgCO₂eq. This view was also supported by one interviewee (HA1), who proposed that there should be a comprehensible roadmap towards ZCBs for the New Zealand building industry. It was suggested that the first step was getting New Zealand’s buildings to meet the global climate target and carbon budget by 2030–2035. Then, the net-zero carbon target for buildings by 2050 could be achieved

onwards (see Figure 5-1). One implication is that policymakers can adopt the use of carbon budgets for individual buildings, to help create carbon performance benchmarks and sketching a well-defined roadmap for achieving ZCBs in New Zealand.

5.3.2 Government Initiatives

5.3.3 Central Government Initiatives

As mentioned in the introduction, MBIE – a central government department launched the “Building for Climate Change” programme, aiming to tackle climate change within the industry. The government suggested two ways to reduce emissions of buildings: (1) set minimum levels of operational efficiency for new buildings and (2) set limits for embodied carbon in new buildings (MBIE, 2020). For example, the government set the operational emissions cap goals for the New Zealand building and construction industry by 2035 (see Figure 5-2).

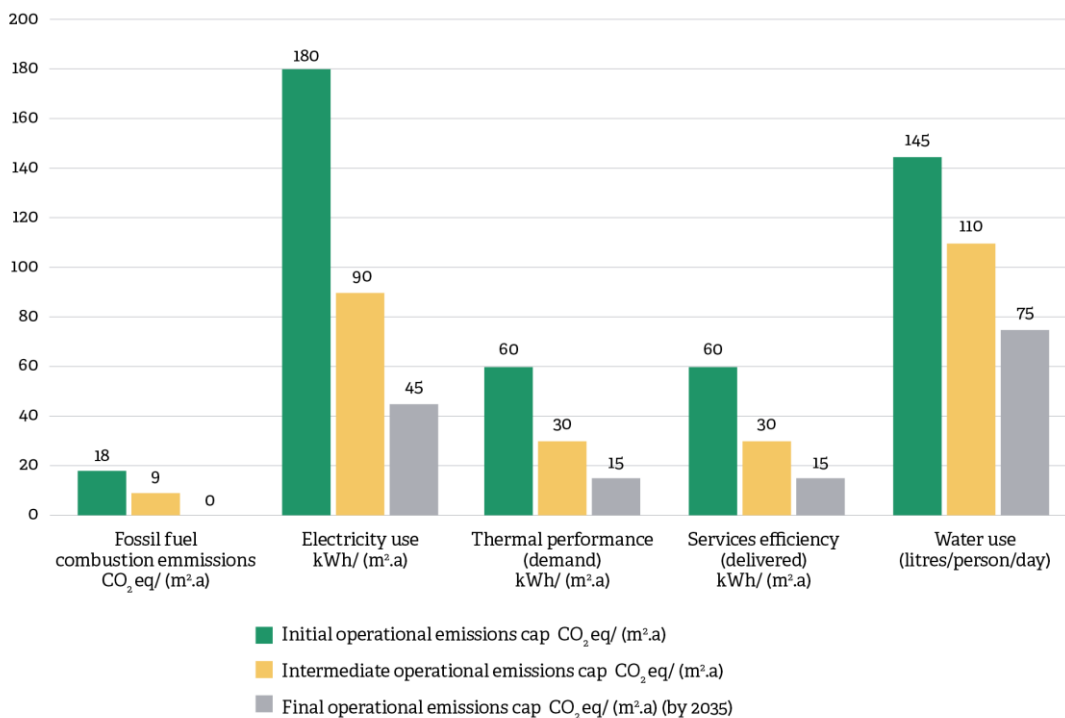


Figure 5-2: Operational emissions Cap goals for the New Zealand building and construction industry by 2035 (MBIE, 2020)

The operational emissions cap had requirements for fossil fuel combustion, electricity use and water use. Initial, intermediate, and final operational emissions caps were the targets that all new buildings must meet at consent and code compliance stages. However, one critical question was that how the government had come up with carbon reduction targets for new buildings. Furthermore, the government strategy focused on new builds only, given that refurbishing the existing building stock to be net-zero carbon has been neglected. Several studies on climate change impacts of buildings in New Zealand emphasised the need to prioritise existing buildings. For example, pre-existing detached houses contributed 66% of the climate impact while the figure for new-built ones was 34% (Chandrakumar et al., 2020). Even though the government claimed that reducing carbon emissions of new buildings would guarantee New Zealand to be get on track for the 2050 goals, the priority for building refurbishment towards net-zero carbon should be placed in the government's climate change plan.

Two mitigation frameworks that address transforming operational efficiency and whole-of-life embodied carbon emissions reduction were introduced in the programme. Commenting on these two frameworks, including *Whole-of-Life Embodied Carbon Emissions Framework* and *Transforming Operational Efficiency Framework*, a local representative (LG1) reported that the former document was related to embodied carbon emissions, which stated how the regulation went to segment but did not specify the attainable targets. While the latter one was straightforward to follow, as it set clear goals and the ways to implement the operational efficiency of buildings, and this policy document considered not only energy efficiency but also water efficiency. Although the operational carbon reduction target could be reached following the *Transforming Operational Efficiency Framework*, the gap concerning the embodied carbon reduction remains, calling for the central government's strong actions on obtaining the overall net-zero carbon goal for buildings. Chandrakumar et al. (2020) recommended that carbon reduction in the operational use stage could be accomplished if technological and systemic building changes were supported by policy and regulation. However, recent overseas studies (Moncaster et al., 2019; Röck et al., 2020) has underlined the urgent requirement to reduce embodied carbon emissions of buildings. An achievable goal and clear protocol, which addressees the embodied carbon reduction of buildings, therefore, is needed to be improved in the *Whole-of-Life Embodied Carbon Emissions Framework*.

Another major government initiative towards the net-zero carbon target for buildings is requiring the public industry to be carbon neutral by 2025 (New Zealand Government, 2020). The government made the climate declaration in late 2020 and would lead by example by getting the government's buildings in order (Radio New Zealand, 2020). This proclaimed initiative was considered as another government's intention to act in climate change mitigation after abandoning the Carbon Neutral Public Service (CNPS) programme in 2009 (J. Birchall, 2014). However, concern was expressed about the slow take-up of reducing carbon emissions in public buildings due to the small proportion of existing office buildings considered in this announcement, for only buildings with new leases in 2021. It was proposed that the government should commit when they build and operate their building stock including public housing, schools, and hospitals, and use available methodologies to allow buildings to be energy efficient and low carbon. Consistent with Ball et al. (2009), who evaluated the issues for the carbon-neutral public sector, this result indicates that the government should contemplate an intelligible implementation process and effective evaluation of the "leading by example" rationale in transiting the public building industry to be carbon neutral by 2025.

The central government has worked closely with the building and construction industry, other government agencies, key stakeholders, local government, and communities to ensure New Zealand's building and construction industry achieve the net-zero carbon target by 2050. However, further work such as formulating net-zero carbon building regulations and guidelines need to be done. Without central government encouragement, overall, carbon reduction activities may not be planned and implemented effectively (Liu & Qin, 2016; Lai et al., 2017).

5.3.4 Local Government Initiatives

As stated by interviewee LG2, local government B launched a comprehensive climate plan, seeking to reduce GHG emissions by 50% by 2030 and achieve net-zero emissions by 2050. Specific actions such as sustainable design and construction, retrofitting buildings, minimising construction, and demolition waste, etc., were proposed for the built environment sector. Interviewee LG2 also revealed that a new minimum beyond building code for renewal works over \$2 million was set to deliver a sustainable asset standard because the assets accounted for 75–80% of the local government B's total carbon footprint. Another participant (LG1) indicated that local government A planned a common policy within the organisation and the building and construction

industry. Two main programmes, named “Eco-design Advice” and “Targeting net-zero carbon” would be implemented in the next couple of years. These programmes considered carbon reduction for the whole life cycle of buildings, one focused on building in general including new builds and refurbishment, whereas the other was designed for building maintenance, energy use, recycling waste, etc. In comparison to A and B, local government C did not have an official policy for buildings, but a business case, working on an environmentally sustainable design policy for local government C’s assets, was expected to be released in 2021, which set certain standards for new builds and refurbishing projects (LG3). Referring to the housing association, interviewee HA1 specified that organisation K – a public housing corporation that delivers the government’s priorities for housing and urban development in New Zealand, was working towards delivering against the Building for Climate Change programme. However, detailed strategies for addressing the net-zero carbon target for housing projects had not been officially announced.

One critical observation is that local government strategies consist of reducing carbon emission for both new and pre-existing buildings in comparison to the central government’s Building for Climate Change plan. According to the findings, we could infer that New Zealand’s local governments and public housing agency has been planning and implementing the greatest carbon reduction goal for public buildings, following the central government initiatives with the requirements for the public industry.

Notwithstanding the capability of managing public building’s carbon footprint, the local governments have a few chances to influence the building and construction industry in maximising carbon reduction. Local governments could be ahead of the curve and a showcase model for the private industry. However, they were limited in being able to encourage the building and construction industry to deliver high performance buildings, as stated, “we do not have the ability to require people to build beyond the code” (LG3). The present results are significant in at least two major aspects. Firstly, there are local government’s financial constraints in the view of net-zero carbon policies for buildings. Even though the central government has a strong will of building towards net-zero carbon, the local governments may not be able to entirely implement this because of the insufficient finances. The findings reported are in line with an existing study of Zhang et al. (2017), confirming that the financial constraint of local government can lead to poor implementation of ZCBs policies in China. Secondly, while local governments continue with ongoing efforts begun during their participation in the

“Building for Climate Change” programme, carbon reduction actions may persist in a scaled-back manner if lacking the assistance of the central government. The Communities for Climate Protection-New Zealand (CCP-NZ) program also highlights the important role of the central government in supporting local government to carbon management activities (Birchall, 2014). The summary of government initiatives towards net-zero carbon buildings is illustrated in Table 5-2.

Table 5-2: A summary of government initiatives towards net-zero carbon buildings in New Zealand

(Source: Authors)

	Initiatives	Classification	Scope of Work	Applicable Areas
Central government	Building for Climate Change programme	National building regulations and guidelines	Setting operational and embodied carbon reduction targets for buildings	New buildings
	The public industry to be carbon neutral by 2025	National policy	Mandating energy efficiency standards for government office buildings	New and existing buildings
Local government	Local government A’s climate change plan	Local government policy	Sustainable design and construction, retrofitting buildings, minimising construction, and demolition waste, etc.	New and existing buildings
	Local government A’s new policy for renewal work	Local government policy	Delivering sustainable asset standards	Existing buildings
	Local government B’s climate change plan	Local government policy	Improving whole-of-life carbon reduction for buildings	New and existing buildings
	Local government C’s sustainable design policy	Local government policy	Setting standards for building projects	New and existing buildings
	Housing association’s climate change plan	Social housing policy	Upcoming	Housing

5.3.5 Industry engagement

Whilst the governments focus on strategies for buildings towards net-zero carbon, the building and construction industry takes direct responsibility for delivering ZCBs. To explore the actions that the building and construction industry has carried out on building projects, building experts were asked to indicate how zero carbon build impacted on construction firms and building projects in New Zealand. Some construction companies’ representatives confirmed that their organisations have committed to reducing carbon emission throughout organisations’ policies. Participant AD1 said that organisation D – a leading architecture firm in sustainable design, set goals for decreasing whole-of-life carbon emissions for their projects by 50% by 2030 from the current benchmark. The details of organisation D’s strategies on carbon reduction are illustrated in Figure 5-3. Similarly, organisation G also planned for its carbon reduction actions by establishing zero carbon policy, as specified, “we are also committing on our website, by 2030 to make our buildings zero carbon building rated” (AD4).

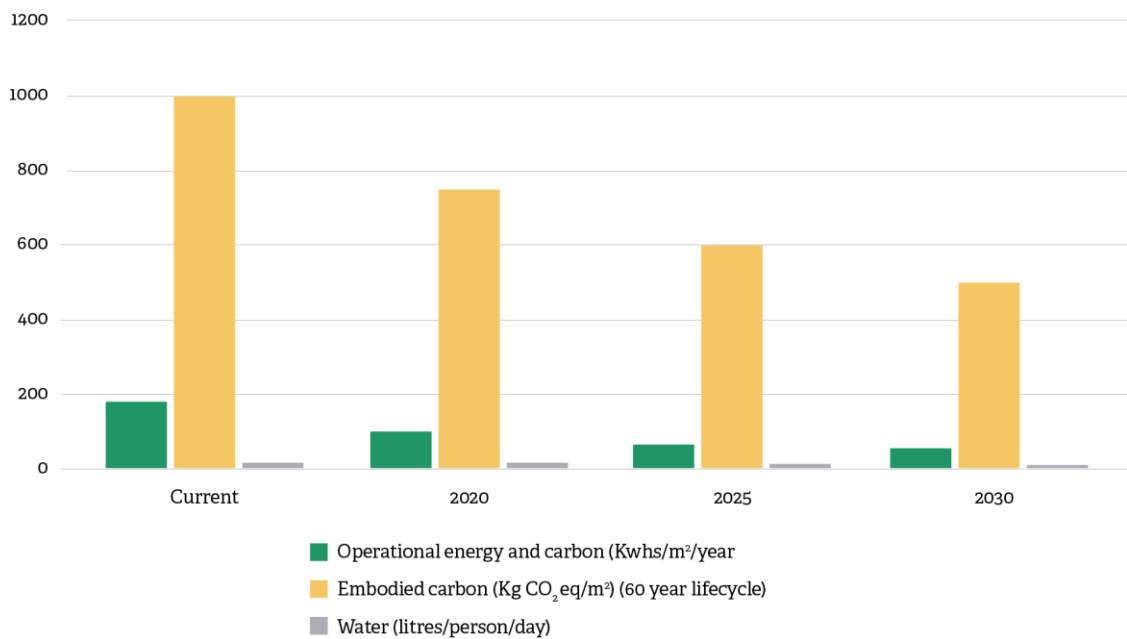


Figure 5-3: Organisation D’s pathway to net-zero carbon design (Source: Organisation D)

From small to medium-sized construction enterprises’ perspectives, one reported that their companies did not have a defined policy, but they started looking at ways to improve the overall carbon performance for their projects (AD2). The findings show that has employed the carbon reduction target in their organisations and

building projects while small to medium-sized enterprises only focus on changing the way of thinking to enhance the general practices. Due to the lack of resources, knowledge, and skills, it may be challenging for small to medium-sized enterprises to adopt zero carbon innovations and construction processes (Kesidou & Sorrell, 2018). Thus, more support such as knowledge development and vocational training in zero carbon innovations should be given these enterprises (Killip, 2013; Giesekam et al., 2016).

Another question was what could help the industry to move towards ZCBs. The most common agreement was related to government leadership and support. Half of the interviewees suggested that the government should make changes to the building code and regulations, “If you want something to happen, you basically got to make it compulsory” (AD2), while others believed that the government must commit to lead by example and support all buildings to be net-zero carbon. From the non-profit construction organisation’s viewpoint, one representative said that the New Zealand building and construction industry was ready to move towards net-zero carbon target for buildings, but it required more action from the government (NGO1). It was suggested that the central government could drive the implementation of ZCBs in the building and construction industry through zero carbon policy, whilst the local government could support the central government initiatives and drive change by requiring carbon reduction specifications in the consenting processes.

The problems raised here align with the principal role of government in the uptake of ZCBs discussed earlier. Even though there is a strong industry engagement towards net-zero carbon buildings in New Zealand, the involvement of the government is critical. Consistent with the findings in the study of H. Li et al. (2018) which shows that the government is the most influential entity relating to sustainable construction in China. Likewise, the authors (Li & Colombier, 2009; Zhang & Wang, 2013) claim that government policy instrument is the key to drive improving energy-efficiency and carbon reduction in the building and construction industry, and incorporating several specific legal measures, especially the building regulations, which control the minimum levels of carbon emission and energy performance. However, the extent to which its intervention in the form of penalties, incentives, or compensation is required in balancing the interests of construction stakeholders presented a major challenge (H. Li et al., 2018). Therefore, further government action is needed to establish the viability of the building and construction industry in building for the net-zero carbon target.

5.3.6 Assessment methods and tools

The issue of available assessment methods and tools was a concern about how the building and construction industry addressed net-zero carbon targets for buildings. Summaries of rating systems and tools are demonstrated in Tables 5-3.

Table 5-3: Summary of rating tools used within the New Zealand building and construction industry

(Source: Authors)

No.	Rating Systems	Organisation	Function
1	Living Building Challenge	International Living Future Institute (ILFI)	The world's most rigorous green building standard
2	Zero carbon/Zero energy certification	International Living Future Institute (ILFI)	A zero carbon/zero energy certification for buildings
3	NABERSNZ	NABERSNZ	Energy rating tool for commercial buildings
4	Green Star	NZGBC	An internationally recognised rating system for the design, construction and operation of buildings, fit out and communities.
5	Home Star	NZGBC	A dependent rating tool for assessing the health, efficiency, and sustainability of New Zealand's homes
6	carboNZero Building Operations certification	NZGBC partnered with Toitū Envirocare	To help the building owners to measure current carbon emissions, manage carbon footprint, offset any unavoidable emissions, and market success once receiving carboNZero building certificate
7	Passive house	Passive House Institute NZ	Energy performance standard
8	Toitū carbonzero certification	Toitū Envirocare	A carbon zero certification for businesses, products and services. Measure greenhouse gas emissions, and put in place strategies to manage, reduce and offset

There are some assessment methods and tools used to measure embodied and operational carbon emissions for buildings in New Zealand, broadly categorised into three groups: (1) rating systems; (2) life cycle assessment tools; (3) energy modelling tools; (4) carbon database tools. Rating systems include Green Star New Zealand,

Homestar New Zealand, The Living Building Challenge and Zero carbon certification, NABERSNZ, Toitū carbonzero certification, carboNZero Building Operations. Life cycle assessment tools include LCAQuick, LCAPlay, eTool, OneClick LCA, EC3, Tally, PHRRibbon. Energy modelling tools include EnergyPlus, IES, PHPP, Design Builder, AccuRateNZ. Carbon database – CO2NSTRUCT, CO2MPARE, CO2RE.

What stands out in Table 5-3 is that many different types of building standards and certifications available in the market applied in the New Zealand building and construction industry. Recently, New Zealand government procurement released a practical procurement guideline to reducing reduce carbon emissions in building and construction, considering Green Star, Homestar, NABERSNZ, Passive House, Living Building Challenge and Zero Carbon Certification as official rating systems that can be used for assessing the whole-of-life embodied carbon and/or operational carbon emission. However, the government had no intention to endorse any system and this guide would be updated in the future to provide further guidance on the most appropriate system to be used (New Zealand Government Procurement, 2021).

There existed an unsolved problem that different organisations used different standards for buildings and the decision on which benchmarks applied for ZCBs was not identified. One interviewee spoke of consideration to use certification and standards in buildings towards net-zero carbon, “we are trying to incorporate the best practice and just deciding what makes the most sense from a certification” (LG3). Participant LG2 mentioned the consideration of building certifications and standards but indicated that all the current assessment methods could be used to measure carbon reduction for buildings, “they are all targeted or at least start to measure getting to net-zero carbon”. Notwithstanding, another participant believed that only Living Building Challenge certification could be applied for ZCBs, “there’s only one zero carbon building in New Zealand that is a certificated Living Building Challenge” (AD1).

This finding raises questions about the misinterpretation of carbon performance of New Zealand’s buildings due to the result of carbon auditing, and benchmarking generated by different rating tools might vary. For Greenstar certification, up to 20 points are awards across GHG emissions credit, where it is estimated that the GHG emission figures are considerably lower than a standard building. While Living Building Challenge offers two levels of carbon certifications, including zero carbon and net carbon positive. The result is in line with Ng et al. (2013)’s findings which have shown that the baseline carbon emission rates of building

environmental assessment tools differ noticeably, leading to the impact on the carbon auditing outcomes and the perception of how “low carbon” the assessed building is.

Moving into LCA, energy modelling and carbon database tools used within the New Zealand building and construction industry, which is illustrated in Table 5-4, the problem occurred again due to many decision support tools which are available within the New Zealand building and construction industry, highlighting the need for further government guidance on the most appropriate systems and tools to be applied as discussed earlier.

Table 5-4: Summary of LCA, energy modelling and carbon database tools used within the New Zealand building and construction industry (Source: Authors)

No.	Tools	Organisation	Function
1	PHRibbon	AECB PHribbon	Carbon calculations for Passivhaus and low energy buildings including retrofits
2	Tally	AUTODESK	An Autodesk Revit application that allows architects and engineers to quantify the environmental impact of building materials for whole building analysis as well as comparative analyses of design options
3	OneClick LCA	Bionova Ltd. (Helsinki, Finland)	A life cycle assessment tool that helps calculate and reduce the environmental impacts of building and infrastructure projects, products, and portfolio
4	LCAQuick	Building Research Association of New Zealand (BRANZ)	A life cycle assessment tool that helps calculate and understand the potential environmental impacts of a building design across the life cycle
5	LCAplay	Building Research Association of New Zealand (BRANZ)	A simple life cycle assessment tool for assessing potential environmental impacts for commercial building design concepts. The tool provides comparative outputs for two different building concept options
6	BRANZ CO ₂ NSTRUCT	Building Research Association of New Zealand (BRANZ)	A database of embodied carbon and energy values for building materials, including concrete, glass, timber and metals, as well as products such as bathroom and kitchen fittings and lifts

7	CO ₂ MPARE	Building Research Association of New Zealand (BRANZ)	A summary carbon footprint and other data and information about reference residential and office buildings for understanding the magnitude and ranges of carbon footprints of New Zealand buildings
8	CO ₂ RE	Building Research Association of New Zealand (BRANZ)	Details on estimated climate change impact for different types of residential roof, wall and floor constructions
9	AccuRateNZ	CSIRO (Australia's national science agency)	Thermal simulation
10	Design Builder	Design Builder	The most established and advanced user interface to EnergyPlus
11	eTool	Cerclos	A life cycle assessment tool for large-scale buildings and infrastructure
12	IES	IES-VE	Whole building energy simulation analysis that covers a wide range of assessment types from energy efficiency, comfort, ventilation, HVAC performance and optimisation
13	EC3	Life Cycle Association of New Zealand (LCANZ)	Embodied Carbon in Construction Calculator (EC3) Tool
14	PHPP	Passive House Institute NZ	A tool for modelling the performance of a Passive House design to comply with the Passive House Standard and submit for Certification
15	EnergyPlus	U.S. Department of Energy's (DOE) Building Technologies Office (BTO) and National Renewable Energy Laboratory (NREL)	A whole building energy simulation program that engineers, architects, and researchers use to model both energy consumption—for heating, cooling, ventilation, lighting and plug and process loads—and water use in buildings

There is also a lack of evidence that demonstrates the accurate calculation of carbon reduction when applying international-carbon-database tools in New Zealand, as the environmental impacts and material databases differ from one country to another. In terms of life cycle assessment tools, LCAQuick is one of the free tools developed by the Building Research Association of New Zealand (BRANZ) that helped architects, designers, and structural engineers to calculate the carbon performance (both operational and embodied carbon) for low carbon design decisions. This tool may be able to provide an accurate building database and evaluate carbon

footprint and other environmental impacts of building designs in New Zealand. There is also potential to integrate the climate target and carbon budget mentioned above into these tools. Likewise, eTool is suggested to apply for New Zealand's buildings because it is set up with a localised life cycle assessment database for New Zealand (Jaques, 2019). Such approaches should be promoted broadly within the building and construction industry as platforms to stimulate the continuous construction innovation and the development of ZCBs.

5.4 Discussion

The research reported in this chapter has critically examined the current practices towards ZCBs in New Zealand. The most obvious finding to emerge from the analysis above is the significant influence of the government in the uptake of ZCBs practices. This leads to a deeper explanation of the government role and policy implications in improving the present adoption of ZCBs approach.

New Zealand's government response to climate change is advancing, however, there is late adoption of the Zero Carbon Act in the building and construction industry. In 1997, a 2012 GHG emissions target "net emissions equal to 1990 gross emissions" was introduced, aligning with the Kyoto Conference of the Parties (COP). Until 2019, the latest amendment was approved in the Climate Change Response Act 2002, with a commitment to reduce GHG emissions to zero by 2050 (New Zealand Legislation, 2019). Compared to other developed countries such as the UK, which assented the Climate Change Act in 2008 with mandated specific carbon-reduction budgets (legislation.gov.uk, 2008), New Zealand launched a Zero Carbon Bill 10 years later, that outlines a plan to reduce GHG emissions and establishes an independent Climate Change Commission to review the target under certain conditions (Ministry for the Environment, 2019).

The late promotion of zero carbon-related legislation leads to the delay of zero carbon policies for New Zealand's buildings. To date, the building code possesses no requirement for embodied carbon reduction (MacGregor et al., 2018). None of the policy documents for ZCBs are officially formulated and implemented as the government's climate change programme for buildings mentioned above has launched in late 2020 and just finished the consultation process. Therefore, the government needs to rapidly establish a pathway for achieving ZCBs in building regulation and guidelines. Lagging behind other developed countries has given New Zealand a considerable opportunity to identify lessons learned in the local context. An insight gained

from the UK case study is that instead of requiring the building and construction industry to build ZCBs at first, which is beyond the industry workability, one of the “allowable solutions” is to mandate markedly increased levels of energy efficiency and embodied carbon reduction as the basis of the “zero carbon” policy for building (McLeod et al., 2012). More importantly, New Zealand has a green electricity grid, and it is anticipated to be 100% sourced from renewable energy by 2030, therefore, the central focus should be on minimising embodied carbon emissions from materials and products rather than improving energy efficiency. These findings have vital implications for developing strategies for implementing zero carbon buildings in New Zealand.

To allow New Zealand’s building and construction industry to build ZCBs, the government must mandate net-zero carbon policies by upgrading the building code and regulations. Commenting on the importance of the building code in improving energy efficiency, the United Nations Environment Program (UNEP) and the International Energy Agency (IEA) have indicated that energy efficiency requirements in the building code to be among the most critical determinants of a building’s energy efficiency (UNEP, 2007; Laustsen, 2008). Concerning ZCBs, such energy efficiency strategies can be included in the building codes to reduce operational carbon emissions, accompanied by the requirement of decreasing embodied carbon emissions for buildings. Moreover, enforcing building rating systems and carbon calculation tools is also a potential solution to standardise the carbon measurement scale and audit, creating synchronism for the entire building and construction industry. This finding agrees with studies (Clark, 2007; X. Li et al., 2019) recommending that the government should incorporate a sustainability rating tool and set minimum standards in the New Zealand building code. An overarching government policy such as well-designed and implemented building codes, regulations and appliance standards is the most effective emission reduction instrument. Central and local governments can also encourage the building and construction industry to reduce GHG emissions in building projects by leading by example, establishing zero carbon policy to transiting the entire public building stock to net-zero carbon. The result is in line with the study of (X. Li et al., 2019), confirming the substantial contribution of the public industry to driving changes in the building and construction industry.

5.5 Conclusion

The present chapter has revealed the current ZCBs practices in New Zealand, regarding the government and building experts' perspectives. One of the more significant findings is that the central and local government's initiatives on ZCBs are underway, including revising building policies and regulations and requiring the carbon-neutral for public buildings by 2025. Building experts support the idea that the building and construction industry should move towards net-zero carbon and engage themselves in maximising the carbon reductions for their projects. The research has also revealed the differences in the carbon performance of New Zealand's buildings because of the use of different rating systems and calculating tools. This leads to the impact on the distinct carbon measurement and auditing outcomes and the misperception of setting zero carbon targets for buildings.

The evidence from this chapter suggests that New Zealand's building and construction industry is still in the early stage of transiting to net-zero carbon built environment and further works need to be done in the near future. The analysis highlights the importance of the government's role and provides policy recommendations for improving ZCBs practices. The government should formulate building policies and regulations and take leadership in implementing ZCBs. This research is the first across-the-board investigation of the ZCBs practices in New Zealand, addressing the current practices and policy implications. Net-zero carbon target for buildings can be achieved through adopting not only well-defined and deliberate building policies, but also integrated building design and construction processes, knowledge sharing and the collaboration among building stakeholders with accessible resources and support mechanisms. This would be a fruitful area for the future work. The research results add to the rapidly expanding field of ZCBs practices internationally, by shedding new light on the New Zealand case.

6 Chapter 6: Towards zero carbon buildings: issue and challenges in the New Zealand building and construction industry

This chapter is based on the following Journal article, which has been published in final form.

Bui, T. T. P., MacGregor, C., Wilkinson, S., & Domingo, N. (2022). Towards zero carbon buildings: issues and challenges in the New Zealand construction sector. *International Journal of Construction Management*, 22(10), 1-8. <https://doi.org/10.1080/15623599.2022.2110642>

Abstract

Chapter 5 has highlighted the current zero carbon buildings practices in New Zealand. However, critical questions about the feasibility of achieving net-zero carbon targets for the entire building stock remain unanswered. To continue with, this chapter reports on the challenges and issues in the building and construction industry towards zero carbon buildings (ZCBs) in New Zealand by undertaking an exploratory study using seventeen semi-structured interviews with New Zealand's building experts. The results illustrate significant challenges to the adoption of ZCBs, including financial problems, the shortage of knowledge, capacity and capability, the insufficiency of legislation, and cultural barriers. The most crucial concern is the ability of New Zealand's building and construction industry to deliver ZCBs across the value chain. The chapter sheds new insight into barriers to ZCBs locally and globally by identifying comprehensive challenges related to whole-of-life building carbon reduction. It is suggested that the governments and building and construction industry must prioritise knowledge development and exchange as critical support mechanisms to enable a future towards ZCBs.

6.1 Introduction

The Paris agreement in 2016 was agreed to limit the global temperature increase from 2°C to 1.5°C above pre-industrial levels by 2050. Stabilising the climate to that global temperature does not exceed 2°C requires maximising carbon reduction worldwide through national commitments and personal action (Rogelj et al., 2015; Niamir et al., 2020). The building and construction industry is one of the most crucial industries for reducing carbon emissions (IPCC, 2014). Since zero energy buildings are not enough to accomplish whole-of-

life carbon reduction, ZCBs need to fit within national emission budgets but also address the impacts of GHG emissions across the building's life cycle, specifically the emissions associated with the embodied carbon of building materials, operational carbon and end-of-life emissions from demolition (WGBC, 2019).

Contributing to the global effort under the Paris Agreement, New Zealand enacts the Climate Change Response (Zero Carbon) Act 2019 (Ministry for the Environment, 2019), which seeks to decrease net emissions of all GHG emissions to zero by 2050. New Zealand's building regulator has introduced ambitious plans to address climate change by adopting the whole-of-life carbon framework, a transforming operational efficiency framework and H1 energy efficiency level changes (MBIE, 2020). The New Zealand government also launched a sustainable construction guide to make procurement practices lower their carbon footprint in 2021 (New Zealand Government Procurement, 2021). Despite these initiatives, large-scale decarbonisation within the building and construction industry is in its infancy (MacGregor et al., 2018; MacGregor et al., 2019; Bui et al., 2021c).

Drawing on the existing literature, there is a need for empirical research on the feasibility of ZCBs adoption in the New Zealand context. This chapter aims to examine the challenges and issues in implementing ZCBs in New Zealand by exploring building experts' experiences and perspectives on regulating, designing, consultancy, and constructing buildings. The research sheds new insight into barriers to ZCBs in New Zealand and internationally by considering comprehensive challenges related to whole-of-life building carbon reduction.

First, the chapter reviews the literature, then outlines the research method. Second, the chapter reports the results and discussion according to three main themes: (1) financial issues; (2) lack of industry knowledge, capacity, and capability; (3) Legislative and cultural issues. Finally, the chapter compares findings between New Zealand and other contexts and suggests a critical support mechanism for delivering ZCBs in New Zealand.

6.2 Literature review

The building and construction industry can help reduce GHG emissions through the design and construction of ZCBs. However, many barriers to the development of ZCBs still exist. Within the UK, Osmani and O'Reilly

(2009) identified numerous legislative, cultural, financial, and technical obstacles facing housebuilders to deliver zero carbon homes in England. The study calls for rethinking the definition of “zero carbon”, the cost of sustainable measures and improving customer demand. In Hong Kong, Pan and Pan (2021) examined drivers, barriers and strategies for developing ZCBs in high-rise and high-density cities. Key drivers and barriers consist of economic, legislative, cultural, supply chain, geographical, and skill and knowledge aspects. ZCBs somehow face the same barriers and challenges as other sustainable construction typologies. Ahmed et al. (2021) determined impediments to implementing and developing sustainable construction worldwide. The most critical barriers identified are inadequate green construction codes and regulations, a lack of information and understanding about new techniques, difficulties gaining skills and expertise, and a lack of funding due to a lack of interest in the local market investment.

The development of ZCBs in New Zealand is new (MacGregor et al., 2018; MacGregor et al., 2019; Bui et al., 2021c). Chandrakumar et al. (2020); Bullen et al. (2021) calculated building carbon budgets for residential and commercial buildings based on the global climate target of limiting global warming to below 1.5°C in New Zealand. The carbon footprint of New Zealand’s building industry for 2018-2050 exceeds the carbon budget by a factor of four and five for the office building and the detached housing sector, respectively. Bui et al. (2021c)’s research study offers an insight into up-to-date practices and policy recommendations for implementing ZCBs in New Zealand. Little is known about the “feasibility” (e.g. challenges and incentives) of delivering ZCBs. Dalirazar & Sabzi, 2020 identified the top three barriers to sustainable construction in New Zealand: lack of political support and incentives, lack of governmental policy, and resistance to change from conventional to sustainable buildings. However, these results are applicable for sustainable construction, a broad term within the general context of holistic sustainability. While ZCBs are considered operational and lifecycle carbon-based terms (Pan, 2014).

The findings from other countries often do not apply to the New Zealand context. The barriers to ZCBs are distinct according to environmental, cultural, economic, and social aspects. For instance, financial barriers are the most significant in Hong Kong, while lack of knowledge and skills is a critical problem in the UK (Heffernan et al., 2015; Pan & Pan, 2021). Concerning the environmental aspect, New Zealand has a high proportion of renewable energy resources contributing to grid electricity supply (currently over 80%, with a

target to increase to 100% renewable electricity generation by 2030). Thus, energy-efficiency-related technical barriers to ZCBs may not be considered over the whole-of-life-carbon-reduction challenges related to construction processes and supply chain management. Furthermore, the concepts of ZCBs are also diverse in the literature, e.g. “zero carbon home” in the UK (Osmani & O’Reilly, 2009); “Nearly zero energy building (NZEBS)” in the European Union (Attia et al., 2017); “low-energy building” and “passive houses” in Sweden (Persson & Grönkvist, 2015); “sustainable housing” or “sustainable construction” (Singh et al., 2019; Ahmed et al., 2021); “zero carbon buildings” (Pan & Pan, 2021). Different understanding of the concept of ZCBs might lead to alternative perceived challenges and issues, particularly when considering operational and embodied carbon reduction throughout the whole life cycle of the building. Therefore, empirical research on the industry’s views on challenges and issues towards ZCBs in New Zealand is needed.

6.3 Research method

This chapter aims to explore New Zealand’s building and construction industry perceptions of the challenges and issues of implementing ZCBs in New Zealand. Thus, a qualitative research method was employed, using semi-structured interviews with the building experts to understand concepts and “seek new insight” into ZCBs topics that were not well acknowledged (Saunders et al., 2016). The method was considered appropriate as it provides reliable and comparable qualitative data when working with a complex issue (Galletta, 2013; Wilson, 2014). The qualitative approach gives opportunities to probe incredible views and gain an in-depth understanding rather than the quantitative method, which often uses generalisable facts about the research context (Saunders et al., 2016; Flick, 2018; Gray, 2018).

Participants were purposively recruited from various parts of the building and construction industry, such as government agencies, non-profit housing organisations, and multiple-sized construction companies, to provide an inclusive view. Expert sampling was used to ensure the desirable criteria (Teddlie & Yu, 2007; Robinson, 2014). Participants were required to (1) attain a tertiary education level, (2) work within the New Zealand building and construction industry for at least five years, and (3) have expertise in sustainable design, construction, project delivery or related skills. A list of government agencies and construction companies was compiled. The people responsible for sustainability issues and/or those who experienced and/or led sustainable/green building projects within the firm were identified. A snowball sampling approach was

undertaken to enhance the interview sample size (Teddlie & Yu, 2007; Robinson, 2014). Due to the shortage of building experts who had knowledge and experience in ZCBs, LinkedIn – a professional networking platform that offers a large-scale database of business professionals (Albrecht, 2011), was used to contact the list of identified key actors. These professionals referred to other potential participants.

Seventeen interviews were conducted between December 2020 and August 2021, ranging from 30 minutes to 75 minutes. Eleven interviews were conducted via online tools such as Microsoft Teams Meeting and Zoom due to the Covid-19 lockdown restrictions, and the remaining six were conducted face-to-face. Participants received an invitation via email then asked to carefully read the project information and sign the written participant consent form following standard ethics protocols. Oral consent was also obtained during the interview. The interviews included questions about: (1) participants' background, (2) the current processes in delivering ZCBs, and (3) relevant challenges and issues.

The decision making on the sample of participants was dependent on the saturation point of the data – an adaptive approach, rather than a priori determination at the beginning of the study following the suggestion of (Sim et al., 2018). As in the case of exploratory research that looks to explore phenomena, the decision over what establishes an adequate sample size to meet the research aim is iterative and context-dependent during the analytical process. After initial analysing data from eleven interviews, six more interviews were carried out to confirm no new themes emerging. Furthermore, the research's sample size is also in line with qualitative research sampling procedures (Guest et al., 2006; Galvin, 2015; Creswell & Poth, 2016), confirming that 12-15 interviews are appropriate for saturation. The study applied the thematic analysis method, which supports organising and describing qualitative data in rich detail and interpreting various aspects of the research topic (Creswell & Poth, 2016; Saunders et al., 2016). The digitally recorded interviews were transcribed and analysed using NVivo 12, following (Braun & Clarke, 2022)'s six step-by-step guidance. Each interview audio recording was listened to at least twice while simultaneously reading the corresponding transcript. After that, the initial codes for challenges and issues to ZCBs in New Zealand were identified by assigning nodes in NVivo 12. Once coding was completed, major themes emerged from the data were synthesised, defined, and reviewed. Three dominant themes: financial issues; industry knowledge, capacity, and capability; and legislative and cultural issues, were presented with the implications of the findings. A comparison of the global

context and the critical support mechanism for delivering ZCBs in New Zealand were also discussed. Table 6-1 illustrates an overview of the participants, including the codes used later in the paper to report the findings.

Table 6-1: Participants demographics (Source: Authors)

Participants	Position	Type of organisation	Gender	Years of experience
LG1	Sustainable Design Advisor	Local government	Female	≥ 10
LG2	Asset Sustainability Specialist	Local government	Female	≥ 5
LG3	Zero Carbon Advisor	Local government	Female	≥ 5
AD1	Sustainability Manager	Architecture & Design	Male	≥ 30
AD2	Senior Architect	Architecture & Design	Male	≥ 30
AD3	Senior Architect	Architecture & Design	Male	≥ 20
AD4	Senior Architect	Architecture & Design	Male	≥ 30
C1	Senior Project Manager	Contractor	Female	≥ 15
C2	Senior Project Manager	Contractor	Male	≥ 15
M3	Carbon & Environmental Performance Manager	Manufacturer/Developer	Male	≥ 10
M4	Head of Innovation Engine	Manufacturer/Developer	Male	≥ 10
RE1	Head of Sustainability	Real Estate	Male	≥ 20
RE2	Environmental Engineer	Real Estate	Male	≥ 5
PM1	Senior Project Manager	Project Management	Male	≥ 15
EC1	Technical Director	Engineering & Consulting	Male	≥ 20
NGO1	Senior Manager in Building and Communities	Non-profit building organisation	Male	≥ 30
HA1	Carbon Neutral Housing Manager	Housing Association	Male	≥ 20

6.4 Findings and discussion

Our research identified ten main problems, categorised into four groups. The most considerable challenges were related to finance and industry knowledge, capacity, and capability. Table 6-2 details the challenges and issues and the number of times each one was raised, providing an overview of the breadth of the findings.

Table 6-2: Main issues and challenges raised by interviewees (Source: Authors)

Category	Challenges	Number of interviewees	Number of times mentioned
Financial issues	Cost-driven industry	11	15
	The perception of high initial investment	16	22
	Lack of financial incentives	9	15
Industry knowledge, capacity, and capability	Inconsistent language and understanding	8	11
	Lack of knowledge and skills	12	30
	Lack of integration and collaboration	7	16
	Data management and shortage issues	7	16
Legislation	Unclear definition of zero carbon buildings	6	11
	Lack of building regulations and guidelines	8	12
Culture	Slow to innovate (e.g. resistance to change)	1	2

6.4.1 Financial issues

6.4.1.1 Cost-driven industry

Within the global building and construction industry, considerations of time, cost and quality influenced the decision making on construction projects, of which, the project budget was often the most critical factor (Lock, 2004). In a similar vein, within New Zealand’s building and construction industry, the cost was also an important concern for clients’ decision-making regarding the design and construction of ZCBs. As a study participant EC1 explained, “how much the building will cost” was in front of clients’ minds. The drive to achieve a minimum cost target led to the failure to balance other significant factors such as quality. As claimed by AD1, “we don’t really worry about quality”.

Building stakeholders used a cost-based question, “how much does a ZCB cost?” instead of a value-based question, “how much value/benefit does a ZCB make”. Therefore, the consideration of carbon reduction criteria did not currently feature in the decision making, as participant HA1 described this rationale, “our industry is very good at pricing and very poor at calculating a value or the benefit of going more sustainable and higher performing”.

Given the New Zealand Government's drive and policies to promote ZCBs, building decision-makers should start incorporating zero-carbon thinking into the delivery of building projects. There is a strong need to understand the carbon, time, cost, and quality objectives when making decisions throughout the life cycle of a building project, from initial concept to construction and occupancy.

6.4.1.2 The perception of high initial investment

Financial impediments expressed by the participants were related to the perceived additional investment costs and the feasibility of ZCBs development. First, participants believed constructing a building with a reduced carbon impact was more expensive than a minimum-standard one. Second, it was thought by study participants that the high capital cost might inhibit the ability of developers to fund and deliver the building project, as AD4 mentioned "feasibility is a very key aspect". Another agreed that implementing ZCBs design and technologies could lower operational carbon by reducing energy consumption. However, the energy-saving sometimes was inadequate to offset the additional investment (EC1). These findings confirm that the investment cost and feasibility remain crucial in international and New Zealand contexts (Davies & Osmani, 2011; Pan & Pan, 2021).

Due to the perceived high initial investment of ZCBs, architects, designers, engineers, and their clients often discarded the choice of ZCBs design without exploring the actual value. For instance, "if they are additional costs, we don't explore them, but they can actually be saving as well" (AD1). Another interviewee thought that the more ZCBs design was applied, the more the costs would decrease (NGO1). Similarly, RE1 stated, "the scale of our projects in New Zealand is a lot smaller than overseas. If the scale is bigger, then the cost is diluted, and it becomes a bit easy to do". This finding suggests that New Zealand's market share may influence the uptake of ZCBs practices.

Furthermore, the construction products' carbon footprint and shipping costs were higher than in other countries due to New Zealand's geography in the south-western Pacific, making the country more isolated with limited local manufacturing (RE1). These results reveal two possible implications. First, there is a lack of knowledge and experience relating to the cost and carbon footprint of ZCBs design and construction. Second, the New Zealand construction supply chain has not been mature to provide zero-carbon and cost-effective building materials and products.

6.4.1.3 Lack of financial incentives

Financial incentives in this section refer to direct grants, tax incentives, rebates, and discounted development applications fees (Olubunmi et al., 2016). The problem raised by participants was insufficient financial incentives for the slow uptake of ZCBs practices. Even though attempts existed to integrate zero-carbon thinking in the design process, it was challenging to select ZCBs design over traditional design. In one case, LG2 mentioned, “if it’s cheaper and easier to put in gas cylinders for my project, I have very little incentive to explore options for other technologies because that just adds to cost on the project”.

Several building experts stressed the need for tax incentives on reducing carbon emissions. Commercial benefits motivated building stakeholders to work towards ZCBs, as AD2 declared, “that’s potentially through tax relief”. Similarly, LG1 proposed that the central government should enforce the delivery of ZCBs by formulating a win-win financial incentives system. The construction companies adopting high emitting carbon construction products and methods should pay a tax. That money, in turn, could be used to incentivise those who implemented ZCBs design and construction.

The results align with the existing literature, indicating that the incentive instruments and funding schemes serve as the foundation for zero-carbon development. Incentives and funding schemes could stimulate the improvement of carbon reduction and energy performance (Osmani & O’Reilly, 2009; Zhang & Wang, 2013; W. Pan & M. Pan, 2020). However, the critical challenge is identifying the extent of incentives to balance other building stakeholders’ interests (H. Li et al., 2018).

6.4.2 Lack of industry knowledge, capacity, and capability

6.4.2.1 Inconsistent language and understanding

Building experts were asked to express their thoughts about the net-zero carbon target for New Zealand’s building and construction industry and what ZCBs meant to them. All agreed that the building and construction industry had to reduce carbon emissions close to the net-zero carbon target by 2050. However, participants understood the meaning of ZCBs in different ways.

On the one hand, ZCBs meant maximising carbon reduction, including operational and embodied carbon reduction throughout the life cycle of buildings. Compensation of the life cycle emissions from materials could

be counterbalanced through renewable energy. The use of bio-based materials such as untreated solid timber also offered an opportunity for carbon sequestration. For example, LG1 explained, “you might produce carbon emissions during the lifetime of the building, but somehow managed to offset them by sequestering CO₂ into the building in the first place”. On the other hand, achieving ZCBs meant purchasing carbon credits to offset carbon emissions for the entire life of buildings. AD1 remarked that purchasing offsets for the remaining carbon emissions was problematic because “there aren’t enough offsets”.

The tension between “offset carbon by using different low-carbon technologies to maximise the carbon reduction” and “offset carbon by purchasing carbon credits” for ZCBs has caused much debate. This tension is related to the meaning and definition of a ZCB. There currently exists two types of carbon offsetting mechanisms for buildings: (1) direct carbon offsetting through incorporating renewable resources and building materials; (2) indirect carbon offsetting through purchasing credits for carbon emissions (McLeod et al., 2012). According to Opher et al. (2021), a building cannot achieve a net-zero carbon balance without feeding surplus on-site renewable energy into the grid and purchasing carbon offsets. However, indirect carbon offsetting does not reduce emissions (Bullock et al., 2009; Pan, 2014). McLeod et al. (2012) argued that the offset mechanisms justifying the emissions elsewhere are not permanent. In that case, the atmosphere could potentially receive two sets of emissions: the original emissions being offset, and the offset mechanism reverted to an emission relative to the national baseline. Consequently, consideration must be given to maximising carbon reduction through improved design and construction practices.

This tension or debate of reducing carbon through design and offsetting is deeply rooted in the terminological confusion in defining ZCBs worldwide (Pan, 2014; Pan & Li, 2016). Various definitions of what constitutes ZCBs worldwide suggest that New Zealand is not alone in identifying tensions. The concept of ZCBs is diverse among countries, as mentioned in the literature review. Inconsistent definitions lead to the complexity of carbon measurement and benchmarking, calculation methods, policy strategies and industry practices. Thus, a definition and boundary of what constitutes a ZCB are required for New Zealand’s building and construction industry. As the majority of interviewees agreed that a common definition of a ZCB in New Zealand would be useful: “I do think we need some clear definitions” (LG2); “a definition would be good. Define it” (AD1). A clear and consistent definition and an agreed measurement of ZCBs are indispensable for the effective

execution of policies and standards (Marszal et al., 2011; Kibert & Fard, 2012). New Zealand's policymakers and industry regulators should provide ZCBs definition, classification and boundary in building regulations and guidelines to provide further clarification for the industry.

6.4.2.2 *Lack of knowledge and skills*

90% of interviewees emphasised that the lack of knowledge was one of the most critical challenges to overcome if the New Zealand building and construction industry can deliver buildings towards zero carbon. Our study participants stressed that the lack of climate change literacy in relation to ZCBs was an impediment, as AD3 described, "I've got people asking me to do it. But I don't know how to do it" (AD3). Participant LG1 highlighted that ZCBs design was innovative within the industry, and there existed a knowledge gap regarding ZCBs, even for senior building specialists. Supporting this explanation, EC1 said that designing ZCBs required the team to understand different knowledge, technologies, and skills from what was traditionally used. For example, the impact of using more timber construction on the building load and "whether the electrical grid can actually have the capacity to essentially supply a building that's fully electrically, heated and cooled?".

Several participants believed that New Zealand's building and construction industry did not have the skills to develop ZCBs, either in the design and construction activities or the regulatory compliance process. As HA1 argued, "there are no skills available in our industry". It was also indicated that only extensive engineering and architecture firms specialising in sustainable construction could plan and implement ZCBs. Apart from large-scale building projects, where "money's not an issue" (HA1), transitioning the entire building stock to be zero carbon was burdensome because of the current building quality issues combined with the ability of building practitioners to construct minimum-quality buildings. Most of New Zealand's buildings, particularly existing ones, were under-insulated and had poor indoor environments (White & Jones, 2015). In addition, participant HA1 believed that New Zealand's builders might not have sufficient skills to deliver as-built buildings as designed. Designers and engineers lacked knowledge and skills around building physics, particularly in the performance of buildings; as AD1 criticised, "we don't put the right glass, the right installation, the right airtightness". LG3 commented on the lack of knowledge regarding the building consent process, "if you were to go to our building consents team and talk to somebody about embodied carbon, I guarantee you that very few people will understand that."

The findings align with the studies from the UK, Hong Kong, and Sweden (Persson & Grönkvist, 2015; Pan & Pan, 2021), confirming that knowledge and skills are essential to developing ZCBs. However, the presented results expose the specific problem to the New Zealand context, where there is a strong recognition that ZCBs are required. However, building stakeholders lack the knowledge, capacity, and capability to deliver ZCBs. It is important to note that achieving net-zero carbon targets for New Zealand's building stock by 2050 may be unfeasible due to the absence of expertise within the industry.

6.4.2.3 *Lack of integration and collaboration*

It should be recognised that decarbonising buildings across their lifecycle required stakeholder engagement and collaboration. Several participants agreed that “partnering and integration are key” (AD4) and “an important part of the process is early engagement with the main contractor” (AD2). EC1 suggested that ZCBs could be attained through the early integration of the building stakeholders as the key decisions were made in the preliminary design stages, which greatly affected the building's carbon impacts.

From the architect's perspective, AD1 expressed the challenges of accomplishing well-designed and high-performance buildings due to insufficient integration in the design process. For instance, the lack of understanding and poor communication between architects and engineers resulted in the inefficient design of building envelopes and building services, “we look at every element individually” (AD1).

The ineffective partnering often prevented the zero-carbon consideration to be part of the design decisions. Decision-makers often obscured the beneficial aspects of zero-carbon technologies and design. They considered the capital cost and actual design benefits (e.g. improved thermal comfort and the potential cost of annual savings) separately. “If you're going to hire a quantity surveyor to calculate the costs, you should hire the building engineer to calculate the benefits. Then we discuss with the decision-makers around the pros and the cons” (HA1). From the main contractor perspectives, C1 and C2 believed that they had no chance to influence ZCBs design and construction if they were not engaged early in the design process. “We don't have much control unless the project uses integrated design process, which is very rare in New Zealand” (C1).

These findings match those observed in earlier studies (Gieseckam et al., 2016; Attia et al., 2017), calling for collaboration among building stakeholders towards ZCBs. The whole-of-life value and benefits can only be

perceived and measured when all stakeholders are engaged throughout the project (Owen et al., 2010). Greater project partner alignment can reduce annual energy consumption by up to 12% and CO₂ emissions by up to 37%, emphasising the project's design stage to resource availability (Papachristos et al., 2020). The integrated design process is one of the most widely used tools to help define an appropriate design path while conforming to budgetary and schedule constraints for buildings towards net-zero carbon (Zimmerman & Eng, 2006; Lu et al., 2020). This approach is recommended to help overcome multiple challenges and issues towards ZCBs in New Zealand and worldwide.

6.4.2.4 Data management and shortage issues

Some interviewees mentioned the problem of data management and the shortage of relevant carbon data. Regarding the application of ZCBs, the deficiency of New Zealand specific embodied carbon data for certain building elements, and construction processes posed a critical challenge for the industry. As M4 mentioned, “you need the right data to start. There needs to be some unified source of truth, and EPDs are probably a big part of it, but where does everyone collect EPDs information? What’s the most current information?”. Similarly, RE1 indicated, “the industry having the data of their products, knowing what their products are doing and what the carbon is for them would make our life a lot easier”.

New Zealand is fortunate to have several locally-made carbon-related tools and databases. The building and construction research institute BRANZ has developed tools to assist with ZCBs and has actively sought to increase the industry's climate change literacy. BRANZ's tools provide much-needed information on embodied carbon and energy values for some building materials, including concrete, glass, timber, and metals. For instance, CO₂NSTRUCT is a freely available embodied-carbon database tool for New Zealand that incorporates New Zealand specific data (BRANZ 2020). However, many of the existing tools in the New Zealand construction market often have data gaps, such as the embodied carbon of the building services (e.g. HVAC equipment) (HA1).

This research shows gaps in the data available for whole-of-life embodied carbon emissions for construction materials and products in New Zealand. Questions on the data quality are also raised. Further work is required to establish a national whole-of-life carbon database and data management system to ensure consistency of

analysis within the industry. Encouraging the market to develop and use EPDs is also necessary. Construction product manufacturers, importers, material suppliers, and service providers can contribute to data sources.

6.4.3 Legislative and cultural issues

6.4.3.1 Lack of legislation

New Zealand did not have a well-developed legislative process for ZCBs. As RE1 claimed, “we’ve got a building code is behind the rest of the world. We have deficient air leakage requirements in our building code, compared to the UK”.

Upgrading the New Zealand Building Code and its related Building Act 2004 was recognised by most participants as a required policy strategy for decarbonising the building and construction industry (Bui et al., 2021c). The government has encompassed energy efficiency changes in the New Zealand Building Code that make New Zealand more aligned with international standards. The government also launched the first public consultation on two proposed policy documents in 2020, which sought to reduce emissions of buildings: *Transforming operational efficiency framework* and *Whole-of-life embodied carbon emissions reduction framework*. However, these policy documents are yet to be improved and finalised. Even though setting low-carbon specifications for buildings might stimulate the industry to work towards ZCBs, critics question how the government policy could widely impact the working practices of building professionals. Most building stakeholders sought to construct a minimum building standard rather than beyond Code requirements (MacGregor et al., 2019).

There is a need to improve general industry practice and user behaviours to enable the building and construction industry in New Zealand to deliver ZCBs. Examples include clarifying the definition and developing knowledge, formulating progressive regulations and policies, encouraging experience sharing and communication, and shaping the market by providing incentives and price controls (Pan & Pan, 2021).

6.4.3.2 Cultural barriers

Another concern was how the New Zealand building and construction industry could overcome the organisational culture barriers to ZCBs. MacGregor et al. (2019) identified the lack of innovation, demand,

and perceived risk as cultural barriers to ZCBs in New Zealand. As LG1 acknowledged, “the majority of the industry is afraid of a change”.

Compared to other countries, the critical weakness of New Zealand’s building and construction industry is that the industry is slow-to-innovate (Wilkinson et al., 2017; MacGregor et al., 2019). This organisational culture barrier will likely prevent the wider implementation of ZCBs within the construction market. It has been noted that the New Zealand building and construction industry appears slow to innovate, mainly due to the industry’s conservative perceptions that innovations should not be given to industrial competitors (Wilkinson et al., 2017). Facilitating a culture of innovation to support the adoption of ZCBs requires system-level changes.

6.4.4 A comparison of the global context

New Zealand’s building and construction industry is still in the early transition to a net-zero carbon future (Bui et al., 2021c). However, the challenges and issues towards ZCBs in New Zealand can be contextualised globally, particularly in developing and small-to-medium developed economies, to perceive the similarities, differences and lessons learnt. The challenges recognised in the New Zealand case are not too different from the experience of implementing ZCBs overseas. The most significant challenges to the global development of ZCBs has been the financial challenges around cost, the shortage of knowledge and skills, and the insufficiency of government policies. The cost-driven and “slow-to-innovate” building and construction industry, the insufficient data for whole-of-life embodied carbon emissions for construction materials and products, and the immaturity of the construction supply chain are typical problems in New Zealand. Inconsistent language and understanding of ZCBs is an issue in New Zealand and Hong Kong, but not in many other countries such as the UK and European nations where ZCBs are clearly defined. Table 6-3 shows the main challenges and issues identified in the research findings compared to other countries.

Table 6-3: Main issues and challenges to ZCBs in New Zealand compared to other countries

(Source: Authors)

Challenges and issues	New Zealand	The UK	Sweden	Southern Europe	United Arab Emirates	Canada	Hong Kong
Finance	Cost-driven industry	[1]					
	High initial investment	[1]	[5]		[7]	[8]	[9]
		[2]					
		[3]					
		[4]					
	Lack of financial incentives	[2]	[5]		[7]	[8]	[9]
		[4]					
Industry knowledge, capacity and capability	Inconsistent language and understanding						[9]
							[10]
	Lack of knowledge and skills	[1]	[5]	[6]	[7]	[8]	[9]
		[2]					[10]
		[3]					
		[4]					
	Lack of integration and collaboration	[1]		[6]			[9]
		[2]					
		[4]					
	Data management and shortage	[4]			[7]		
Legislation	Unclear definition of zero carbon buildings			[6]			[9]
	Lack of building regulations and guidelines	[1]	[5]	[6]	[7]	[8]	[9]
		[2]					
		[3]					
Culture	Slow to innovate (e.g. resistance to change)	[1]	[5]				

Note (s): [1] Heffernan et al. (2015), [2] Osmani & O'Reilly (2009), [3] Davies & Osmani (2011), [4] Gieseckam et al. (2016), [5] Persson & Grönkvist (2015), [6] Attia et al. (2017), [7] Mokhtar (2019), [8] Singh et al. (2019), [9] Pan & Pan (2021), [10] Pan & Pan (2020)

The primary challenge to ZCBs within the New Zealand context is the lack of skills and knowledge. This finding is similar to the UK but appears different from Hong Kong and Canada due to a misunderstanding of the ZCBs concept. In developing ZCBs globally, the knowledge gap about the importance of embodied carbon and operational carbon reduction needs to be bridged to transition from a “zero energy building” to a “zero carbon building”. Irrespective of the transition to ZCBs, New Zealand’s building and construction industry has faced severe obstacles. For example, an industry focuses on cost-drivers that deliver minimum-code buildings rather than high-performing buildings that concentrate on health, well-being, and operational efficiency. Improving industry knowledge, capacity, and capability to deliver higher-performing buildings that are healthy, and zero-carbon should also be prioritised.

6.4.5 The key support mechanism for the delivery of ZCBs in New Zealand

As New Zealand wants to implement zero carbon targets for the building and construction industry, the challenges remain in how to achieve these targets. The key recommendation arising from this study is the priority on knowledge development and exchange for implementing ZCBs. The building and construction industry is used to deliver minimum-code buildings while developing ZCBs is complex. Building stakeholders are required to adopt an entirely new language. There is also a need to upskill design techniques, construction, and procurement methods, building consent and compliance, and whole-of-life carbon assessment. The government and industry should work closely together to provide education and training programmes to improve the knowledge and skills and increase public awareness of the impact of climate change and the importance of working towards ZCBs.

Cultivating knowledge sharing and exchange is also recognised as necessary for knowledge development for ZCBs. New knowledge concerning advanced technologies is essential in the zero-carbon transition processes. Regarding ZCBs, where carbon reduction must be addressed throughout the project’s life cycle, the process will be made only if all project participants are engaged and understand both theory and practice. It is recommended that there is a need for creating a knowledge-sharing platform for ZCBs to promote carbon literacy. The government and construction organisations must be involved in enabling these initiatives.

6.5 Conclusion

This chapter has examined the feasibility of implementing ZCBs in New Zealand by identifying and investigating the challenges and issues within the industry. The critical challenges to implementing and delivering ZCBs are financial issues, the shortage of knowledge, capacity and capability, the lack of legislation, and organisational culture barriers. This research has shown that the challenges recognised in the New Zealand case are similar to those faced globally. Cost-driven and slow-to-innovate building and construction industry, the insufficient data for whole-of-life embodied carbon emissions for construction materials and products, and the immaturity of the construction supply chain are critical problems in New Zealand that are barriers to the widespread adoption of ZCBs. It is suggested that improving industry skills and knowledge might help change the cost-driven perspective to value-based benefits, encourage innovation, and enhance the practice of delivering minimum-code buildings to ZCBs that offer health and environmental benefits for people's lives.

This chapter emphasises knowledge development and exchange on carbon literacy, especially a whole-of-life carbon approach is an important support mechanism for delivering buildings towards zero carbon. Bridging the knowledge gap in whole-of-life carbon and operational carbon reduction to transition from “zero energy buildings” to “zero carbon buildings” is necessary for the global building and construction industry. The governments and construction industries devote more effort to establishing education and training programmes and knowledge-sharing platforms to implement ZCBs. Low capacity and capability, lack of knowledge and skills in carbon literacy, low carbon data efficiency, and slow-to-innovate appear to be global problems. By making plans to address the perennial issues outlined in this chapter, the implementation of ZCBs can be more widely to meet 2050 emission reduction requirements.

7 Chapter 7: Challenges to zero carbon refurbishment of existing buildings in New Zealand: An exploratory study

This chapter is based on the following conference paper, which has been published in final form. The paper was accomplished Theme Highly Commended Paper Award for Sustainability in Built Environment.

Bui, T. T. P., MacGregor, C., Domingo, N., Wilkinson, S. (2022). Challenges to zero carbon refurbishment of existing buildings in New Zealand: An exploratory study. In: S. Perera & M. Hardie (Eds.), *Proceeding of 45th AUBEA conference 2022: Global Challenges in a Disrupted World: Smart, Sustainable and Resilient Approaches in the Built Environment*, Australia (pp. 522-542). <https://10.26183/a6pq-mg06>.

Abstract

Following the findings from international perspectives (Chapters 2, 3 and 4), which indicated a lack of detailed investigation into decision-making process for building refurbishment towards zero carbon in the current industry practices, as well as the current zero carbon building practices in New Zealand (Chapters 5 and 6), where little known about the refurbishment of existing buildings towards zero carbon, this chapter pays particular attention the current development and implementation of zero carbon refurbishment of existing buildings in New Zealand. The chapter probes opportunities and challenges in reducing carbon emissions throughout the refurbishment process by undertaking an exploratory study using seventeen semi-structured interviews with building experts within Aotearoa New Zealand. The findings reveal that even though refurbishing existing buildings presents a significant opportunity to reduce embodied carbon emissions by reusing existing buildings' components, it must still carefully consider embodied carbon emissions of newly-added construction materials and products. The research also indicates several challenges to reducing carbon emissions in the refurbishment process, including (1) inexplicit carbon goal setting, (2) ineffective building condition assessment, (3) deficient and incomprehensive relevant whole-of-life carbon information to support the decision-making, and (4) inconsistent and ambiguous carbon-calculation guidelines and benchmark. To address these challenges, a comprehensive decision support framework incorporating whole-of-life carbon-reduction initiatives for building refurbishment is, therefore, suggested for future work. The results from this

chapter provide recommendations to enhance industry practices in reducing whole-of-life carbon emissions for building refurbishment.

7.1 Introduction

In the light of climate change, the world wrestles with reducing global warming to no more than 1.5 degree and achieve net-zero GHG emissions by 2050. Having responsibility for more than 40% of international energy use and one-third of global GHG emissions, buildings contribute significantly to global GHG emissions (UNEP, 2009). In New Zealand, research has highlighted that the building and construction industry contributes roughly 16% of New Zealand's GHG emissions (MBIE, 2020). To meet targets of reducing emissions by 2050, there is a need to maximise carbon reduction in the design and construction of buildings. Moreover, implementing zero carbon strategies for refurbishing existing buildings should be prioritised as refurbishment is a better carbon mitigation measure than constructing a new build (Hasik et al., 2019). For instance, a life cycle assessment of an office building in Wellington, New Zealand, showed that the refurbishment building saved approximately 3100 tonnes of carbon emissions compared to a new building (BRANZ, 2018). Thus, this chapter focuses on understanding the opportunities and challenges of undertaking zero carbon refurbishment (ZCR) of existing buildings.

Several opportunities exist for reducing carbon emissions in building refurbishment, such as improving building energy performance and using low-carbon materials and products (Giesekam et al., 2016; Luo et al., 2019). However, implementing ZCR also faces challenges in mitigating carbon emissions, such as enabling building regulations, financial barriers, and expected user comfort (Bui et al., 2021a). These challenges can be critical for making carbon-reduction decisions in the refurbishment process. In reviewing the literature, there is little consideration for the opportunities and challenges regarding integrating whole-of-life carbon reduction in refurbishment decision-making practices. This chapter examines opportunities and challenges to reducing carbon emissions in the refurbishment process in New Zealand. The remaining part of the paper proceeds as follows: (1) review the literature, (2) describe the methodology used in the study, (3) report findings and discussion, and (4) outline the conclusion and recommendations for further research.

7.2 Literature review

Two main opportunities for reducing carbon emissions in building refurbishment include operational and embodied carbon emissions. Improving building energy performance may be the most effective and common measure to reduce operational carbon emissions in building refurbishment. It can be achieved mostly via upgrading energy-efficient systems, implementing passive design, and installing renewable energy technologies (Pan & Li, 2016; Luo et al., 2019). However, improving building energy performance requires extra materials and systems that increase the embodied carbon of the whole building (Asdrubali et al., 2019). Therefore, it is argued that using alternative materials with lower embodied carbon, such as reusing existing building elements and utilising recycled materials, is also critical for refurbished buildings (Giesekam et al., 2016; Moncaster et al., 2019). Although debate continues about prioritising operational or embodied carbon reduction strategies for building refurbishment, the building stakeholders' perspectives on this matter have received little attention in the research literature.

Many studies have examined the barriers and challenges to zero carbon buildings, including new buildings and refurbishing existing buildings that focus on improving energy efficiency and carbon reduction worldwide (Osmani & O'Reilly, 2009; Pan & Pan, 2021; Bui, MacGregor, et al., 2022). Particularly for the refurbishment, Davies and Osmani (2011) investigated the key challenges for achieving low carbon housing refurbishment in England from architects' perspectives. It is concluded that high capital costs for micro-generation technologies and energy-efficient materials, the disparity in tax between new build and refurbishment, and the complexity of the United Kingdom (UK)'s existing housing stock are the most considerable challenges. But Mokhtar (2019) was more interested in identifying both the technical and the financial difficulties when developing refurbishment guidelines within the context of The United Arab Emirates (UAE). The technical challenges include the variation in construction systems, the quality of construction, and energy modelling challenges. The financial challenges include the subsidised price for electricity, the cost estimation for various energy conservation methods, and the payback for installing local renewable energy sources. However, these studies pay attention to the common challenges of adopting zero carbon initiatives for the refurbishment of existing buildings. Research on whole-of-life carbon reduction refurbishment practices and building stakeholders' decision-making on balancing the carbon-reduction factor with others in their decision-making process for

refurbishment is still lacking. Not to mention, various constraints and limitations influence the refurbishment process that focuses on zero-carbon strategies (e.g. project objectives, budget, and available refurbishment techniques, approaches, and expertise). This chapter contributes by identifying carbon-related opportunities and challenges found in different areas of the pre-design and design stages of the refurbishment process, specifically in the New Zealand case.

7.3 Research method

The exploratory study employed a qualitative research method, using semi-structured interviews with the building experts to examine opportunities for and challenges in reducing carbon emissions in building refurbishment in New Zealand. The qualitative research method was chosen because it is particularly useful for exploring and seeking new insight into the research topic and providing reliable and comparable qualitative data when working with a complex issue such as carbon reduction for building refurbishment (Saunders et al., 2016; Gray, 2018).

Participants were purposively recruited from various parts of the building and construction industry to provide a comprehensive view, covering government agencies and multiple-sized construction companies. Participants were also required to have knowledge and expertise in carbon reduction and sustainable construction. Eventually, 11 online and 6 in-person interviews were conducted with building experts between December 2020 and August 2021, ranging from 30 to 75 minutes. Participants received an invitation via email then asked to carefully read the project information and sign the written participant consent form following standard ethics protocols. Oral consent was also obtained during the interview. The interviews included questions about: (1) participants' background, and (2) participants' perspectives on opportunities and challenges to reducing carbon emissions in the refurbishment process. The sample size is consistent with qualitative research sampling procedures (Galvin, 2015; Creswell & Poth, 2016), confirming that 12-15 interviews are appropriate for data saturation.

Thematic analysis was utilised for data analysis. Thematic analysis is a foundational method for qualitative analysis. It is often used to identify, analyse, organise, describe, and report themes within the interview data set. To conduct a trustworthy thematic analysis, we followed a step-by-step approach demonstrated by (Nowell et al., 2017). Interviews were audio-recorded with permission from the participants and then transcribed.

Transcripts and notes were logged and coded using NVivo 12. The themes from data analysis include opportunities and challenges in reducing carbon emissions in building refurbishment in New Zealand. Table 7-1 illustrates an overview of the participants, including the codes used later in the paper to report the findings.

Table 7-1: Overview of the respondent type and codes (Source: Authors)

Respondent type	Code
Client presentative (public sector)	LG1, LG2, LG3, HA1
Client presentative (private sector)	RE1, RE2
Architect	AD1, AD2, AD3, AD4
Contractor	C1, C2
Manufacturer/Developer	M3, M4
Project manager	PM1
Engineer	EC1
Non-profit building organisation presentative	NGO1

7.4 Findings and discussion

7.4.1 Opportunities for reducing carbon emissions in building refurbishment

The first set of analyses examined the participants' perspectives on the opportunities for reducing carbon emissions in building refurbishment. Table 7-2 demonstrated several participants' views on design opportunities to reduce carbon emissions in building refurbishment.

Table 7-2: Examples of participants' views on design opportunities to reduce carbon emissions in building refurbishment (Source: Authors)

Design opportunities	Illustrative quotes
Reusing existing buildings (e.g. building structure, envelope, services, etc.)	“The first thing is that we try to reuse the building where we can. That is the lowest carbon development in practice so far. We’ve refurbished existing buildings with keeping the structure, and we keep the glazing systems” (RE1).
Improving energy efficiency	“Historically, the buildings haven’t been well insulated. They lose a lot of heat, which is hard to heat and cool. Thus, you would consider where the thermal envelope will go throughout refurbishment for low carbon” (EC1).

When the participants were asked to elaborate on design opportunities to reduce carbon emissions in building refurbishment, most answers focused on lowering operational carbon emissions rather than considering whole-of-life embodied carbon emissions. A common view amongst interviewees was that reusing the existing building, such as keeping the structure and other building components, like the glazing system, was the best way to lower embodied carbon emissions. As a result, the primary focus for building refurbishment was maximising operational carbon reduction by improving energy efficiency. Another way our participants sought to reduce carbon emissions was by using environmentally sustainable products, which a minority of the participants reported.

While preliminary, these findings help us to understand the current practices in selecting refurbishment design opportunities to lower carbon emissions of building refurbishment in New Zealand. However, one of the issues that emerged from these findings was the existing priority on reducing operational carbon emissions. This finding is consistent with that of Moncaster et al. (2019) and Röck et al. (2020), confirming that the global building and construction industry currently focuses on optimising “operational” energy use of buildings and the associated carbon emissions rather than assessing the whole-of-life carbon emissions. Moreover, major energy refurbishment is associated with significant carbon emissions, mainly due to the use of energy-intensive construction materials. Measures to promote energy efficiency refurbishment may not reduce overall environmental impacts. This appears to be not only the case of New Zealand (Ghose et al., 2017; Ghose et al., 2019; Ghose et al., 2020), but also other advanced economies such as UK (Pomponi et al., 2015), Sweden (Wallhagen et al., 2011) and Italy (Ardente et al., 2011). Therefore, building refurbishment towards zero carbon must consider whole-of-life embodied carbon reduction of newly-added construction materials and products, alongside operational carbon reduction associated with energy use and the reuse of existing building components.

7.4.2 Challenges to reducing carbon emissions in building refurbishment

Issues related to ineffective decision-making in the refurbishment process were particularly prominent in the interview data. Four broad sub-themes emerged from the analysis: (1) inexplicit goal setting, (2) ineffective building condition assessment, (3) inadequate design information and consideration of whole-of-life carbon reduction, and (4) inconsistency in calculating and accounting carbon emissions for building refurbishment.

7.4.2.1 *Inexplicit goal setting*

A common view amongst interviewees was that the building refurbishment practices generally lacked clear goals and objectives in the initial planning stage. Setting a carbon-reduction goal was necessary for a successful building refurbishment that focused on reducing carbon emissions. It was also important to note that specific carbon goals should be established at the earliest stage of the refurbishment process. Table 7-3 shows participants' perceptions on goal setting to reducing carbon emissions in building refurbishment.

Table 7-3: Examples of participants' perceptions on goal setting to reduce carbon emissions in building refurbishment (Source: Authors)

Perceptions	Illustrative quotes
There is a requirement for setting embodied carbon emissions targets	“The first thing to do is to set some goals and targets, saying that a 20% reduction in embodied carbon emissions must be achieved. You must set an energy goal, a water goal, or a carbon goal for embodied and operational, a percentage reduction over a benchmark” (AD1).
Specific carbon goals should be established in the design brief at the earliest stage of the refurbishment process	“First is clarifying the briefing, ensuring all design aspects stated in brief are being worked. What rating system are you going to use? What are the pros and cons, or the benefits or costs associated with making design decisions? How do those decisions align with the client’s values?” (EC1).

This finding confirms the importance of setting the right goal in the early stages of the refurbishment process, which is in line with previous studies found in the literature (Ferreira et al., 2013; Bui et al., 2021b). Goal setting, where refurbishment objectives and criteria are defined, is the most critical stage because all subsequent stages during the refurbishment process are about implementing the set goal. However, the present research strongly emphasises the inexplicit carbon goal setting in the current New Zealand industry practices can lead to several barriers affecting the design decisions about carbon benchmarking, such as the trade-off between cost and carbon performance and identification and performance assessment of refurbishment solutions.

7.4.2.2 Ineffective building condition assessment

Several problems were identified regarding ineffective building condition assessment of existing buildings, which resulted in uncertainty in the design and implementation of building refurbishment. First, the current building condition was assessed mostly against the performance requirements of the New Zealand Building Code or beyond the Code with the focus on improving energy efficiency, which did not include carbon performance metrics and benchmarks. The historical data regarding building performance, such as energy bills, water bills and maintenance costs, was often inadequate due to poor building management practices. These practices led to insufficient and inconsistent performance assessments for existing buildings before and after refurbishment. An interviewee said about this issue: “We don’t develop a brief that addresses performance issues. There was one upgrade where we put an installation, but we didn’t do any calculations on what the consumption reduction would be or anything quantifiable” (LG2).

Another reported issue was the lack of a comprehensive existing building condition assessment. As opposed to constructing new buildings, most participants agreed that the constructability of building refurbishment was one of the most significant factors. Especially for the major refurbishment involving the upgrade of existing features and the construction of newly-added components, deficient existing building data collection and assessment caused the selection of inappropriate refurbishment solutions and unforeseen constructability problems in the construction process. These characteristics were described in the following evidence: “The challenges we had with stripping the building back to its structural frame and building back up from there are many unknowns. There’s not only so much that designers, engineers and quantity surveyors can also see in designing solutions for an existing building” (PM1).

In general, these findings suggest that ineffective building condition assessment is mainly due to: (1) the inadequate existing building data and (2) the lack of guidelines and methods for building condition assessment. Regarding the refurbishment focusing on carbon reduction, it is important to benchmark energy use and associated operational carbon emissions. Building rating systems such as Greenstar, LEED, BREEAM, etc. and other multi-criteria assessment approaches may provide a direction for building condition assessment as they offer a structured framework to evaluate building energy and environmental performance (Ma et al., 2012; Nielsen et al., 2016). However, our research has been unable to demonstrate this aspect. Furthermore, the

question about how effective building condition assessment could help reduce embodied carbon emissions in building refurbishment remains unanswered and should be a focus for future research.

7.4.2.3 *Inadequate design information and consideration of whole-of-life cycle carbon reduction*

Concerns about the lack of design information and consideration for whole-of-life carbon reduction when making design decisions for refurbished buildings were expressed. First, design decisions were often made without considering complete information regarding refurbishment options such as whole-of-life carbon savings, whole-of-life cost, client expectations, stakeholder values (e.g. co-benefit for users), and constructability risks. This practice resulted in a delay in the design and construction processes for refurbished buildings. In one case, the participant commented: “That’s the risk of not getting the design brief right at the beginning and giving enough thought to the design decisions and some information, such as benchmarking” (EC1).

From clients’ perspectives, one participant claimed that there was insufficient information about whole-of-life carbon emissions to support their decision-making. For example, concerning embodied carbon information and the possibility of integrating long-term refurbishment strategies, the participant stated: “There’s one wall that’s entirely single-glazed windows. If we replace it, is that a lot of embodied carbon emissions? How do you get the building to perform better unless you replace those? What are the different options that we have? If you can’t afford to do everything at once and look toward the future, what are the things you can line up in the building? So that, ten years down the track, you can start adding those things” (LG2).

A recurrent observation in the research was that energy modelling and LCA were not generally applied in the early design stages of the refurbishment process to estimate carbon performance. Particularly for small to medium refurbishment projects, the discussions around energy modelling and whole-of-life carbon reduction initiatives were not usually involved, even though there were always opportunities to identify and implement carbon-reduction refurbishment solutions.

These findings are consistent with that of Asdrubali et al. (2019) and Bui, Domingo, et al. (2022), suggesting that a holistic multi-objective approach considering whole-of-life carbon, economic factors, co-benefits, and other impacts is necessary for making carbon-reduction decisions in building refurbishment. However, the

reported results identify insufficient and incomprehensive relevant information to support the decision-making in the refurbishment process in the New Zealand context. In contrast to earlier findings in other developed economies (e.g. European nations), where multi-objective optimisation processes integrating advanced building energy simulation, LCA and LCC methods are applied to identify the most carbon-and cost-effective refurbishment alternatives in the early design stages (Kamari et al., 2021; Serrano-Jiménez et al., 2021). But this does not appear to be the case in this study. This observation may support the hypothesis that refurbishing towards zero carbon in New Zealand is in its infancy.

7.4.2.4 Inconsistency in accounting and calculating carbon emissions for building refurbishment

Turning to the evidence of the inconsistency in calculating carbon emissions for building refurbishment, most participants believed there were no consistent carbon calculation guidelines, standards and benchmarks within the New Zealand building and construction industry. More importantly, the participants mentioned that they were not fully aware of how life cycle carbon assessment was reported in the current building refurbishment projects. These aspects have led to many debates concerning methods and scope of work for calculating carbon emissions; as one participant described: “There is no standard in New Zealand for carbon design. Only a couple of companies report carbon emissions in their projects, but it’s not clear what they’re recording and how they’re counting their carbon calculations” (RE1).

Two divergent and often conflicting discourses emerged in the findings related to life cycle carbon accounting for building refurbishment. Opinions differed on whether embodied carbon emissions of existing building components were accounted for when conducting LCA for refurbished buildings. Some participants thought that the boundaries of LCA for refurbished buildings only included embodied carbon emissions of newly-added materials and products. In contrast, others argued that embodied carbon emissions of all existing building components should be considered as one individual stated: “If it is a refurbishment, how do you count for existing components, and how are you adding other things? For refurbishing a commercial building’s fit-out, how will the concrete that has been there for 20 years be accounted for in LCA analysis?” (M4).

These results reflect those of (Vilches et al., 2017; Hasik et al., 2019). They also found various carbon calculation assumptions and scope of work for refurbished buildings in the literature and current industry practices within the global building and construction industry. More importantly, this variation challenges New

Zealand's construction stakeholders in calculating life cycle carbon emissions for refurbished buildings as the sector is in its early transition to a zero-carbon future. It is suggested that an appropriate calculation method for estimating the LCA of building refurbishment may help prevent inconsistent and ambiguous knowledge and understanding within the industry.

7.5 Conclusion

This chapter aims to investigate opportunities and challenges to reducing carbon emissions in the refurbishment process in the New Zealand context. It has found that whole-of-life embodied carbon reduction of newly-added construction materials and products should be considered alongside operational carbon reduction and the reuse of existing building components in the planning and implementation building refurbishment. The more significant findings are challenges to reducing carbon emissions in different areas of the pre-design and design stages of the refurbishment process, including (1) inexplicit carbon goal setting leading to several barriers affecting the design decisions regarding carbon benchmarking, trade-off between cost and carbon performance, identification and performance assessment of refurbishment solutions, (2) ineffective building condition assessment due to the inadequate existing building data and the lack of user guidelines and methods for building condition assessment, (3) deficient and incomprehensive relevant whole-of-life carbon information to support the decision making, and (4) inconsistent and ambiguous carbon-calculation guidelines and benchmark. The insights from this chapter, while preliminary, may assist in enhancing the current industry practices in reducing whole-of-life carbon emissions in the refurbishment process. What is now needed is a comprehensive decision support framework that incorporates whole-of-life carbon reduction initiatives for building refurbishment in New Zealand. A further in-depth investigation into the decision-making process of real-life building refurbishment case studies considering whole-of-life carbon reduction is strongly recommended to validate this chapter's findings, provide a greater understanding and assist in developing the guideline for better-delivering building refurbishment towards zero carbon.

8 Chapter 8: Decision making in reducing carbon emissions for building refurbishment: Case studies of university buildings in New Zealand

This chapter is based on the following Journal article, which has been published in final form.

Bui, T. T. P., Wilkinson, S., MacGregor, C., & Domingo, N. (2023). Decision making in reducing carbon emissions for building refurbishment: Case studies of university buildings in New Zealand. *Building and Environment*, 242, 110557. <https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110557>

Abstract

The findings outlined in previous chapters have indicated a need for detailed investigation into the decision-making process of building refurbishment considering whole-of-life carbon reduction. This chapter examines decision-making in reducing carbon emissions in the early stages of the refurbishment process by investigating three real-life case studies that incorporate carbon-reduction decisions. The important findings emerged from an interactive analysis between theoretical propositions and cross-case synthesis. The chapter sheds a new insight into (1) the effective adoption of building rating systems, (2) the required whole-of-life carbon reduction targets, (3) the importance of establishing a dedicated financial budget for carbon-reduction refurbishment solutions, (4) the need for adaptable refurbishment designs and long-term strategies, (5) holistic design reports, (6) the promotion of early contractor involvement (ECI) approach, (7) government funding and incentives, and (8) the availability of supply chains and data. The chapter contributes to existing knowledge by providing a new understanding of the decision-making practices and challenges faced in the refurbishment process, in which lessons learnt for improving the implementation of building refurbishment towards zero carbon are recommended. The research expands theoretical knowledge and practical experience in whole-of-life carbon analysis and performance estimation for building refurbishment. The insights gained from this chapter offer practitioners and researchers a streamlined interdisciplinary guide to better deliver refurbishment projects towards zero carbon.

8.1 Introduction

As climate change poses a catastrophic global risk, reducing carbon emissions is imperative to alleviating extreme climate change impacts (IPCC, 2014). The building and construction industry contributes significant harm to the environment. It accounts for more than 40% of global energy use and one-third of worldwide greenhouse gas (GHG) emissions (Lucon et al., 2014). The design and construction of buildings has been identified as a crucial area to reduce carbon emissions (Ahmad & Afzal, 2020). In New Zealand, buildings are directly and indirectly responsible for up to 20% of New Zealand's GHG emissions (BRANZ, 2020). Radical improvements in building design and construction are therefore required to help reduce environmental impacts, supporting the mitigation of climate change, achieving a low-carbon economy, and uplifting the quality of people's lives (Pan & Pan, 2021).

Refurbishment projects generate only half the embodied carbon emissions of new builds, thus representing a promising area to support climate change mitigation goals (Hasik et al., 2019). In New Zealand, existing buildings are forecasted to account for an estimated 65% of the total climate impact of the detached-house sector between 2018–2050, while new buildings make up the remaining 34% (Chandrakumar et al., 2020). While the carbon emissions related to the development of the new building stock can be reduced by imposing strict carbon-reduction requirements for new buildings, attaining these goals for existing buildings remains a challenging task. Therefore, it is crucial to ensure that existing buildings are refurbished properly to reduce whole-of-life carbon emissions.

A complex and challenging decision-making process is necessary when pursuing the limiting of carbon emissions during building refurbishment projects. In a refurbishment process, numerous decisions are made throughout the different phases, from the initial decisions on why and when to refurbish, the design of refurbishment strategies, the optimal selection among design alternatives, to decisions made during the process of construction, operation, usage, and finally, demolition and reuse. More importantly, most critical decisions are made in the pre-design and design phase (Ferreira et al., 2013; Nielsen et al., 2016). It is argued that the decision-making process is an art, fine-tuned over a long period through experience and learning from trial and error. Nowadays, decision-making is even more complicated due to the availability of “more alternatives to choose from”, the “large cost of making errors”, “more uncertainties”, and “the need for quick decisions”

(Turban et al., 2005). Accordingly, making decisions incorporating zero-carbon targets for building refurbishment can be difficult as it is a multi-objective problem influenced by various constraints and limitations (i.e. project target, budget, building techniques) (Ma et al., 2012). Likewise, government policies and social factors such as user comfort can also impact decision-making in the refurbishment process (Al-Ragom, 2003; Rose et al., 2021; Bui et al., 2021b). The involvement of multiple stakeholders adds further complexity (Rey, 2004; Klotz & Horman, 2010). Managing clients' requirements and stakeholders' values with the need to focus on zero-carbon strategies can be problematic (Bui et al., 2021a). To successfully deliver building refurbishment towards zero carbon, there is a need to better support and encourage decision-makers to make effective decarbonisation decisions throughout the refurbishment process.

In recent years, decision making in reducing carbon emissions for building refurbishment has been a significant research area of interest. Due to a large volume of literature in the research area, it is important to discover uncovered knowledge structures and gaps and emerge the conceptual framework of the refurbishment decision-making process. In doing so, both up-to-date systematic and critical reviews of the literature in the research field have been performed. A systematic review was undertaken to examine the state-of-the-art research on zero carbon refurbishment due to its organised, transparent, and reproducible way to synthesise research findings and discover future studies. Simultaneously, a critical literature review was undertaken to assess, critique, and synthesise the literature on decision support for building refurbishment in a way that facilitates a new conceptual framework for the decision-making process of building refurbishment considering whole-of-life carbon reduction. Both reviews considered the bibliometric search strategy using the keywords: "zero carbon" OR "net zero carbon" OR "zero emission" OR "zero energy" OR "nearly zero energy" AND "refurbishment" OR "retrofit" OR "renovation" via Scopus to determine the relevant literature. To narrow the scope of the review, a set of selection criteria were considered, including (1) English journal articles published at the final stage in recent years, (2) relevant subjects in the construction research field, (3) papers published in top-ranking journals in the construction field ranked by Scimago Journal and Country Rank (e.g. Building and Environment, Energy and Building, etc.), publishing the largest number of papers in the research context. As a result, the systematic review considered the final selection of 147 up-to-date research articles, which were analysed using mixed-method data analysis, including quantitative (science mapping) and qualitative

(thematic) analysis (Bui, Domingo, et al., 2022). The critical review considered the final selection of 15 state-of-the-art decision support mechanisms to reduce carbon emissions in building refurbishment (Bui et al., 2021b). More details on systematic and critical reviews of the literature in the research field are found in (Bui et al., 2021b; Bui, Domingo, et al., 2022).

Findings from the literature reviews revealed that there has been an increasing amount of literature on developing decision-support mechanisms to aid in identifying the optimal refurbishment solutions at the design phase of the refurbishment process (Juan et al., 2010; Xing et al., 2011; Jensen & Maslesa, 2015; Li & Froese, 2017; Gade et al., 2018; Serrano-Jiménez et al., 2021). It is suggested that a holistic multi-objective decision-support mechanism considering whole-of-life carbon, economic factors, co-benefits, and other impacts is necessary for building refurbishment towards zero carbon. In contrast, fewer studies have investigated the decision-making process for building refurbishment in any systematic way (Mickaityte et al., 2008; Kolokotsa et al., 2009; Ma et al., 2012; Bhuiyan et al., 2015). However, these studies have focused on the decision-making processes for energy management and sustainability, leaving behind the focus on a particular area, such as whole-of-life carbon reduction. Furthermore, there has been little discussion about the decision-making process for building refurbishment in practice that considers the impacts of whole-of-life carbon emissions and integrating necessary decision-support resources and tools. Most prior studies that focus on decarbonisation decision making in building refurbishment are limited to the theoretical context and lack clear evidence of application in current industry practice. In addition, various simple-to-complex decision support methods, tools and systems can be found in the literature but empirical research reporting on how these methods, tools and systems are actually adopted to support decision making in the practical refurbishment process is lacking. Key stakeholders' perspectives (e.g. clients, consultants, contractors, and the user group) and the documentation of real-life refurbishment projects are considered as reliable references for investigating decarbonisation decisions and the performance of building refurbishment. It is also important to identify existing challenges to reducing whole-of-life carbon emissions in the refurbishment decision-making process and potential opportunities for improvement. Lessons learnt and suggestions for improvement that extend the theoretical and practical knowledge and bridge the gap between theory and practice, might offer a basis and foundation for future work in this research area.

This chapter aims to address the knowledge gap by examining the practical decision making in reducing carbon emissions for building refurbishment in New Zealand. It focuses on the major refurbishment, which, among other things, involves a significant improvement in energy and carbon performance (Jensen, Maslesa, & Brinkø Berg, 2018). The scope of work focuses on the early stages of the refurbishment process, including the pre-design and design phases. Drawing on the literature, the critical components of the refurbishment decision-making process were identified. This process was then explored in practice using a case study approach. After that, unexpected outcomes, tensions, and lessons learnt towards the implementation of building refurbishment towards zero carbon were discussed based on the critical analysis of theoretical and empirical findings.

8.2 Literature review

It is often difficult to distinguish the refurbishment process clearly from that of new builds. The refurbishment process is assumed to be similar to the new building process, including pre-design, design, construction, and operation phases (Nielsen et al., 2016). However, Jensen, Maslesa, Berg, et al. (2018) identified seven different characteristics between a refurbishment and a new build. The main difference is that a preliminary investigation of the existing building is the basis for developing design solutions, whereas a new building has the building site as a foundation. Existing building design, condition, performance, and users are key considerations. Pre-evaluation and post-evaluation of refurbished buildings are necessary to measure the improvement of building conditions, energy performance, carbon and cost savings, and user satisfaction.

The early-stage refurbishment decision-making process traditionally incorporates the following main phases (1) building condition assessment, (2) goal setting, (3) generation of refurbishment alternatives, (4) performance estimation and evaluation (Ma et al., 2012; Ferreira et al., 2013; Nielsen et al., 2016). Recent evidence suggests that outlining refurbishment strategies is a critical step that should be considered before generating refurbishment solutions (Jensen, Maslesa, & Brinkø Berg, 2018; Bui et al., 2021b; Serrano-Jiménez et al., 2021). Thus, the early-stage decision-making process of building refurbishment proposed in this study is shown in Figure 8-1.

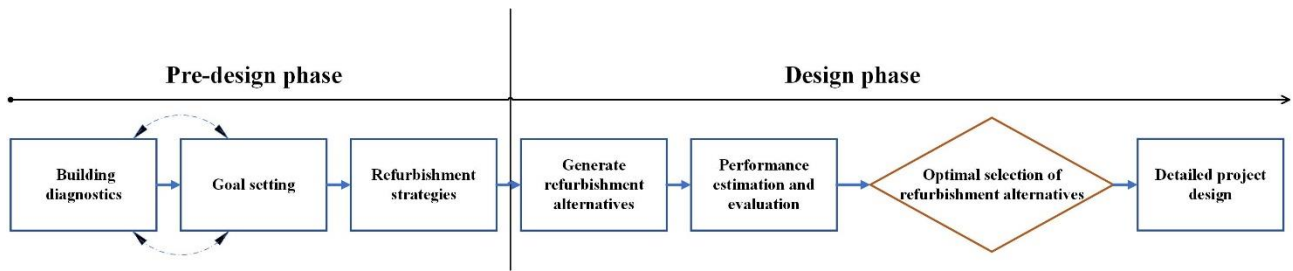


Figure 8-1: The early-stage decision-making process of building refurbishment (Source: Authors)

Setting goals, objectives, and criteria is often the starting point of the refurbishment process since all subsequent phases are adapted to these strategic and significant aspects. Selecting the right goal helps building stakeholders address existing problems and seek the best refurbishment solutions (Ferreira et al., 2013; Bui et al., 2021b). The goal and objectives can be based on the client's requirements, values from involved stakeholders, building rating systems (e.g. BREEAM, LEED, Green Star, etc.) and life cycle carbon budgets for individual buildings to define the carbon performance goal (Chandrakumar et al., 2020; Bui et al., 2021b).

However, the building condition assessment can be done before the goal setting to reveal the actual state of the building, and thus its refurbishment requirements, the site's advantages and disadvantages, and the appropriate refurbishment solutions (Nielsen et al., 2016). Therefore, these two steps could be undertaken iteratively to ensure the achievable goal is set considering the existing building condition problems. The procedure can continue with formulating refurbishment strategies, which represent different levels of refurbishment, from a few actions to a major refurbishment, and provide proposals for refurbishment solutions such as upgrading building fabrics, installing efficient equipment, and installing microgeneration (Xing et al., 2011; Jensen, Maslesa, & Brinkø Berg, 2018; Serrano-Jiménez et al., 2021).

The next step is a generation of refurbishment alternatives, where a multi-criteria analysis of the refurbishment components is performed, and the best possible options are selected (Ma et al., 2012; Li et al., 2017). Then, the performance of these possible options can be estimated using simple economics, energy calculations, rough estimates, energy simulation tools (e.g. EnergyPlus, IES, etc.), life cycle assessment (LCA) tools (e.g. LCAQuick, eTool, OneClick LCA, etc.), life cycle costing (LCC) methods and other complex and comprehensive decision support systems that incorporate multi-objective optimisation factors (Nielsen et al., 2016; Vilches et al., 2017; Bui et al., 2021c). However, there has been limited investigation of how these

methods, tools, and systems are applied to support building stakeholders making carbon-related decisions for building refurbishment in practice (Bui, Domingo, et al., 2022). This is an important area for further work.

After estimating performance, refurbishment alternatives can be evaluated quantitatively and qualitatively based on the project goals and objectives set earlier. Evaluation should be done continuously and iteratively throughout the design process, for example, evaluation of simulation results and calculations as well as cost and time implications at the end of each design stage (Ferreira et al., 2013; Nielsen et al., 2016). Then, the optimal refurbishment alternatives are selected before proceeding to the following stages of the project (e.g. detailed project design, construction, operation).

8.3 Research method

8.3.1 Research approach

The aim of this chapter is to investigate the pragmatic early-stage refurbishment process to identify what carbon-reduction decisions were made and how building stakeholders delivered building refurbishment towards zero carbon in New Zealand. This investigation adopted an exploratory case study approach, which was found appropriate for gaining first-hand experience with current refurbishment approaches and understanding the practical context of the decision-making process. The case study strategy is a reliable means of capturing rich information in complex situations such as construction projects. It generates insights into the phenomenon being studied and allows the investigator to retain the holistic and meaningful characteristics of real-life events (Ogawa & Malen, 1991; Barrett & Sutrisna, 2009; Yin, 2014). Figure 8-2 shows an overview of the research process.

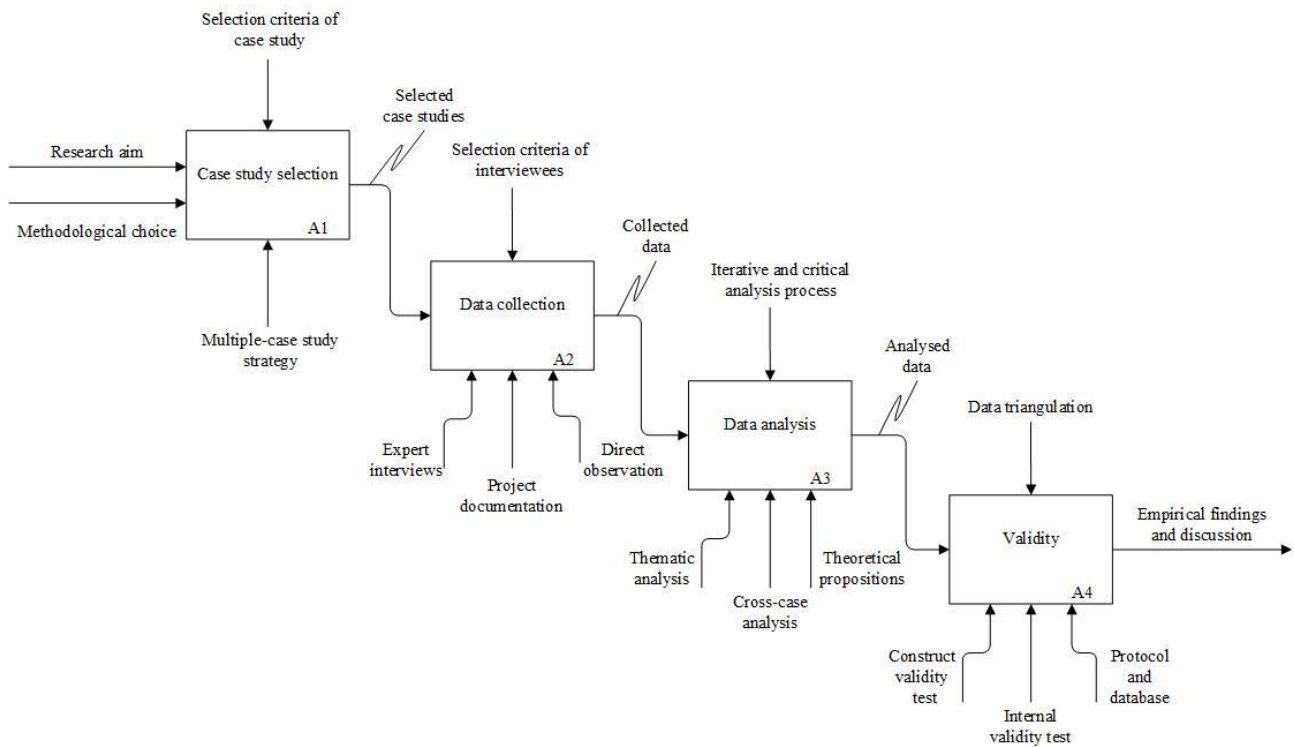


Figure 8-2: Research process (Source: Authors)

8.3.2 Case study selection

An important step in developing case studies is defining cases which will be studied (Knight & Ruddock, 2009; Gray, 2018). This research selected multiple case studies to reflect the major refurbishment towards net zero-carbon targets by 2050. The criteria for case selection included refurbishment projects that: (1) targeted a high level of sustainability/zero carbon certification or equivalent goals; (2) sought to integrate sustainable/low-carbon practices or products; (3) provided sufficient access to data, reports, and stakeholders; (4) were a similar building type; (4) were launched by different organisations within the past five years. Consequently, three university buildings were selected for the study. These recently refurbished buildings showcased examples of low-carbon designs and technologies.

Case study 1 was explored as a pilot study. A pilot case allows the investigator to observe different phenomena from many different angles or try different approaches on a trial basis (Yin, 2014). Case 1 was a refurbished educational building - a part of a sustainable redevelopment project. The project consisted of a new atrium that connected a new building with the existing library, lecture theatres, and the refurbished building. The project aligned with the organisation's green building standards and vision of moving towards net-zero GHG

emissions consistent with national and international commitments. Table 8-1 summarises the main characteristics of three selected case studies.

Table 8-1: Summary of the main characteristic of three case studies (Source: Authors)

Characteristics	Case study 1	Case study 2	Case study 3
Type of client	State sector (Tertiary Education)	State sector (Tertiary Education)	State sector (Tertiary Education)
Main use	Teaching facilities, office spaces, learning spaces	Learning spaces	Teaching facilities, office spaces, learning spaces
Project size	approx. 10,000 sqm	approx. 10,000 sqm	approx. 24,500 sqm
Project timeline	2018-2024	2020-2023	2019-2024
Status	Under construction	Under construction	Under construction
Total project budget	Not disclosed	\$60.5m	Not disclosed
Original built	1980s	built in 1968 and extended in 1985	1970s
Existing conditions	Unoccupied with poor and unsustainable conditions	In operation with poor condition	Under operation with poor thermal and performance comfort
Certification	In-house green building standards	carboNZero Building Operations (Targeted)	6 Star - Green Star
Main refurbishment considerations	Exterior wall and roof insulation, double-glazed windows, LED lighting, BMS system, centralised heat pump and chiller plant, off-site PV system	Low-e solar control double glazing, insulated walls and roof, external solar shading, operable windows, mixed-mode ventilation	Super-insulated and airtight curtain wall system, low-energy mechanical ventilation system, high-performance solar glazing, PV system, LED lighting

Case study 2 was a university library building transformation, showing the organisation’s commitment to reducing GHG emissions and achieving carbon neutrality by 2030. The existing library is conjoined into two-story buildings. The project targeted carboNZero Building Operations accreditation that included a range of environmental measures to improve building performance and reduce carbon footprint.

Case study 3 – an education building located at a university campus was a part of an adaptive reuse project towards a net-zero carbon future in New Zealand. The redevelopment project encompassed refurbishing two sections, North and East buildings, and constructing a new atrium that connected two parts of the existing building. The project was awarded six Green Stars for design by New Zealand Green Building Council (NZGBC), achieving 93 out of 100 points – the highest Green Star points given to any New Zealand building.

8.3.3 Data collection

The use of various sources of evidence enhances credibility and the richness of data due to the data triangulation opportunities in case study designs (Gerring, 2007; Swanborn, 2010; Yin, 2014). Accordingly, , multiple evidence sources were used to improve the overall quality of the research and accurately render the refurbishment decision process. The primary data sources were interviews with stakeholders involved in the case studies, project documentation (e.g. sustainable strategy reports, sustainability plans, site investigation reports, building performance reports, energy efficiency reviews, sustainable design briefs, building condition assessment reports, drawings, design specifications, study reports) and direct observation (e.g. site visits). One of the most important sources of case study evidence was interviews, which were employed to gain insights into the refurbishment process and carbon-reduction decisions. Interviewees from different building stakeholders' backgrounds, roles, and positions, who were involved in the decision-making process of the cases studied, were chosen to gather in-depth and supplementary information, reflect participants' relativist perspectives and attain an overall picture of the case (Eisenhardt & Graebner, 2007; Gray, 2018). They were also able to provide a shorthand history of the case study and helped identify other relevant sources of evidence (Yin, 2014).

The subject matter experts were selected using purposeful sampling techniques (Babbie, 2013; Maxwell, 2013; Neuman, 2014), as it allowed the selection of individuals with vast knowledge on reducing carbon emissions for building refurbishment to offer meaningful and insightful details. The selection of participants varied on a case-by-case basis depending on each case study's key actors involved in the refurbishment process, including but not limited to clients, project managers, consultants, cost advisors, facilities managers, contractors, etc. First, permission to investigate three case studies was obtained from the project clients. Based on the project clients' references, additional key actors involved in the refurbishment decision-making process were

identified, making up to twenty-five key actors in total. Once key actors and their profiles were identified, they were assessed based on the following requirement criteria: (1) have attained a tertiary education level, (2) have worked within the New Zealand building and construction sector for at least five years, and (3) have expertise in sustainable design, construction, project delivery or related skills. There was an attempt to select multiple case studies, which were pioneering showcases to reflect the major refurbishment towards net zero-carbon targets by 2050. Therefore, all identified participants came from industry-leading organisations in the field. All had expertise in sustainable building refurbishment since they had been involved in successfully delivering building refurbishment projects that incorporated sustainability and carbon reduction objectives. Some of them were in top positions in their various companies and organisations, actively involved in sustainable design, construction, and project delivery. Eventually, invitations were sent to all identified participants of three case studies who met the selection criteria. With project clients' permission and reference, most selected participants agreed to contribute to the research, apart from two invitees, due to their work commitments and other priorities.

Twenty-three semi-structured interviews were conducted with project team members of three case studies, which allowed probing views and opinions and encouraged extensive answers (Gray, 2018). During the interview, stakeholders were first asked to describe the refurbishment process and then explain what, how, and why carbon-reduction decisions were made. The interviews included questions about: (1) participant information, (2) project brief, the refurbishment process and stakeholders involved, and (3) the decision-making process and carbon-reduction decisions. Additional questions were discussed to identify further problems and unexpected subjects related to the refurbishment. Most of the interviews were held virtually via Microsoft Teams between July 2021 and January 2022 due to COVID-19 impacts and restrictions in New Zealand. The use of virtual groups created a healthy and safe environment where participants can contribute at their leisure and individual places (Dodds & Hess, 2021). The interviews lasted between 30 and 60 minutes and were digitally recorded subject to the participant's permission and transcribed for data analysis. Table 8-2 shows interviewees' demographics in three case studies.

Table 8-2: Interview participants' profiles (Source: Authors)

Case	Participants	Positions	Type of organisation	Years of experience in the construction industry	Years of experience in building refurbishment	Education degree and/or accreditation
Case 1	C1-CR1	Client Representative	Tertiary education	≥ 40	≥ 30	BEng, CMEngNZ, IntPE(NZ), APEC Engineer, FFMANZ
	C1-E1	Mechanical Engineer - Lead	Engineering & Consulting	≥ 10	≥ 10	BEng, MEngNZ
	C1-E2	Structural Engineer	Engineering & Consulting	≥ 10	≥ 10	BEng, Meng, MEngNZ
	C1-A1	Principal Architect - Zero carbon specialist	Architecture & Design	≥ 30	≥ 15	BArch, NZRAB Registered Architect, NZIA Member
	C1-A2	Architect - Lead	Architecture & Design	≥ 20	≥ 10	BArch, NZRAB Registered Architect, NZIA Member
	C1-A3	Architect - Carbon analyst	Architecture & Design	≥ 5	≥ 5	BArch, MArchProf, NZIA Member
	C1-CT1	Quantity Surveyor	Main Contractor	≥ 10	≥ 5	BConst, NZIQS Registered QS, GSAPs
	C1-CT2	Construction Project Manager	Main Contractor	≥ 10	≥ 5	BConst, NZCB Member
	C1-QS1	Cost Manager	Cost Management	≥ 15	≥ 15	BConst, NZIQS Registered QS
Case 2	C2-CR1	Client Representative - Project Manager	Tertiary education	≥ 20	≥ 10	BSc, Prince2 Practitioner
	C2-QS1	Quantity Surveyor	Multinational Engineering Consulting	≥ 15	≥ 10	BConst, PhD, NZIQS Registered QS
	C2-A1	Architect - Lead	Architecture & Design	≥ 10	≥ 10	BArch, March, RIBA Registered Architect, GSAPs
	C2-SC1	Sustainability Manager	Engineering & Consulting	≥ 20	≥ 20	BBS, CEng, MCIBSE, GSAPs, NZGBC Accredited Energy Modeller

	C2-E1	Principal Engineer	Engineering & Consulting	≥ 20	≥ 20	BEng, CMEngNZ, CIBSE Member
	C3-CR1	Client Representative - Lead	Tertiary education	≥ 30	≥ 20	BSc, DipBldgCons(RICS), MBA, CBS, FRICS
	C3-CR2	Client Representative - Building Services Engineer	Tertiary education	≥ 10	≥ 10	BEng, MSc, MIPENZ, CPEng, MCIBSE, MIET, IntPE(NZ)
	C3-E1	Technical Director - Lead	Engineering & Consulting	≥ 20	≥ 15	BEng, MEng, CPEng
Case 3	C3-E2	Building Services Engineer	Engineering & Consulting	≥ 10	≥ 10	BEng, CMEngNZ
	C3-SC1	Sustainable Buildings Specialist	Engineering & Consulting	≥ 15	≥ 15	BEng, CEng, CMEngNZ, GSAPs, WELL AP, MCIBSE, LEED AP BD+C
	C3-PM1	Project Manager	Project Management	≥ 15	≥ 10	BAS, BArch, NZRAB Registered Architect, NZIA Member, Prince2 Practioner
	C3-A1	Principal Architect	Architecture & Design	≥ 25	≥ 15	BArch, NZRAB Registered Architect, NZIA Member
	C3-QS1	Quantity Surveyor	Cost Management	≥ 15	≥ 15	BConst, NZIQS Registered QS
	C3-CT1	Construction Project Manager	Main Contractor	≥ 20	≥ 10	BEng, MSc

8.3.4 Data analysis

In an exploratory case study, qualitative data analysis involves iterative observation, analysis, and reflection (Mills et al., 2009). The data obtained from interviews and observations was compared to the written evidence gathered from project documentation, triangulating information. Follow-up emails were sent, and phone calls were made to the participants to clarify inconsistencies and missing data. The qualitative software package NVivo 12 was used to organise information and code, analyse data, identify themes, and for interpretation.

Following Sutrisna & Barrett (2007)'s; Yin (2014)'s; (Bennett & Checkel (2015)'s suggestions, a general qualitative strategy for analysing data was applied first, using theoretical propositions from literature review, descriptive frameworks and rival explanations to understand the preliminary data and provide an explanatory view for each case. Then, a cross-case synthesis was used as a specific analytical technique. Major themes were identified for each case before analysing the similarities, differences, and associations across cases. After that, patterns were determined using replication logic within and among cases before confronting the existing theoretical propositions in an iterative process. The discussion resulted from an interactive analysis between the literature and the cases studied.

8.3.5 Validity

Three design tests were conducted to confirm the validity and reliability of the findings following Yin (2014)'s; Birt et al. (2016)'s; Gray (2018)'s recommendation. The first test was to ensure construct validity, including using multiple sources of evidence and data triangulation. In addition, mistakes and errors were avoided by thoroughly checking transcripts and codes. The data and initial analysis results were returned to the interviewees to validate and revise. The findings were peer-reviewed by communicating and discussing the analytical results with key informants. Second, implementing pattern matching, explanation building and addressing rival explanations during the data analysis assisted in strengthening internal validity. Third, a case study protocol and database were created to improve the reliability. A case study protocol consisted of the overview of the case study, data collection procedures, research objectives and questions, and a tentative outline for the case study report. The case study database represented all sources of evidence using the computer-aid qualitative data analysis software NVivo12, word-processing tools (e.g. Word and Excel files), and cloud storage.

8.4 Findings

8.4.1 Building condition assessment

8.4.1.1 Initial building condition assessment

In all cases, the client representatives conducted an initial building condition assessment to support the development of the business case. In case 1, the client team undertook systematic registration of the degradation state of the building components and services. A walk-through assessment addressing the physical condition was performed during a site visit, including evaluating building structure, building services (e.g. fire, lighting, HVAC, and hydraulic systems) and building envelope (e.g. leaky building inspection, thermal performance, etc.). The results indicated that the existing building had a suitable concrete structure with seismic strengthening, however most building services needed replacing as they were at the end of their lifespan, and the thermal envelope required upgrading. Similar to case 1, the initial building assessment in cases 2 and 3 revealed poor conditions and operational problems. Particularly in case 2, the seismic building report called for urgent earthquake strengthening work to meet the Building Code requirements. A pre-refurbishment survey was also carried out to better understand the current users' activities and expectations. Table 8-3 shows an example of an initial walk-in HVAC system assessment in case 1.

Table 8-3: Example of an initial walk-in HVAC system assessment in case 1 (Source: Authors)

Areas	HVAC system				
	Ducted Preconditioned Outside Air	Ducted Return Air	Toilets AC and Exhaust	AC in Offices Teaching Spaces and Corridors	Full BMS Control
C1-Level 1	Y	Y	Y	Y	Y
C1-Level 2	Y	Y	Y	Y	Y
C1-Level 3	Y	Y	N	Y	Y
C1-Level 4	Y	Y	N	Y	Y

Note: Y: Yes – items to be replaced; N: No change

8.4.1.2 In-depth building condition assessment

After the initial building condition assessment, the consultant team (i.e. engineers, architects, sustainability and carbon consultants) in cases 2 and 3 were involved to assess the building performance and identify the

potential reuse of existing building. For instance, in case 2, “*a key aspect of this project was moving from fossil fuelled heating to an electric supplied system, while staying within the limitations of the existing electrical supply infrastructure. High level estimates were carried out during early stages to evaluate what system options would be capable of staying within the existing capacities*”, explained C2-E1. Although there was no specific energy audit done at this stage, the project team undertook several energy reviews for heating, lighting, and electricity usage. In case 3, the consultant team conducted a façade assessment study, confirming that the facades were thermally poor and weighty which could potentially cause seismic issues. Though the structural test proved that the structure could be reused despite several limitations, the building services were beyond the life expectancy. The high cost of ongoing maintenance, the replacement of services, and energy bills was expected if the refurbishment focused on upgrading the façade only. The inefficient building operation also led to higher energy use and operational carbon emissions. This is an important finding demonstrating the practical building condition assessment.

A major refurbishment level was preferably chosen for all cases, which was necessary to achieve radical improvements in energy efficiency and operational carbon reduction. Notably, case 3 was intended to be partially refurbished following initial building condition assessment. The scope of work was to extend the building lifetime to around 15 years, then demolish and build a new building. However, the results of further building assessment mentioned above called for implementing the major refurbishment, which benefited both carbon and cost aspects in the long term. This empirical finding emphasises the importance of the consultant team participating in producing a comprehensive building condition assessment, which is a basis for selecting appropriate refurbishment level and strategies as well as generating refurbishment solutions later in the process.

8.4.2 Goal setting

All cases had an overall refurbishment goal to achieve a better learning and working environment for learners, researchers, and staff, aligned with the organisations’ sustainability and net-zero carbon strategies. Table 8-4 demonstrates each case study’s specific carbon goals.

Table 8-4: Specific carbon goals of case studies (Source: Authors)

	Case 1	Case 2	Case 3
Building rating systems	<ul style="list-style-type: none"> • In-house green building standards 	<ul style="list-style-type: none"> • carboNZero Building Operations certification – a specific carbon performance tool 	<ul style="list-style-type: none"> • Green Star – a holistic sustainability certification
Energy performance target	<ul style="list-style-type: none"> • Energy Intensity Design and Performance Target after opening – 80kWh/sqm/year (based on the client’s experience with the annual energy consumption of other similar buildings within the portfolio) 	<ul style="list-style-type: none"> • As per carboNZero Building Operations certification 	<ul style="list-style-type: none"> • Targeted 6-star Green Star
Operational carbon reduction target	<ul style="list-style-type: none"> • Based on energy performance target 	<ul style="list-style-type: none"> • As per carboNZero Building Operations certification 	<ul style="list-style-type: none"> • Targeted 6-star Green Star
Embodied carbon reduction target	<ul style="list-style-type: none"> • No specific target • Qualitative-based approach such as reusing existing materials, using low carbon materials, and minimising new added-in materials and demolition waste 	<ul style="list-style-type: none"> • No specific target 	<ul style="list-style-type: none"> • Targeted 6-star Green Star

It was observed that building rating systems were suggested to be applied from the beginning stage. According to the client team in case 3, the Green Star rating system offered a structured way to incorporate sustainability criteria into the design process. Similarly, the refurbishment solutions in case 2 followed the specific operational carbon performance targets in carboNZero Building Operations certification. Using rating systems also helped prioritise the main improvement of refurbished buildings, such as energy, carbon emissions, water, etc. A critical lesson learnt in case 1 was that using the Green Star rating system might embrace low-carbon design features when experiencing unforeseen construction delays such as the COVID-19 situation that may

result in cost cutting. *“We should have had a Green Star rating on it, then some of these sustainable things would be non-touchable because people wouldn’t want to lose the points”*, C1-CR1 admitted.

However, several limitations were found in the application of these rating systems in the current practices. Regarding Green Star, cases 1 and 2 took this certification into account but decided not to adopt it due to its high cost, precise requirements and inflexibility in selecting design options: *“Sometimes, to get the points, it causes you to go down a road that doesn’t make sense for your building... instead of spending that X\$ on consultants and all the work you have to do to get a Green Star rating, we’d rather spend it on physically making the building better”*, C1-CR1 declared.

As mentioned in case 2’s design brief, there could be a tendency with the Green Star tool to put a capital cost value on points and target points based on their cost rather than the value that criteria offered. C3-PM1 echoed challenges when executing Green Star in case 3, explaining that some of the credits, such as waste management, were based on Australian standards and not applicable in New Zealand’s context. Another limitation was that this assessment method provided no detail about embodied carbon reduction targets and calculation.

In terms of carboNZero Building Operations certification, the scope of work considered only operational carbon emissions. *“Some clients and designers think going for a project that’s carboNZero certified means that they are delivering a building that uses no carbon. But that still uses loads of the embodied carbon, which is, sometimes, a larger portion than the operational carbon”*, C2-A1 stated. The tool was going through the launching process and not officially ready for use at the time of the project. There was also an unclear requirement of undertaking LCA to calculate whole-of-life carbon emissions of the refurbishment. This challenged the consultant team in targeting and quantifying the life cycle carbon performance.

In summary, the application of these rating systems in the current practice is limited to setting embodied carbon reduction targets and providing detailed calculation method. Table 8-5 describes the lifecycle carbon targets considered in the current version of building rating systems applied to cases 2 and 3.

Table 8-5: A comparison of life cycle carbon targets in building rating systems applied for cases 2 and 3

(Source: Authors)

	Green Star	CarboNZero Building Operations certification
Operational carbon emissions	<ul style="list-style-type: none"> • Awarded up to 20 points where operational carbon emissions figures were significantly lower than a standard building • Awarded 10 points if predicted operational GHG emissions reductions were >100% in comparison to the reference model (standard building) for education projects 	<ul style="list-style-type: none"> • Targeting 4 Star NABERSNZ rating or higher for all office buildings OR 8 out of 20 points (base building) or 9 out of 23 points (whole building) in the ‘Greenhouse Gas Emissions’ Credit of Green Star Performance • Demonstrating a carbon reduction plan for the building to phase out fossil fuel consumption on site by 2025 • Offsetting the remaining operational carbon by purchasing carbon credits
Embodied carbon emissions	<ul style="list-style-type: none"> • Awarded embodied carbon credits for the use of materials that were responsibly sourced, transparency and lower embodied impact over their life • No detail about embodied carbon reduction targets and calculation 	<ul style="list-style-type: none"> • No specific target

Due to the limitation of mentioned building rating systems, setting an embodied carbon budget as a necessary project deliverable was suggested by the participants in cases 2 and 3, though faced complications due to the lack of compulsory national targets and diversity of the building stock. From experience in case 2, C2-QS2 said, “*defining what reasonable targets should be... the target or a budget, how much carbon can we use on this project?*”. The lack of compulsory carbon reduction targets in New Zealand led the consultant team to refer to various standards on embodied carbon reduction overseas to compare against the actual carbon performance in case 3. However, critics questioned the feasibility of setting an equal allocation of carbon reduction for the existing building stock. “*If you divided the target on square meters, you’d find that some buildings work and others don’t. Some buildings can be delivered more than others. We should not try to be too prescriptive about any individual building but take a holistic view of the whole portfolio*”, C3-CR1 argued.

Importantly, the carbon budget for the refurbishment should be different from the figure for new buildings. As C2-SC1 believed, “if lifecycle carbon is *X kilograms per square meter*. You’re refurbishing a building, and it’s easier to hit those targets than building a new building... But you can still do a refurbishment in a high carbon way. You could do heaps of shading and fins, and there’s a lot of aluminum”.

Interestingly, the consultant team in case 3 suggested that there should be a specific financial budget for carbon-reduction solutions established in the goal setting to avoid unexpected costs and limiting the consideration of lower carbon options later in the process. “We need to find a budget for carbon and sustainability”. The budget should include the additional cost of reviewing carbon-reduction initiatives, energy modelling, life cycle assessment, and possible investment costs for low-carbon materials, products, and green technologies. Although these approaches supported making informed decisions on reducing carbon emissions, clients still faced challenges around their willingness to spend additional money on these services. “They have values, but sometimes it is hard to demonstrate them to clients”, said C3-E2.

8.4.3 Refurbishment strategies

Identifying refurbishment strategies was crucial as it set out the plan of action to achieve an overall long-term aim of refurbishment projects. The refurbishment strategies that were considered in case studies are illustrated in Table 8-6 and Figure 8-3.

Table 8-6: Refurbishment strategies considered in case studies (Source: Authors)

Case 1	Case 2	Case 3
<ul style="list-style-type: none"> • Refurbishment proposals as follows: <ol style="list-style-type: none"> (1) Passive Design (2) System efficiencies (3) Environmentally friendly local-preferred materials and equipment (4) Reuse existing construction materials (5) Efficient waste management (6) Renewable energy generation 	<ul style="list-style-type: none"> • A top-down refurbishment strategy includes (see Figure 8-3): <ol style="list-style-type: none"> (1) Extent of building (2) Passive and embodied design (3) System efficiencies (4) Renewable energy generation 	<ul style="list-style-type: none"> • A carbon reduction strategy includes: <ol style="list-style-type: none"> (1) Incorporate industry-leading “passive house” design principles, (2) Adopt an “ultra-low energy” mechanical ventilation system (3) Use low-carbon and locally sourced materials (4) Reuse the existing structures (5) Minimise waste (6) Use renewable energy technologies

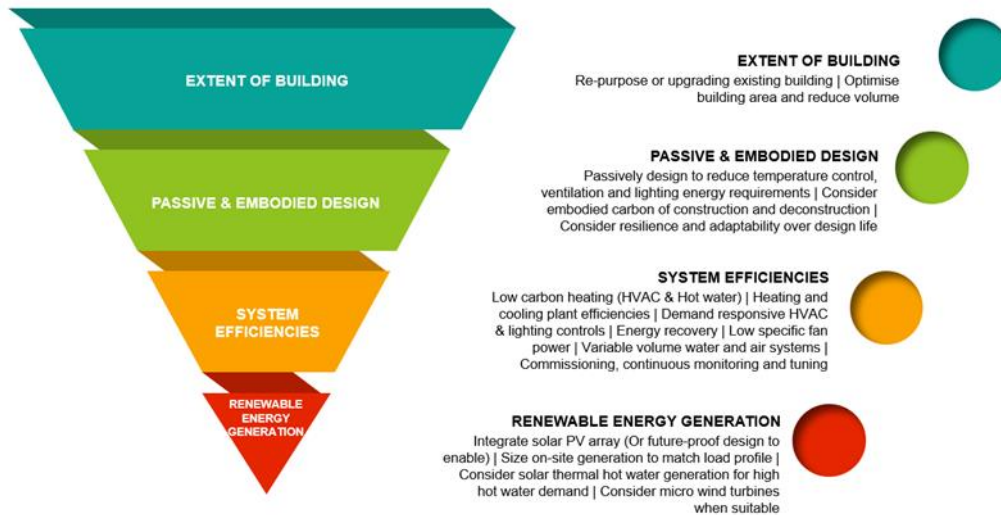
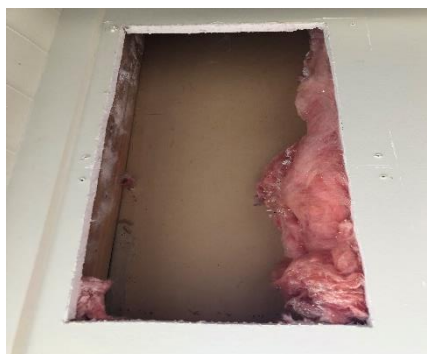


Figure 8-3: Hierarchy of low carbon building design approach in case 2 (Source: Authors)

The findings revealed that passive design strategies were chosen as a primary refurbishment solution over system efficiencies and renewable energy generation. It was stated that the preference for passive design solutions resulted in the efficient use of building services systems, fewer construction materials, and cost savings. However, the consultant team in case 1 expressed challenges and difficulties when prioritising passive design. It was thought that upgrading the insulation system using phase change materials to a higher standard might be unnecessary as it was not beneficial to the performance and were a cost premium. “For elements like that, if you took half \$X of phase change materials out and put in half \$X of photovoltaic generation. Your overall carbon footprints can be significantly reduced”, said C1-E1. Figure 8-4 illustrates examples of refurbishment strategies in case 2.



a) Passive design (windows)



b) Passive design (wall insulation)



c) Reuse (reused stair)

Figure 8-4: Examples of refurbishment strategies in case 2 (Source: Authors)

Renewable energy technology such as PV systems was selected in case 1 and case 3 as a long-term strategy for optimum energy generation on site and feed-in national grid towards a net-zero carbon future. A large solar array was a part of the refurbished building, expected to deliver about 10% of the overall electricity usage in case 3. In contrast, an off-site PV system was not implemented during the refurbishment due to the budget constraint in case 1. Yet, the off-site infrastructure was prepared for future installation. However, the perception of “must-have” renewable technologies as a showcase of zero carbon initiatives was perceived in these cases. The consultant team acknowledged that a PV system was included to improve energy generation and public perception, notwithstanding the performance analysis showing the high carbon and cost payback period in the New Zealand context, where the electricity grid is relatively green. *“It seems that unless you stick solar panels on the roof, people can look and say: that’s pretty cool, and you must be sustainable now”*, C3-E1 claimed. Both wind turbine and PV system were considered in case 3’s design brief. The consultant team convinced the client not to install the wind turbine based on the performance analysis and lessons learnt from case studies in other countries such as the UK. However, the PV system was still enforced to showcase sustainable design elements.

In all cases, strategies to reduce embodied carbon emissions from construction materials and products were employed. For example, existing building components and materials were recycled and reused. In particular, materials with high embodied carbon such as steel and aluminium were obtained locally in cases 1 and 3, as New Zealand was expected to produce approximately 80-90% of its electrical supply from renewables. Conversely, construction materials and products used in case 2 were primarily sourced from countries outside of New Zealand, such as China, Europe, and America.

8.4.4 Generation of refurbishment alternatives

8.4.4.1 Initial production of refurbishment alternatives

For case 1, the consultant team appraised the refurbishment strategies and alternatives identified in the client’s high-level brief, which was established based on the results of building condition assessment. The brief encompassed refurbishment strategies and a comprehensive list of potential refurbishment options that required the consultant team’s acceptance. A narrow range of possibilities had to be generated from the brief, limiting the consultant team to the creative and innovative design.

Cases 2 and 3 differed from case 1 in developing refurbishment alternatives. The refurbishment alternatives lay with the consultant team and were aligned with the client's objectives and requirements. In case 2, the consultant team supported the client consider potential refurbishment alternatives. An expansive list of Environmentally Sustainable Design (ESD) opportunities was classified following the results of building condition assessment and refurbishment strategies. Each opportunity was identified as either a "must-have" or "nice-to-have" item and evaluated subject to value-added project cost and the alignment with the requirements of relevant building rating systems. This approach has not been widely recognised in the literature. Likewise, the consultant team in case 3 also identified various design opportunities such as energy-efficient façade and different types of building services, following the client's sustainability objectives.

8.4.4.2 *Qualitative assessment of refurbishment alternatives*

After the initial evaluation, a qualitative approach was used to narrow down the refurbishment options in all cases. With respect to carbon reduction, the consultant team in all cases assessed design implications using experience, heuristics, qualitative estimation of carbon performance, consulting and partnering with other project team members such as client representatives and cost advisors. The engineers conducted the qualitative measure of building design performance while the architects considered the architectural design aspects. In all cases, a narrowing set of refurbishment options was selected by the end of this stage and different refurbishment alternatives were generated.

There were important recommendations for future work observed in cases 1 and 3. A lesson learnt from case 1 was that an initial carbon analysis could be performed at this early stage using LCA tools, which provide generic carbon impacts of different building elements, to recognise carbon-intensive elements and their trade-offs between operational and embodied carbon emissions. Replacing the glazing was an example. As explained by C1-A1, using the double-glazed façade increased embodied carbon emissions while there was little payback in terms of thermal comfort and operational carbon performance in some typical building locations. From experience on case 3, the consultant team suggested that an initial carbon analysis should be performed early to identify refurbishment alternatives, which they then discussed with project partners before selecting the key options carried through the design process. External carbon specialists were contracted to provide independent peer reviews on the embodied carbon impacts of potential design opportunities. "*We did have some discussions*

early on in the project because obviously, you don't need a comprehensive LCA to quantify the embodied or operational carbon that is essentially going to be spent on a construction project", said C3-SC1.

8.4.5 Performance estimation and evaluation

After qualitative assessment, the carbon performance of refurbishment alternatives was quantitatively estimated and evaluated by undertaking energy performance assessment, life cycle carbon assessment, cost benefit analysis as well as adopting an early contractor involvement approach. Table 8-7 demonstrates a comparison in the use of assessment methods and approaches in case studies.

Table 8-7: A comparison in the use of assessment methods and approaches in case studies (Source: Authors)

	Energy performance assessment	Life cycle carbon assessment	Early contractor involvement (ECI) approach	Cost benefit analysis
Case 1	<ul style="list-style-type: none"> • Use building energy modelling tool to evaluate the operational energy and carbon of refurbishment alternatives 	<ul style="list-style-type: none"> • Use LCA tool to quantify the life cycle carbon emissions of the whole refurbished building at the end of the design phase as a retrospective analysis to extrapolate learning for future work 	<ul style="list-style-type: none"> • Use ECI approach to evaluate the quality and buildability of low-carbon design and technologies • Mitigate construction waste that went to landfill • Identify the potential for construction materials reuse and recycling 	<ul style="list-style-type: none"> • Use cost benefit analysis to identify the most cost-effective refurbishment alternatives
Case 2	<ul style="list-style-type: none"> • Same as case 1 	<ul style="list-style-type: none"> • Not applicable 	<ul style="list-style-type: none"> • Not applicable 	<ul style="list-style-type: none"> • Same as case 1
Case 3	<ul style="list-style-type: none"> • Same as case 1 	<ul style="list-style-type: none"> • Use LCA tool to quantify the life cycle carbon emissions of selected refurbishment alternatives to further improve the design in detail 	<ul style="list-style-type: none"> • As same as case 1 • Support the selection of construction products and materials (e.g. providing embodied carbon emissions information) 	<ul style="list-style-type: none"> • Same as case 1

8.4.5.1 Energy performance assessment

Energy simulation was conducted to assess building performance and operational carbon impacts. The engineers, in all cases, conducted a quantitative analysis using building energy modelling to evaluate refurbishment alternatives regarding their energy and operational carbon performance. In addition, thermal comfort analysis and daylighting analysis were also performed to quantify the refurbishment solutions' comfort and well-being benefits. Energy consumption was calculated using thermal load and energy modelling software, IES Virtual Environment. Based on the energy model, annual operational carbon emissions were calculated using the emissions factors according to the Ministry for the Environment “Measuring emissions: A guide for organisations – 2019 detailed guide”. Taking case 2 as another example, five refurbishment alternatives were modelled based on the set of refurbishment options – these options were divided into two general categories: façade and HVAC system upgrades. The comparison of annual operational carbon emissions between alternatives is illustrated in Figure 8-5.



Figure 8-5: Annual operational carbon emissions of case 2 (Source: Authors)

8.4.5.2 Cost benefit analysis

The cost benefits of several refurbishment options were also compared in all cases, considering several indicators such as capital cost, annual savings, payback period, Net Present Value (NPV), and Internal Rate of Return (IRR). In particular, the LCC of building services was reviewed to determine the most cost-effective options. For example, C3-SC1 explained the case 3 situation, *“We ran design options out on 30-year whole-of-life cost model. We looked at the upfront capital costs and the various replacement costs during the life of this equipment. The central plant, for example, might only last 15 to 20 years before it needs to be replaced. Those costs were tabulated into a net present value (NPV) for each system. That was then used to identify the least costly option from a whole of life perspective”*.

8.4.5.3 Life cycle carbon assessment

A comprehensive LCA using Etool LCD was adopted in cases 1 and 3 to assess the carbon performance from a cradle-to-cradle perspective. eTool is the primary Australian-based tool to conduct the LCA study of building and infrastructure projects. The original tool was launched in 2012 with Australian and international Life Cycle Inventory (LCI) databases. Its reports are compliant with international standards EN 15978 and ISO 14044. Although eTool’s materials products database includes the Australian and New Zealand representative bodies for LCA, its design benchmarks and strategies, such as buildings for different primary construction uses, are mainly based on national Australian statistics data.

In case 1, the architects commissioned an external carbon specialist to quantify the life cycle carbon emissions of the refurbished building at the end of the design phase. However, the results did not contribute to the design improvement because this was a retrospective analysis to extrapolate learning for future work. While in case 3, the consultant team conducted LCA to estimate the carbon impacts of selected refurbishment alternatives, which were then reviewed and certified by the external carbon specialist. *“We used the LCA to validate our approach in the later design stage rather than identify different variations and options that we knew from a qualitative perspective was the right thing to do. This was providing that quantitative analysis to support that”*, C3-SC1 argued. The result from LCA was a baseline to improve the design in detail, such as comparing operational carbon emissions of different building services and considering embodied carbon emissions of construction materials and products through New Zealand’s specific Environmental Product Declarations

(EPD) database and some benchmarks based on relevant research provided by the Building Research Association of New Zealand (BRANZ). This original finding emphasises the necessity of using LCA tools in the early stages of the decision-making process to identify carbon hotspots and improvement opportunities.

8.4.5.4 Early contractor involvement (ECI)

The early contractor involvement (ECI) approach was employed in the design phase to evaluate selected refurbishment options in both case 1 and case 3. It was used to gain early advice and participation from subcontractors and suppliers in the buildability and optimisation of designs. In case 1, the subcontractors produced four trial windows with various double-glazed specifications to examine the quality and buildability. This activity helped ensure the feasibility of refurbishment solutions from a supply chain perspective as low-carbon design and technologies were innovative in New Zealand's construction supply chain. In case 3, the suppliers supported selecting construction products and materials by providing embodied carbon emissions information. The ECI approach also assisted in mitigating construction waste that went to landfill and identifying the potential for construction material reuse and recycling.

As the design continued to be improved, evaluation of refurbishment alternatives was carried out continuously and iteratively throughout the design process. Particularly for cases 2 and 3, selected refurbishment alternatives were assessed based on the design requirements of building rating systems. Energy performance assessment, life cycle carbon assessment, and other analyses such as thermal comfort and daylighting were constantly reviewed and demonstrated in design reports at the end of each design stage. It was important to note that embedding sustainability and carbon impacts with the design reports could drive the design decision and overcome the financial tensions of selecting low-carbon design characteristics. *“Our design reports, especially in the early phases, we're making a comparison of options. We will comment and indicate what's sustainable and the impact on sustainability from the operation and, in some cases, embodied carbon. It's a holistic approach to avoid criticism when people think that's not a value management item and delete to save some money”* claimed C1-E1.

8.4.6 Other factors affecting carbon-reduction decision making

8.4.6.1 Funding and incentives

Another important finding was that all cases received the government's financial support, encouraging decarbonisation decisions. Both cases 1 and 2 sought government incentives to facilitate the implementation of the low-carbon design. The projects received finance assistance from EECA's State Sector Decarbonisation fund to reduce carbon emissions. The government investment helped replace natural gas boilers and chillers for space heating and cooling with low emission alternatives and install efficient lighting in case 1. Whereas the grant empowered case 2 to adopt a high-performing façade as part of the refurbishment solutions, contributing to further operational carbon reduction. *"We've received a grant of \$2 million that enables us to bridge the gap between the different things that would achieve a net-zero carbon"*, said C2-CR1. An energy efficiency report, including energy modelling and performance analysis, was produced to justify carbon-reduction decisions.

On the other hand, case 3 secured the "shovel-ready" government funding to stimulate the construction and environmental industries and economy, public or regional benefit, and create jobs in response to COVID-19. The large-sized refurbishment provided an essential boost for the local building and construction industry through a locally-based and sourced construction supply chain. The fund permitted the project to incorporate industry-led practices and carbon-reduction refurbishment options.

8.4.6.2 Supply chain and data availability

Supply chain availability was acknowledged in the research findings as a tension that inhibited the decision on low-carbon designs and technologies, as mentioned in case 3. There were few alternatives to low-carbon products within New Zealand's construction supply chain, such as curtain walling and PV systems. The traditional façade manufactured in New Zealand was carbon-intensive aluminium frame compared to state-of-the-art timber frame produced overseas. According to C3-QS1, only two different PV systems were available in New Zealand, also sourced from other countries. With New Zealand's electricity grid being comparatively green, installing these PV systems in New Zealand might lead to a much longer carbon payback than in Australia.

Concerns were also expressed about the carbon data availability for the New Zealand building and construction industry, especially data related to construction products and materials. While some of New Zealand's construction manufacturers have provided EPD's products such as cement and insulation, many gaps existed in other areas that should be addressed in future work. Furthermore, as part of the LCA analysis, C3-SC1 claimed an inadequate benchmark for large commercial buildings. *"We had to build a reference building to compare ourselves against, and part of that process was coming up with a counterfactual"*. Many assumptions were made during the LCA process, which affected the carbon calculated and quantified results.

8.5 Discussion

This chapter examines the practical early-stage refurbishment process that incorporates decisions on maximising carbon reduction. This process is considered to be a way of developing and implementing building refurbishment towards zero carbon. The chapter investigates *what*, *how* and *why* carbon-related decisions are made in three case studies. In doing so, we acknowledge that the refurbishment decision process in the practical context is in line with theoretical frameworks. However, the empirical analysis has uncovered unexpected outcomes, tensions and lessons learnt that emerge from the three processes studied. This section discusses these aspects based on the literature and a cross-case analysis among three case studies.

The first important finding is in line with the previous studies (Ma et al., 2012; Nielsen et al., 2016), confirming that building rating systems can be used early as a structured methodology to incorporate carbon performance criteria into the refurbishment process. These rating systems support the decision-making process by providing a direction for setting goals, prioritising objectives and specific areas of improvement, and their potential design implications. The decision to use these rating systems in the early stage rather than assessing the finished building encourages the project team to incorporate the carbon-reduction design consideration throughout the process. However, our findings emphasise that using these rating systems might create inflexibility in the selection of refurbishment design solutions. These systems are also time-consuming to include in the early stages of the refurbishment process and are limited to recognising project values (e.g. cost benefits, co-benefits for users). Thus, there should be a more effective way to apply these rating systems in building refurbishment. The study suggests that the refurbishment solutions' actual critical benefits should be identified separately to align with the project's specific targets. These benefits can then be considered alongside

the design requirements of rating systems, rather than using these rating systems as a framework to inform refurbishment design approaches.

The study also identifies another limitation of applying building rating systems to determine the carbon reduction goal for building refurbishment in practice. Most of the rating systems fail to prioritise whole-of-life carbon reduction targets and the assessment approach to whole-of-life carbon reduction is mainly qualitative (e.g. using low-carbon materials) at the time the research is being conducted. This finding highlights a need for setting whole-of-life carbon reduction goals, especially specific embodied carbon reduction targets and calculation methods for the refurbishment of existing buildings. The observation of studied cases is in line with Chandrakumar et al., (2020)'s; Bui et al., (2021b)'s; Bullen et al., (2021)'s suggestion, which call for the use of scientific climate change targets and a carbon budget to define the life cycle carbon performance goal. Although there are carbon budgets for new buildings in New Zealand, the study suggests that a bespoke carbon budget for existing buildings is needed. This is due to the scope of LCA assessment of refurbished buildings differs from that of new buildings (Vilches et al., 2017; Hasik et al., 2019). Furthermore, using the carbon budget for new buildings (Chandrakumar et al., 2020) as a reference could encourage refurbishing existing buildings in a high carbon way. For example, a major refurbishment considers retaining the existing building structure, resulting in a large amount of carbon savings. But it still uses carbon-intensive construction materials such as steel, aluminum, phase change materials, refrigerants, and carpets, etc. for other building components such as windows, façades, services and equipment, and internal finishes. Although the total carbon emissions of a refurbished building may be lower than that of a new building and within the carbon budget of a new building, it may prevent the practice of identifying lower carbon refurbishment options in each building element category to achieve overall maximum carbon reduction. Moreover, it is important to note that the carbon budget should be allocated based on the potential carbon reduction of each refurbished building as well as the level of refurbishment ranging from partial to major refurbishment. A carbon budget should be allocated for an existing building portfolio instead of individual existing buildings. From there, building owners could evaluate and establish feasible targets for every single building. These observations have not been adequately recognised in literature. In addition to the carbon budget, a specific financial budget is suggested as an allowance for carbon-reduction refurbishment solutions to avoid unexpected costs in reviewing carbon-

reduction initiatives, energy modelling, LCA, and upfront investment costs for low-carbon construction materials and products, and green technologies, subsequently limiting the consideration of lower-carbon options later in the process. However, it could create potential bias, especially from the client's perspectives, carbon-reduction solutions are associated with higher cost, leading to the reluctance in making decarbonisation decisions.

Another significant issue that emerges from empirical findings is using a reference building as benchmark in the current LCA practices. The choice of the reference building determines to some extent the carbon performance of the selected building design. For example, the building is x% better than the reference building, which is usually a standard building that meets the minimum requirements of the Building Code. For refurbished buildings, it may not be comparable to benchmark against a new standard building. Therefore, the real test should be how the refurbished building performs against its carbon budget or the aim to achieve near or zero carbon emissions. For example, Asdrubali et al. (2019) compared the carbon performance of an optimal refurbishment against two refurbishments for achieving the NZEB standard. This approach can support the project team to conduct a comparative life cycle carbon reduction analysis for the optimisation of the building design.

There are similarities between the empirical findings of building condition assessment in this study and those described in the literature. In a building refurbishment, building condition assessment are used to benchmark building energy use, recognise the degradation state of building components and services, identify operational problems, and find appropriate refurbishment solutions (Ma et al., 2012; Ferreira et al., 2013). At this stage, a pre-refurbishment survey is also recommended to better understand the current users' activities and expectations (Nielsen et al., 2016). However, the results of the present study underline a requirement for an in-depth building condition assessment to help (1) establish the refurbishment level (e.g. partial or major refurbishment); (2) acknowledge life cycle carbon and cost benefits; and (3) set out appropriate long-term refurbishment strategies (e.g. site preparation for future installation of renewable technologies). In terms of refurbishment strategies, the findings somewhat support the idea of a hierarchical approach towards zero carbon refurbishment, which prioritises refurbishment strategies in the following order: (1) retrofit fabrics, (2) more efficient equipment, (3) micro generation (Xing et al., 2011). Nevertheless, the study proposes that there

needs to be a flexible approach to implementing passive design, efficient building services and renewable technologies that are appropriate to the physical condition of the existing building and project budget. Performance assessment and feasibility studies are required to understand trade-offs and the advantages and disadvantages of renewable technologies before making a decision that prioritises overcoming public perception. Other important strategies found in this study include prioritising local materials, using low-carbon materials, maximising reused and recycled materials of existing buildings, which should be considered to reduce embodied carbon emissions.

Many decision support systems are available in the literature for the generation of refurbishment alternatives, performance estimation and multi-objective optimisation in the design phase of the refurbishment process (Loli & Bertolin, 2018; Hashempour et al., 2020; Bui, Domingo, et al., 2022). However, these do not appear to be used in the real-life cases studied. A possible explanation is that the existing decision support systems might not be commonly employed in the construction market. Using complex simulations and generic algorithms to support the decision-makers in selecting the best refurbishment solutions could sideline the strength of real-world experience-based knowledge and team collaboration in the process. Incorporating the existing knowledge and industry practices, the findings from this study suggest a better approach to the generation of refurbishment alternatives and performance estimation and evaluation. First, a wide range of potential refurbishment options should be considered following project goals, objectives, and client requirements in the generation of refurbishment alternatives. The intention is to include all possible refurbishment options in the decision-making at each stage of the design and encourage creativity and innovation in choosing refurbishment options. Then, refurbishment options can be selected using experience, heuristics, lessons learnt from global case studies, qualitative estimation of carbon performance, and consulting or partnering with other project team members. In New Zealand, several simple LCA tools (e.g. LCAPlay), complex LCA tools (e.g. LCAquick, eTool) and carbon database tools (e.g. CO₂NSTRUCT) which provide generic carbon impacts of different building elements, are suggested to be used for initial life cycle carbon assessment. After that, methods including comprehensive computer-aided energy simulations, LCA and financial analysis are used to quantitatively examine carbon performance and continually improve the design, which is in line with Asdrubali et al. (2019)'s recommendation.

The present results are significant in offering new perspectives on the way of implementing building refurbishment towards zero carbon. Holistic design reports that show the decision on carbon reduction solutions aligned with project values should be presented to overcome the financial restrictions. The Early Contractor Involvement (ECI) approach allows the project team to understand the requirements of implementing innovative low-carbon designs and technologies and gain insight into embodied carbon emissions of construction materials and products early. Government funding and incentives are essential, enabling the maximum carbon reduction for refurbishment projects. The grant assists the building stakeholders to achieve the required operational carbon performance targets by implementing cost-effective refurbishment measures and reducing the financial payback period. There is still abundant room for further progress in improving the supply chain and data availability that affect the selection of low-carbon products and the carbon calculated and quantified results.

The study reports on the decision-making process of three major building refurbishments where the decision to refurbish existing buildings has apparently been taken by the time the more detailed work is done. This can be explained by the fact that the decision to refurbish versus demolish and build a new building was preferred due to several factors such as building vacancy, refurbishment prospects, time and cost savings and carbon reduction benefits. Demolishing and rebuilding could be time-consuming and expensive due to building locations and the limited timeframe of occupant relocations. Repurposing the usable existing building components, on the other hand, might reduce the length of construction by years, saving significant construction costs and minimising construction materials and construction waste. However, in practice it may be dependent on the specific project and such decisions would be considered at very different stages. Sometimes, the decision is made without an in-depth analysis due to strongly held pre-assumptions about project outcomes or preferences. In other cases, the decision is determined by thorough consideration of the evidence for and against. It is suggested that an opportunity for further work assessing the decision to refurbish or demolish should be undertaken and the impact of the decision should be critically evaluated. Decisions made without in-depth analysis may not necessarily be the most appropriate ones in terms of sustainability (Baker et al., 2017).

8.6 Conclusion

This chapter examines decision making in reducing carbon emissions in the early stage of refurbishment. The investigation has identified carbon-reduction decisions and critical factors supporting these decisions in the refurbishment process of three case studies. First, the field data revealed that using building rating systems is inflexible in the selection of refurbishment design solutions, time-consuming to include in the early stages of the refurbishment process and limited to recognising project values (e.g. cost benefits, co-benefits for users). Therefore, the study proposes an effective use of building rating systems, which should integrate carbon performance criteria, the client's requirements, and stakeholder's values to recognise the actual benefits of refurbishment solutions. Second, the findings report on the lack of determining the carbon reduction goal for building refurbishment in practice. These targets are required to be established for whole-of-life carbon assessment, benchmarking, and the optimisation of the refurbishment design. Thus, the study suggests that setting whole-of-life carbon reduction targets for refurbished buildings is imperative. Third, the findings highlight the implication of the specific financial budget for carbon-reduction initiatives, which encourages the consideration of lower-carbon refurbishment options. However, further investigation is required to identify the extent that this specific financial budget for carbon-reduction initiatives could potentially stimulate decarbonisation decisions from different perspectives. Fourth, the empirical findings have shown several limitations in practical building condition assessment. The need for implementing flexible, appropriate, and long-term refurbishment designs and strategies that are appropriate to the physical condition of an existing building and project budget is therefore emphasised. Fifth, incorporating the findings from existing knowledge and industry practices, the study suggests a better approach to the generation of refurbishment alternatives and performance estimation and evaluation with a new insight into the use of decision support mechanisms in the refurbishment process, which strengthens the idea that real-case experience-based knowledge and team collaboration should be considered. Finally, the results highlight the significance of several aspects in delivering refurbishment projects towards zero carbon, including holistic design reports, ECI approach, government funding and incentives, and supply chain and data availability. These aspects are significant in better delivering building refurbishment towards zero carbon.

This work contributes to existing knowledge of the decision-making process of building refurbishment towards zero carbon by investigating three refurbishment projects in practice that adopt similar and different approaches to reducing carbon emissions. The novelty of this research is providing the practical knowledge of the decision-making process with existing challenges in making decarbonisation decisions and adopting decision support mechanisms, and suggestions for improvement that expand the theoretical knowledge and bridge the gap between theory and practice. The findings will be of interest to practitioners and researchers who wish to expand their knowledge and experience in life cycle carbon analysis and performance estimation for refurbishment projects. The decision-making process revealed in this study can be a benchmark for comparable projects and studies. In exploring the current decision-making practices, the findings of this study have several important lessons to better deliver building refurbishment towards zero carbon for future practice.

The generalisability of these results is subject to certain limitations. The most important limitation lies in the fact that the paper is reliant on interviews and the views of participants provide the foundation of the conclusions. Such interviews can be misleading in terms of how decisions were actually made, with an element of post hoc justification. Notwithstanding, reflection and lessons learnt are still valuable for continuous improvement in decision-making for future refurbishment projects. It is unfortunate that the study has not been able to include the decision to refurbish or demolish existing buildings in detail. This is an important issue for future research. The research also focuses mainly on major refurbishments for university buildings in New Zealand, in particular projects which received funding from the government. Future research should include other types of buildings and levels of refurbishment (e.g. a partial refurbishment) in different locations and context. In addition, the study is limited by the lack of information on external validity. Further work needs to be done to validate the research results in the broader building and construction sectors.

9 Chapter 9: Collaboration and integration towards zero carbon refurbishment: A New Zealand case study

This chapter is based on the following Journal article, which has been published in final form.

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Abstract

Due to the increasing complexity of reducing carbon emissions for existing buildings, there is a need for a more collaborative and integrative approach in the refurbishment decision-making process. Extensive research has shown the importance, benefits, and challenges of collaboration and integration in implementing sustainable buildings. However, limited research report on collaboration and integration in refurbishment projects that focus on reducing life cycle carbon emissions. In line with Chapter 8, this chapter explores the collaboration and integration in the decision-making process towards zero carbon refurbishment through the investigation of three real-life case studies in New Zealand. The findings resulted from an interactive cross-case analysis using replication logic within and among cases. Empirically, the chapter emphasises the importance of (1) organisational commitment and compatibility of team members, (2) the timely involvement of key stakeholders, (3) the highest level of integration in the design process, and (4) a centralised and integrated information system. The chapter also divulges the current practices and challenges faced in the integration process, where lessons learnt are identified for future refurbishment projects. A collaboration and integration framework towards successfully delivering refurbishment projects towards zero carbon is proposed. The research implications may assist the real-world uptake of the zero carbon refurbishment approach by promoting effective collaboration and integration.

9.1 Introduction

Reducing global warming to no more than 1.5 degrees and achieving net-zero GHG emissions is crucial to avoiding catastrophic climate change impacts (IPCC, 2014). The design and construction of buildings have

been identified as the greatest opportunity within the building and construction industry to reduce carbon emissions (United Nations, 2009). To date, the zero carbon buildings approach is an innovative model of sustainable development for reducing carbon emissions, reducing climate change impacts, and elevating the quality of people's lives (Pan & Pan, 2021). Implementing a zero carbon buildings approach means maximising carbon reduction throughout a building's life cycle (Bui et al., 2021c). To achieve the highest zero carbon level, building stakeholders must adopt innovative low-carbon designs that integrate smart facades, ventilation, and surface heating and cooling to achieve low to zero energy (Jones et al., 2015). Another key strategy is to increase the use of alternative construction materials with lower embodied carbon such as new bio-based materials (Gieseckam et al., 2014). Furthermore, the carbon emissions of locally generated energy from renewable sources, such as photovoltaic (PV) panels, solar thermal, and heat pump must counterbalance the embodied emissions from materials (Moschetti et al., 2019).

Maximising carbon reduction through the refurbishment of existing buildings offers great potential for achieving the net-zero carbon target by 2050. In New Zealand, for example, existing residential buildings are forecast to account for an estimated 65% of the total climate impact between 2018 and 2050, while new buildings make up the remaining 34% (Chandrakumar et al., 2020). The carbon emissions related to the development of the building stock can be addressed by imposing strict requirements for new buildings. Achieving carbon-reduction goals for existing buildings, however, remains a challenging task. Therefore, this research deliberates on zero carbon refurbishment (ZCR), which is the refurbishment of existing buildings that attain the highest level of whole-of-life carbon reduction.

The increasing complexity of applying innovative low-carbon design in building refurbishment calls for a more collaborative and integrative approach. For instance, integrating innovative technologies, such as energy generation with energy storage, mixed-mode ventilation and heat recovery in existing building structure and envelope, requires interaction and the seamless flow of information between different disciplines (i.e. engineering and architecture) and actors (i.e. project team members and the user group). A high level of collaboration and integration, ideally extending over several building projects, therefore, is a mechanism for facilitating the sharing of information, resources, and knowledge in radical and incremental low-carbon design and construction processes (Kesidou & Sovacool, 2019). Collaboration is a creative process undertaken by

two or more interested individuals who share their collective skills, expertise, understanding, and knowledge in an atmosphere of openness, honesty, trust, and mutual respect to jointly deliver the best solution that meets their common goal (Wilkinson, 2005). Collaboration is a primary element in the integration concept, which contains not only the notion of collaboration but also the “unification” of separate parts and the act of “making a whole” (Moharana et al., 2012).

In reviewing the literature, many studies have been published on collaboration and integration in building projects, demonstrating their beneficial impact, identifying the importance of collaborative and integrative aspects that improve building performance and successful project outcomes, and determining challenges for collaboration and integration (Rahman et al., 2014; Le et al., 2022). However, recent research has focused on collaboration and integration in sustainable buildings within the general context of holistic sustainability rather than the specific area prioritising maximum carbon reduction (Azari & Kim, 2016; Kesidou & Sovacool, 2019; Leoto & Lizarralde 2019a). In addition, a detailed investigation of collaboration and integration towards delivering ZCR projects worldwide is still lacking (Bui, Domingo et al., 2022). This chapter fills the gap by exploring collaboration and integration in the early-stage decision-making process towards ZCR. Three real-life case studies in New Zealand were investigated to reveal the current practices and challenges faced in the refurbishment process. The findings propose lessons learnt and a collaboration and integration framework for successfully delivering future ZCR projects. The chapter is organised into six sections, including this introduction. Section 9.2 reviews the literature on ZCR research and the characteristics of and approaches to collaboration and integration. Section 9.3 describes the research method, followed by section 9.4, which reports empirical findings from the case studies. Section 9.5 presents a discussion that emerged from cross-case analysis and interpretation and the proposed collaboration and integration framework. Section 9.6 summarises research implications, limitations, and recommendations.

9.2 Literature review

9.2.1 Carbon reduction in the refurbishment process

Since refurbishing existing buildings provides a better carbon-savings opportunity than constructing a new build, the existing literature on the ZCR field is extensive and focuses particularly on the refurbishment

strategies in advanced technologies, design evaluation and optimisation for ZCR. Recent comprehensive and critical reviews of ZCR literature are found in Bui et al. (2021b); Bui, Domingo, et al. (2022). Here, the main themes in this research context are summarised

The refurbishment process is assumed to be similar to the new building process, including pre-design, design, construction, and operation phases. However, the main difference is that a preliminary investigation of the existing building is the basis for developing design solutions in the refurbishment process, whereas a new building has the building site as a foundation. The existing building design, condition, performance, and users are critical considerations for existing buildings (Jensen, Maslesa, Berg, et al., 2018). The decision-making process for the refurbishment incorporates the following steps (1) building condition assessment, (2) goal setting, (3) refurbishment strategies, (4) generation of refurbishment alternatives, (5) performance estimation and evaluation, (6) optimal selection of refurbishment alternatives, (7) detailed project design, (8) construction, (9) operation (Ma et al., 2012; Ferreira et al., 2013; Nielsen et al., 2016). It is important to note that decisions regarding carbon reduction for the refurbishment are mainly made in the early stages of the process (i.e. from step 1 to step 6) (Vilches et al., 2017; Bui et al., 2021b).

Two main opportunities for reducing carbon emissions in building refurbishment include operational and embodied carbon emissions. Improving building energy performance via upgrading energy-efficient systems, implementing passive design, and installing renewable energy technologies may be the most effective and common measure to reduce operational carbon emissions (Jones et al., 2015; Loli & Bertolin, 2018). An integrated system upgrade package including windows, energy-efficient building services, occupant demand control ventilation, energy monitoring, which is widely implemented, can result in significant energy consumption reduction compared to standard practices (Gultekin-Bicer et al., 2018; Rabani, et al., 2021). However, this approach requires embodied-carbon-intensive materials and systems that increase the lifecycle carbon of refurbished buildings (Ghose et al., 2017; Asdrubali et al., 2019). For example, installation of systems for on-site renewable energy generation further increases the embodied carbon of the refurbished building. Moreover, while a refurbishment prolongs the building's service life, it is often still shorter than that of a newly built structure, so the upfront embodied carbon expenditure may be disproportionate to the savings in operational carbon gained over the remaining life (Opher, et al., 2021). Thus, maximising the use of

alternative materials with lower embodied carbon, reused and recycled building components and materials are critical for refurbished buildings (Gieseke et al., 2014; Moncaster et al., 2019). The refurbishment of existing buildings must consider whole-of-life embodied carbon reduction of building materials and products, alongside operational carbon reduction associated with energy use (Bui, Domingo, Wilkinson, et al., 2022).

Several studies have examined the barriers to refurbishing existing buildings that focus on improving energy efficiency and carbon reduction worldwide. Davies and Osmani (2011) investigated the key challenges for achieving ZCR in England from architects' perspectives, including high capital costs for micro-generation technologies and energy-efficient materials, the disparity in tax between new build and refurbishment, and the complexity of the UK's existing building stock. But Bui, Domingo, Wilkinson, et al. (2022) were more interested in identifying carbon-reduction challenges found in different areas of the pre-design and design stages of the refurbishment process in New Zealand. These challenges include (1) inexplicit carbon goal setting, (2) ineffective building condition assessment, (3) deficient and incomprehensive relevant whole-of-life carbon information to support the decision-making, and (4) inconsistent and ambiguous carbon-calculation guidelines and benchmarks. However, further in-depth investigation is required to provide recommendations for improving the decision-making process of ZCR.

There is a growing and continuous research interest in decision-making in the early stages of the refurbishment process with multi-objective optimisation systems, which support decision-making in selecting the best fit-for-purpose refurbishment alternatives (Bui, Domingo, et al., 2022). Multi-objective optimisation systems often incorporate various methods, tools and approaches to support decision-making. These include the integration of Building Information Modelling (BIM), energy simulation tools (e.g. EnergyPlus, IES, etc.), life cycle assessment (LCA) tools (e.g. LCAQuick, eTool, OneClick LCA, etc.), and life cycle costing (LCC) methods (Hu, 2018, 2019; Rabani et al., 2020). For example, Kamari et al. (2021) proposed a novel Building Information Model (BIM) based decision support system PARADIS to generate and evaluate optimal and holistic refurbishment alternatives. Thomas et al. (2018) developed a systems simulation framework for analysing the life cycle energy use in a building and determining net-zero building energy retrofits by incorporating the various dynamic events over the lifecycle. Even though these decision support mechanisms were tested using case studies in the local contexts, there has been a lack of evidence on their actual and wider

application to the current industry practice. In particular, the perspectives of building stakeholders involved in the refurbishment process (i.e., clients, architects, engineers, cost advisors, facilities managers and end-users) on adopting the complex and comprehensive decision support mechanisms have been neglected. The question of how building stakeholders work collaboratively to integrate multi-objective optimisation systems in the refurbishment process remains unanswered.

9.2.2 Collaboration and integration in sustainable building projects

There are two major approaches towards integration and collaboration in sustainable building projects found in the literature, namely Integrated Design (ID) and Supply Chain Integration (SCI). The main objective of SCI is collaborative relationships, which is a process of sharing skills, expertise, understanding and knowledge in an environment of trust, openness, and mutual respect, intending to deliver optimum solutions and meet common goals (Kesidou & Sorrell, 2018). ID aims to enhance collaboration by allowing key stakeholders (e.g. clients, architects, engineers, contractors) to work together from the beginning of the project, making decisions collectively and integrating fragmented design inputs and outputs (Leoto & Lizarralde, 2019a). Whatever integration and collaboration approach is adopted in a building project, an ideal process of collaboration and integration should include the following common attributes: accountability, commitment, communication, compatibility, timely involvement, joint operations, and trust (Azari & Kim, 2016; Hosseini et al., 2016; Kesidou & Sovacool, 2019). These collaboration and integration attributes will be further discussed in the discussion section.

There is a large body of literature on collaboration and integration in the building and construction industry. Many studies demonstrate the positive impact of collaboration and integration, identifying the importance of integration aspects that leads to the improvement of building performance and successful project outcomes and barriers to collaboration and integration in the design and construction processes (Swarup et al., 2011; Lundström et al., 2016; Holmén et al., 2017; Leoto & Lizarralde, 2019a). For example, Korkmaz et al. (2011) identified a range of critical success factors for delivering sustainable buildings, such as owner commitment, an integrated project delivery system, team procurement, contract conditions and design integration (e.g. timing of project participants' involvement such as contractors, commissioning agent, mechanical and electrical contractors). Similarly, Homayouni et al. (2014) examined high-performance projects' collaboration

and integration aspects. The authors concluded that (1) early and frequent involvement of the team members, (2) commitment and integrity of team members, (3) advanced implementation of BIM technologies, and (4) setting ambitious environmental objectives are necessary conditions but insufficient for creating a causal recipe for reaching higher energy-efficient buildings. A broader perspective has been adopted by Azari & Kim (2016), who developed an integrated evaluation framework for comparison, benchmarking, and educational purposes for integration evaluation and improvement in the ID context. Among four evaluation categories, including context, input, process and product, the evaluation factors are collaboration, leadership and system thinking. Conversely, Leoto & Lizarralde (2019a) uncovered the challenges of implementing ID in sustainable buildings through a multi-lens framework. The research results shed light on ID's limitations in practice, including tensions between collaboration and process efficiency, between short-term and long-term goals, and between integrated and traditional methods. In general, it can be seen that the significance of the early involvement of contractors in the project and sustainability performance, relational contracting and long-term orientation relationships between supply chain actors has been recognised. However, the timely inclusion of subcontractors, suppliers, and manufacturers and the involvement of users have not been investigated in detail. The findings from most studies apply to sustainable buildings within the general context of holistic sustainability rather than zero carbon context that focuses on maximising carbon reduction for buildings. Critics question to what extent collaboration and integration help decrease GHG emissions by reducing embodied and operational carbon emissions. Leoto & Lizarralde (2019b) recently addressed this issue by examining three case studies of certificated LEED buildings. The authors produced a Life Cycle Assessment (LCA) for these case studies, confirming that the ID approach can help achieve a 60% reduction in global warming potential (GWP) and 62% in energy consumption. However, maximising carbon reduction was not the priority of these case studies. Little information was obtained regarding the actual life cycle carbon analysis and how the project participants worked collaboratively to optimise design decisions to achieve the maximum carbon-reduction goal.

In reviewing the literature, there has been little research into collaboration and integration in the decision-making process, particularly focusing on carbon reduction in building refurbishment projects. The benefits of collaboration and integration have been widely demonstrated within the building and construction industry.

However, the question is not whether to collaborate or not, but *how* to collaborate to maximise carbon reduction in the decision-making process of building refurbishment projects. This chapter explores collaboration and integration in the early-stage decision-making process towards ZCR. More importantly, it examines how to collaborate and integrate to achieve building performance, project outcomes and long-term relationships between supply chain actors beyond the refurbishment project level.

9.3 Research method

This chapter investigates the practical refurbishment decision making process to identify how building stakeholders collaborate and integrate to maximise life cycle carbon reduction. This investigation adopted an exploratory case study approach, which was found appropriate for gaining pragmatic evidence on collaboration and integration in the practical context of the decision-making process. The case study strategy has a reliable means of capturing rich information, generating insights into the phenomenon being studied and allowing the investigator to retain the holistic and meaningful characteristics of real-life events (Barrett & Sutrisna, 2009; Yin, 2014). In collaboration and integration research, a deep case study research design is more suitable for exploring such dynamic interactions and relationships between different supply chain actors within the project and beyond into contextual and environmental attributes than other approaches such as quantitative research design (Kesidou & Sovacool, 2019).

The selection of multiple case studies needs to follow the replication logic to address the issue of external validation (Creswell, 1994; Yin, 2014). This research applied literal replication, which entails choosing cases with similar settings and expected to achieve similar results (Yin, 2014). Three refurbished university buildings were selected for the study, which showcased examples of low carbon designs and technologies. The criteria for choosing these refurbished projects were: (1) targeting a high level of sustainability/zero carbon certification or equivalent goals; (2) integrating sustainable/low carbon practices or products; (3) providing sufficient access to data, reports, and stakeholders; (4) being a similar building typology/use; (4) being launched by different organisations within the past five years.

Using various sources of evidence enhances credibility and the richness of data due to the data triangulation opportunities in the case study design (Swanborn, 2010; Yin, 2014). Accordingly, multiple evidence sources were used to improve the overall quality of the research. The primary data sources were interviews with

stakeholders involved in the case studies. This approach offers an opportunity to gather in-depth and supplementary information, reflect participants’ relative perspectives and attain an overall picture of the case (Eisenhardt & Graebner, 2007; Gray, 2018). Extensive interviews (twenty-three semi-structured interviews) were conducted to: (1) gain insights into what parties were engaged and their timely involvement in the refurbishment decision process; (2) understand how the project participants cooperated, coordinated, and collaborated to achieve carbon-reduction goals; and (3) identify problems and unexpected subjects related to collaboration and integration in the refurbishment decision process. The selection of participants varied on a case-by-case basis. For example, there were no project managers appointed in Case 1 and Case 2. However, this selection did not affect the data quality as information was adequately collected from other key actors and data sources. The sample size was considered appropriate as it satisfied the information saturation of both evidence and alternative explanations of the cases (Francis et al., 2010; Crabtree & Miller, 2022). The decision making on the sample of participants was dependent on the saturation point of the data – an adaptive approach, rather than a prior determination at the beginning of the study following the suggestion of (Sim et al., 2018). The decision over what establishes an adequate sample size to meet the research aim is iterative and context-dependent during the analytical process. Furthermore, the research’s sample size is also in line with qualitative research sampling procedures (Galvin, 2015; Creswell & Poth, 2016), confirming that over twenty interviews are appropriate for saturation. Table 9-1 shows participants by category.

Table 9-1: Participants by category (Source: Authors)

Respondent Type/ Cases	Case 1	Case 2	Case 3
Client representatives	C1-CR1	C2-CR1	C3-CR1, C3-CR2
Engineers	C1-E1, C1-E2	C2-E1	C3-E1, C3-E2
Project managers	N/A	N/A	C3-PM1
Architects	C1-A1, C1-A2, C1-A3	C2-A1	C3-A1
Sustainable consultants	N/A	C2-SC1	C3-SC1
Quantity Surveyors	C1-QS1	C2-QS1	C3-QS1
Contractor representatives	C1-CT1, C1-CT2	N/A	C3-CT1
Total	9	5	9

Other data sources were also collected, including project documentation (e.g. sustainable strategy reports, sustainability plans, site investigation reports, building performance reports, energy efficiency reviews,

sustainable design briefs, building condition assessment reports, drawings, design specifications, study reports) and direct observation (e.g. site visits). Qualitative data analysis involves iterative observation, research, and reflection (Mills et al., 2009). Therefore, the data obtained from interviews and observations were compared to the written evidence gathered from project documentation to triangulate information. Participants were questioned further in the follow-up emails and phone calls when inconsistencies and missing data were discovered.

Interviews were audio-recorded with permission from the participants and then transcribed. Each interview audio recording was listened to at least twice while simultaneously reading the corresponding transcript. After that, the initial codes were identified before major themes which emerged from the data were synthesised, defined, and reviewed. The qualitative software package NVivo 12 was used to assist with organising information, code and analyse data, identify themes, and interpret findings. Following Sutrisna & Barrett (2007)'s; Yin (2014)'s; Bennett & Checkel (2015)'s suggestions, the researcher first applied a general qualitative strategy for analysing data, using theoretical propositions from the literature review, descriptive frameworks and rival explanations to understand the preliminary data and provide an explanatory view for each case. Then, the researcher used cross-case synthesis as a specific analytical technique to recognise the similarities, differences, and associations across cases. The findings and discussions resulted from an interactive analysis using replication logic within and among cases.

Several evaluation techniques were applied to confirm the validity and reliability of the findings following Yin (2014)'s; Gray (2018)'s recommendations. In terms of construct validity, multiple sources of evidence were used to ensure data triangulation. Mistakes and errors were avoided by thoroughly checking transcripts and codes. The data and initial analysis results were returned to the interviewees for validation and revision. The findings were peer-reviewed by communicating and discussing the analytical results with key informants. In addition, a case study protocol and database were created to improve the reliability. A case study protocol consists of the case study overview, data collection procedures, research objectives and questions, and a tentative outline for the case study report. The case study database represented all sources of evidence using the computer-aid qualitative data analysis software NVivo12, word-processing tools (e.g. Word and Excel files), and cloud storage.

9.4 Findings

9.4.1 Overview of case studies

Before reporting on each case study’s empirical findings on collaboration and integration, an overview of three case studies is provided in this section. Table 9-2 illustrates the key refurbishment features of three case studies.

Table 9-2: Key refurbishment features of three case studies (Source: Authors)

	Case 1	Case 2	Case 3
Building envelope	<ul style="list-style-type: none"> • Upgrading insulation for exterior walls and roofing systems • Adding vapour barriers to the external façade • Replacing double-glazed windows 	<ul style="list-style-type: none"> • Upgrading high-performance façade with double-glazed windows and vertical shading fins 	<ul style="list-style-type: none"> • Replacing the façade with a super-insulated, airtight, and lightweight curtain wall • Upgrading high-performance solar glazing • Adding green roof
Building services	<ul style="list-style-type: none"> • Installing efficient LED lighting systems • Establishing a high-quality Building Management System (BMS) • Adding a new centralised heat pump and chiller plant with energy recovery • Installing four-pipe fan coil units 	<ul style="list-style-type: none"> • Installing mixed-mode ventilation • Installing LED lighting systems 	<ul style="list-style-type: none"> • Installing mix-mode ventilation • Upgrade electric heating, ventilation, and air-conditioning systems
Renewable energy	<ul style="list-style-type: none"> • Preparing off-site PV system infrastructure for future installation towards net-zero energy by 2025. 	<ul style="list-style-type: none"> • NA 	<ul style="list-style-type: none"> • Installing a PV system.

Case study 1 was a refurbished educational building, part of a large-scale redevelopment project in New Zealand. The existing four-story building was erected in the 1980s, with a 3500sqm footprint. Before refurbishing, the standalone concrete block building was abandoned due to its poor and unsustainable condition and lack of green design features.

Case study 2 was a refurbished library building in New Zealand. The existing two-story library consists of two conjoined parts. The front part was built in the 1960s, and the rear was extended in the 1980s. The existing reinforced concrete building had GFA of approximately 10,000 sqm. The library was partly operational during the refurbishment process.

Case study 3 was an adaptive-reuse university building in New Zealand. The building was built in the 1970s with concrete cladding, including North and East sections. Before refurbishing, it had poor operational performance, especially for thermal comfort. The newly refurbished building and a spectacular new timber atrium were expected to welcome new occupants in 2024.

9.4.2 Case study 1

The refurbishment aligned with the organisation's vision towards a net zero-carbon future consistent with its national and international commitment. Its goals and objectives were established based on the organisation's sustainability strategies and green building standards. In the business case stage, the client team visited sustainable building showcases in the Northern Hemisphere to gain insight into low carbon design and construction. The field trip helped the client team acquire practical knowledge of low carbon features before producing a high-level design brief for the refurbished building. The results of the field trip were reported and distributed to ensure that each stakeholder shared a common goal and vision towards zero-carbon development and implementation.

After the client team conducted an initial building condition assessment and established refurbishment strategies, the project engineers, architect, and cost advisor were engaged from the generation of the refurbishment alternatives stage in the design phase. The knowledgeable and experienced client team took the lead and champion role in the project, willing to prioritise low carbon features and pay a premium cost for better outcomes in terms of environmental performance. They were actively involved throughout the design process, encouraging the adoption of low-carbon design strategies, and ensuring that these initiatives were preserved. One of the client representatives was promoted as the "*sustainability gatekeeper*", as C1-CR1 described: "*when we had design reviews, people are trying to make cost savings by chopping out a crucial sustainability design element. I had the power of veto*". Additional championing roles were architects and engineers who were part of skilled firms specialising in passive design, efficient building services, energy

modelling and life cycle carbon assessment. More importantly, an experienced cost advisor participated throughout the design process, providing estimates, and advising on the costs involved in the project.

An integrated design approach was employed throughout the design process. In the early design phase, workshops were held every two weeks to review contextual conditions and generate potential refurbishment options. The participants used collective knowledge and experience in low carbon design and technologies to evaluate the refurbishment strategies. The architects coordinated with the engineers to qualitatively assess life cycle embodied and operational carbon emissions. The client provided a shared office in the later design phase, where the consultant team collaboratively worked on the detailed design. *“When your design partners are within talking distance, it’s much easier to go and have a chat rather than waiting until the next time you see them a week later or sending an email and getting a response two days later”*, said C1-E1. Formal collaborative procedures were employed, such as adopting a cloud-hosted BIM environment with the design parties operating in a single design model. The cost advisor often visited the shared office to provide cost reviews on various refurbishment options and confirmed the design decisions were over or under the budget. In addition, the architect team commissioned an external carbon specialist to quantitatively calculate life cycle carbon emissions using the LCA tool at the end of the design phase. Even though the team worked collaboratively at the highest integration level, they sometimes faced challenges balancing design decisions due to various perspectives. The client’s knowledge of low carbon design allowed them to negotiate and defend several refurbishment solutions, such as using premium phase change materials for insulation. However, according to the engineers, that might deliver better outcomes but be more expensive and challenging to implement in the refurbished building, *“in some situations, it’s not worthwhile spending money to do some upgrades, there are scenarios that we can over insulate”* (C1-E1).

An early contractor involvement approach was implemented during the design phase. The client and consultant team appointed some sub-contractors and suppliers to evaluate the buildability and review potential materials sources of low carbon refurbishment options such as high-performance windows, HVAC plants, lighting systems, and BMS control systems. *“Any feedback about something that’s not buildable, I’ll take it out”*, explained C1-CR1. The main contractor was engaged to assess designs and drawings before construction began. However, it was believed that the early involvement of the main contractor could contribute

considerably to the maximum carbon reduction for the refurbished building. The earlier the constructor investigated the existing building, the more information on appropriate refurbishment solutions and how much existing building materials could be recycled and reused could be found. It was thought that this information might contribute to a better evaluation of refurbishment alternatives in the design phase, further reducing carbon emissions from construction materials and waste. “We’ve recently gone through a process of taking some furniture out as part of the strip-out, and the consultant team was like: we didn’t realise that there was quite a nice existing timber floor there. We should keep that”, explained C1-CT1. Figure 9-1 illustrates stakeholders’ relationship and timely involvement in different stages of the decision-making process of case 1. The solid line shows the direct relationship between clients and other stakeholders, while the dotted line demonstrates the interrelationship and communication among stakeholders.

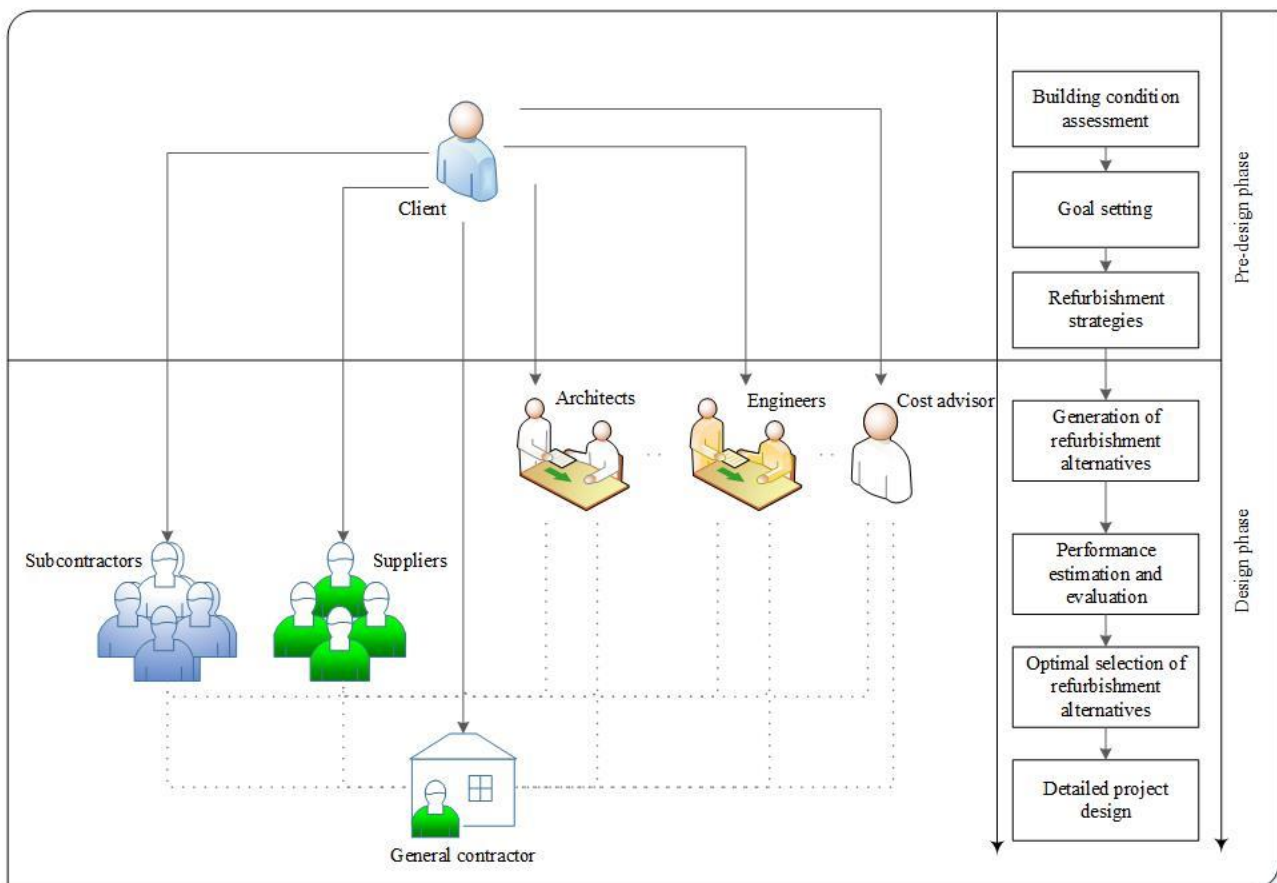


Figure 9-1: Stakeholders’ relationship and timely involvement in the decision-making process of case 1

(Source: Authors)

According to client representatives, the user group was not highly involved in the decision-making process. However, historical occupant behaviours and activities were carefully observed and considered for the design input. For example, the number of staff and students were the critical factor affecting the design layouts and the estimation of energy performance. Upgrading the lighting systems with automatic controls was thought to avoid the dependency on users to switch them off. At the end of each design stage, the team held several workshops to present the design results and update the current work to relevant stakeholders.

9.4.3 Case study 2

The refurbishment aligned with the organisation's zero-carbon plan, which committed to reducing GHG emissions and achieving a goal of net-zero carbon by 2030. The commitment enabled the organisation to balance the financial and zero-carbon gain to achieve the overall benefit of the refurbishment. The client's aspirations for alleviating their carbon footprint influenced the design approach and value engineering early in the design stage, prioritising zero-carbon designs and technologies.

While the effective leadership of the client acted as an enabler for accomplishing low carbon solutions, engineers and sustainable consultants were the champions who actively and enthusiastically promoted low carbon refurbishment alternatives throughout the refurbishment process. The client engaged engineers and sustainability consultants from the goal-setting stage in the pre-design phase to help set the right goals, assess building conditions, and establish refurbishment strategies. A sustainability workshop was held where the consultant team assisted the client with carbon goal setting. As a result, an environmental sustainability brief was produced, which included environmental sustainability certification options, design implications of certification options, a strategy aligned with the organisation's values, and a pre-assessment of design opportunities. *"That report was really good, which talked about the different ratings, design options and what we would need to do"*, expressed C2-CR1. Another champion role was the architect majoring in sustainable design. The architect was involved in the design phase, in which some pre-selected refurbishment strategies were already implemented. For instance, the floor-to-ceiling glass was a design decision established early without considering embodied carbon impacts, leading to the difficulty in making changes later. The cost advisor supported the client with the cost estimation of detailed low carbon refurbishment options throughout

the design process, such as providing comments on the prices of different façade solutions and thermal properties.

The project team worked interactively in the design process but did not follow a specific integrated design process. The client, architects, engineers, and sustainability consultants discussed and agreed on the desired performance criteria upfront, enabling integrated design solutions to become available. For example, the upgraded façade was optimised to stay within the limits of the heating system that could be supported by the electrical infrastructure. The team shared access to a BIM model but could only see modelled elements of the others' work. *“We meet two or three times a week, and we publish the model every week, so everyone gets an update on their model. It is not the same as being a centralised calculation model because that's separate”*, said C2-A1. Although the team collaborated at a certain level, the members still took their tasks away and returned to re-integrate them into the design. Different toolkits and software were used across the consultant team to estimate thermal performance, energy modelling, embodied carbon, and operational carbon emissions—this approach limited collaboration and integration in optimising the carbon benefits of refurbishment solutions.

An intention was to appoint early contractor involvement in the detailed project design. However, getting this agreed upon was complicated due to some challenges the client faced with the internal procurement requirements. It was thought that early contractor involvement could provide the refurbishment with certainty around costs and low carbon deliveries. However, the consultant team perceived their potential contribution to reducing energy consumption and operational carbon emissions as limited.

Various user groups, including the building owner, facility manager, students, and staff, were highly involved in the refurbishment process. In the building condition assessment stage, a user survey was conducted to better understand the user activities in the existing building and their expectation for the refurbishment. The user groups actively attended regular meetings and provided input regarding their behaviours and ideal building features throughout the design stages. There were several examples of the design considering user dependency. Mixed-mode ventilation, which incorporated natural and mechanical ventilation, included the automation of key opening windows to minimise human factors such as people being unable to close them at night. It also enabled the windows to open before the temperature was too high. In addition, the refurbishment also

considered facility management, including a clear zone for façade maintenance. The serviceability of tall windows was a concern for ongoing maintenance, and the compromise was the actuators on windows with control mechanisms at a lower height. These approaches might help bridge the performance gap between pre- and post-occupancy. Figure 2 illustrates stakeholders' relationship and timely involvement in different stages of the refurbishment decision-making process of case 2.

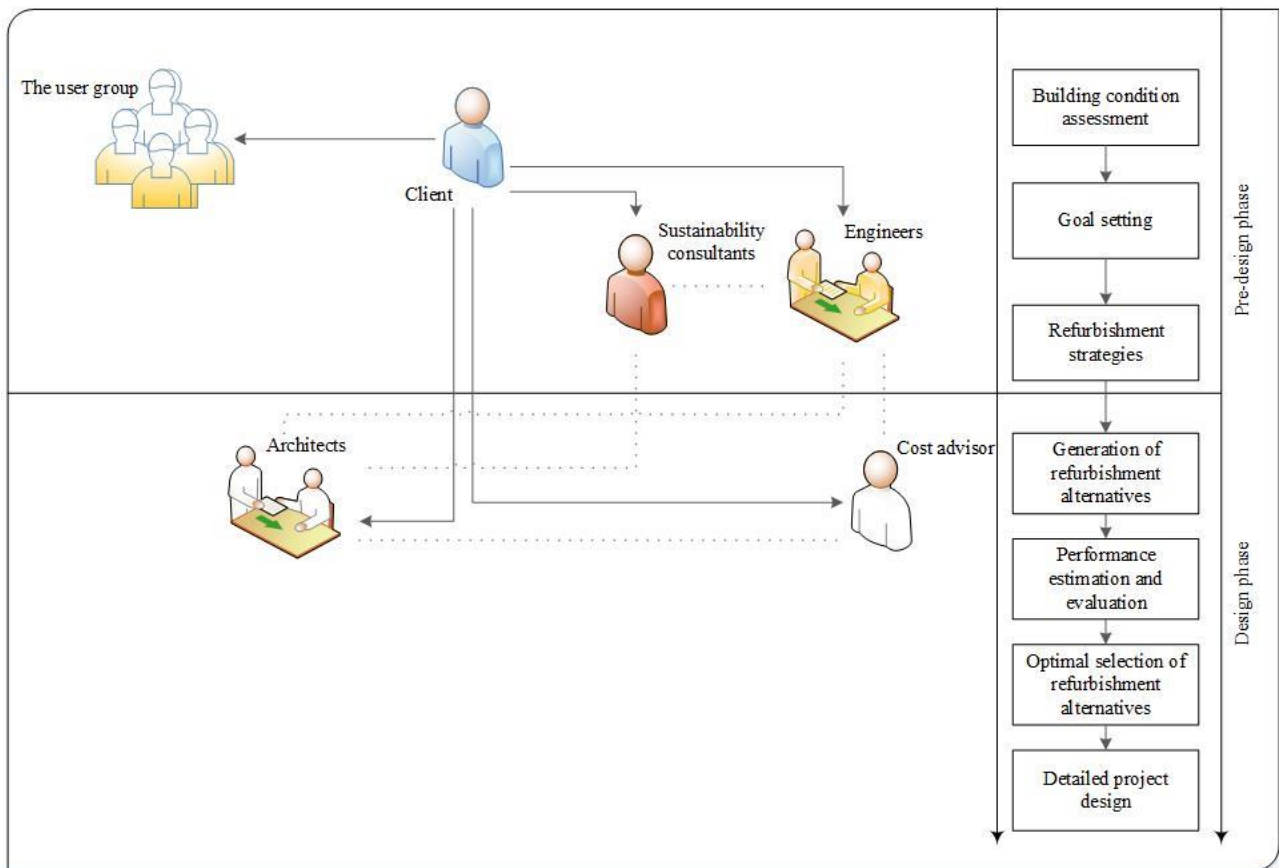


Figure 9-2: Stakeholders' relationship and timely involvement in the decision-making process of case 2

(Source: Authors)

9.4.4 Case study 3

The refurbishment was reported as an example demonstrating the organisation's strategies and policies towards environmental sustainability. The project was awarded six Green Stars for design by the New Zealand Green Building Council (NZGBC), achieving the highest Green Star points among New Zealand's green buildings. In the past, decision-making for building projects was always driven by capital cost. However, within this refurbishment project, adopting a life cycle costing approach became essential in making design decisions

based on zero-carbon and sustainability initiatives. The evolution of organisational core strategic initiatives allowed the adoption of low carbon design and construction for the refurbished building.

The client team was highly involved in the project with the support of the project manager to drive focus around specific low carbon designs and technologies and to ensure the deliverables of Green Star certification. The consultant team, including architects, engineers, and sustainability consultants championing sustainable design and life cycle carbon assessment, was appointed from the building condition assessment stage in the pre-design phase to help the client assess the performance of the existing building, identify the level of refurbishment, and establish refurbishment strategies. An external carbon specialist was not part of the consultant team but participated in the generation of refurbishment alternatives stage to provide independent peer reviews on embodied carbon impacts of potential refurbishment alternatives. In addition, the cost advisor was also involved in advising on the most cost-effective refurbishment strategies and options proposed by the consultant team from the pre-design phase. Figure 9-3 illustrates stakeholders' relationship and timely involvement in different stages of the refurbishment decision-making process of case 3.

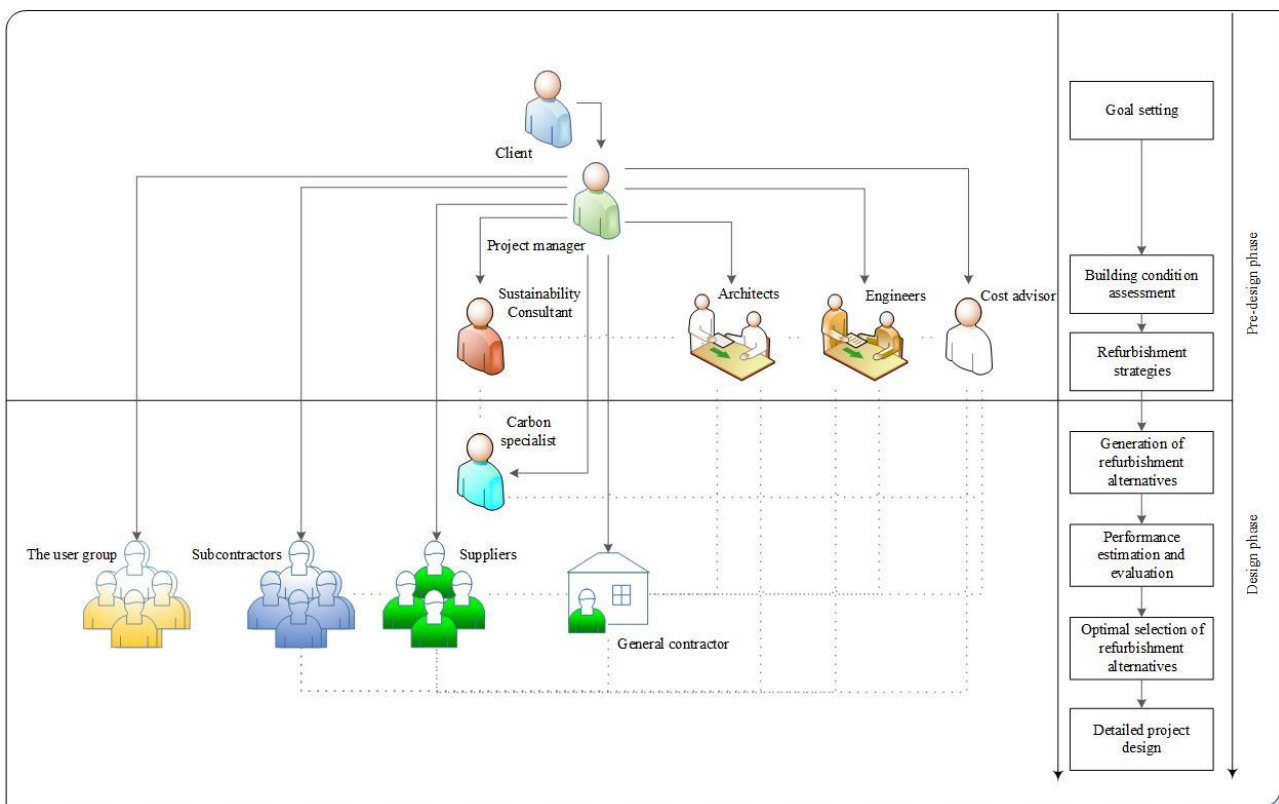


Figure 9-3: Stakeholders' relationship and timely involvement in the decision-making process of case 3

(Source: Authors)

An integrated design approach incorporating collaborative methods and digital tools (e.g. BIM, energy modelling, LCA tool) was applied to encourage and enable the project team to work together to produce an optimal design. Weekly meetings allowed all participants to collaborate and align early in the design process. Regarding selecting low carbon refurbishment alternatives, the sustainability consultant considered different options, such as upgrading insulation concerning performance requirements, cost-effectiveness, and life cycle carbon benefits. The advantages and disadvantages of these options were then discussed with architects, engineers, and the carbon specialist before presenting them to the client team. Later, the consultant team undertook the comprehensive LCA analysis, while the carbon specialist provided reviews and certified carbon assessment results. The collaborative approach also empowered participants to adapt to the client's expectations and design changes. For example, when the client wanted to include PV panels on the roof of the refurbished building, the consultant team cooperated to assess possibilities and develop design solutions. At the same time, the cost advisor came up with a cost plan and additional comments on these solutions. The engineers also conducted further financial analysis to compare lifecycle operational carbon and cost benefits. The client team then reviewed all information before making the decision. More importantly, the project team was stimulated to open honest discussions about problems that occurred in the process. *“Any issues come up, and someone will not be afraid to put their hand up and say: “we can't source the EPD-certified timber. What do we do?”. If they can put their hand up early, we can look at solutions rather than when it becomes too late to change things”*, explained C3-PM1. Interestingly, regular team-building activities such as seminars and sports events were organised for the project team, which helped strengthen the relationship and build trust.

The contractor, sub-contractors and suppliers were employed in the design phase. The project was designed in collaboration with contractors and sub-contractors. There were early discussions with sub-contractors and suppliers regarding embodied carbon emissions of construction products and materials. For example, a supplier was engaged to provide several options for upgrading the façade with a recycled aluminium frame. The supplier also offered detailed information on the level of energy performance the specific façade system could achieve, which was helpful for decision-making that might affect operational carbon reduction. Another sub-contractor assisted the architects in proposing solutions for enhancing airtightness. It was believed that having early contractor involvement was significant in reducing carbon footprint, particularly in supporting the

selection of low carbon products and materials and minimising construction waste. However, the contractor may not have provided much input on assessing the carbon emissions of refurbishment alternatives.

Little evidence of user involvement in the decision-making process was found in this case study according to the empirical data. It was reported by the participants that the refurbished building was expected to accommodate new occupants with new occupancy arrangements. Limited investigation into occupant behaviours and activities challenged the consultant team to evaluate energy and carbon performance in the design stage. According to C3-E1, assumptions were made in consultation with the client and historical data regarding *“how this building might be used when it’s occupied”*. Another challenge was related to facility management in the post-occupancy stage. Various user groups were allocated to different building areas, leading to the difficulty of minimising the impact of user dependency in building maintenance. There were attempts to alleviate the performance gap by presenting the design expectation to the user groups. For example, *“we have a lot of meetings with different departments where we present the same thing repeatedly and make sure that they understand what we are trying to achieve for this building”*, said C3-PM1. However, concerns about changing the user behaviours in managing the refurbished building to achieve the operational carbon reduction goal were expressed.

9.5 Discussion

This chapter examines the practical refurbishment decision process to identify how building stakeholders collaborate and integrate to maximise life cycle carbon reduction. In three case studies, we investigate what, how and why building stakeholders collaborate and integrate to make decisions. It is acknowledged that the collaboration and integration process in the practical New Zealand context is in line with the literature. However, the cross-case analysis and interpretation uncovers unexpected findings that can be applied towards implementing ZCR. This section discusses collaboration and integration attributes identified in the literature and new insights found in case studies. A collaboration and integration framework towards successfully delivering ZCR projects is proposed (see Figure 9-4 below). The framework demonstrates stakeholders’ relationship, timely involvement and key attributes required in the decision-making process.

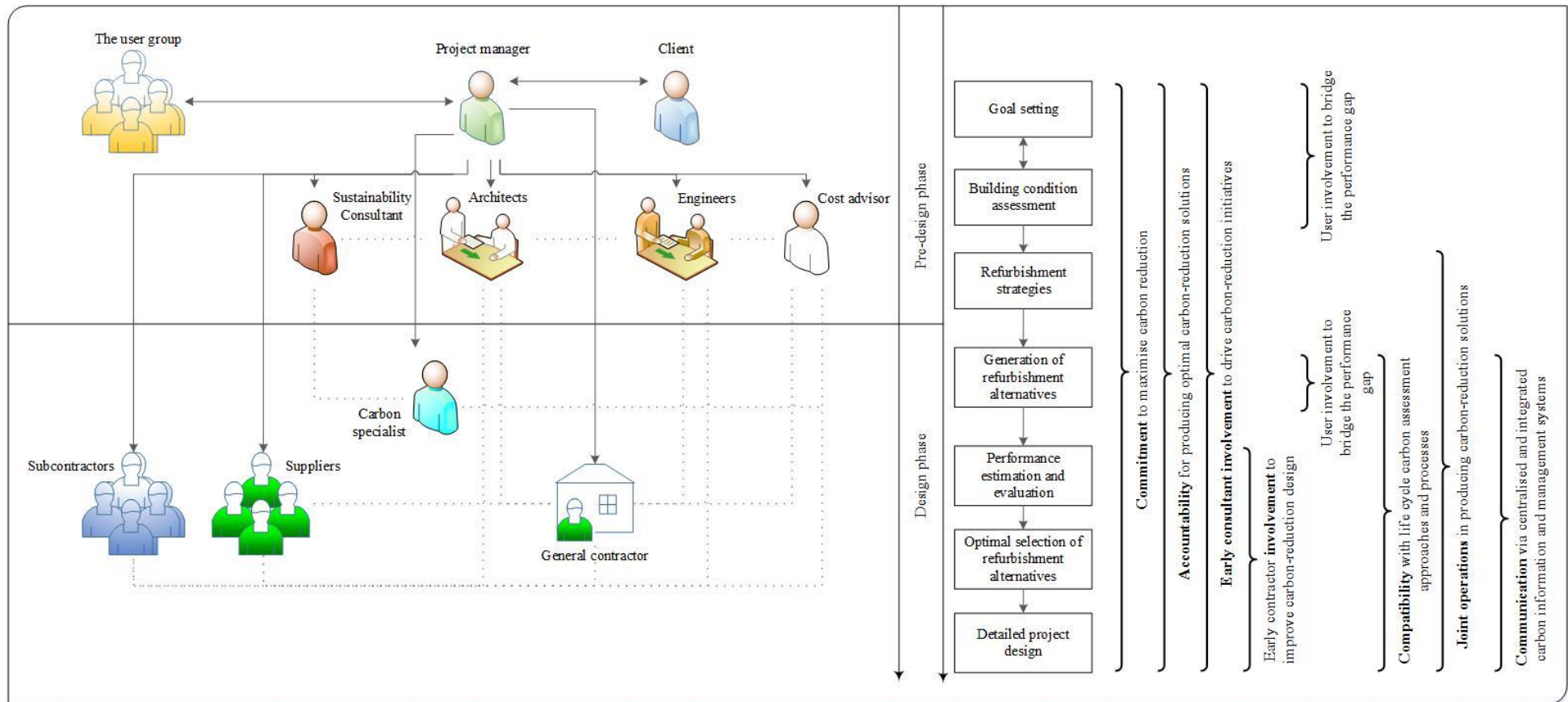


Figure 9-4: A collaboration and integration framework towards successful delivery of ZCR projects (Source: Authors)

The findings confirm the importance of the commitment and integrity of team members regarding ZCR implementation and are in line with previous studies in the sustainable building literature (Korkmaz et al., 2011; Homayouni et al., 2014). In all cases, the clients express their commitment and aspiration towards net-zero carbon. At the same time, team members work in concert towards the delivery of specific carbon-reduction goals. However, compared to previous studies, the results from this research additionally highlight that organisational vision towards a net-zero carbon future is the driver for pursuing carbon-reduction objectives. The organisational commitment enables the client to balance the financial and carbon-reduction gain to achieve the overall benefit of the refurbishment and prioritise low carbon features in choosing refurbishment solutions. It also encourages knowledge development within the organisation to better implement zero-carbon projects. Likewise, other team members' organisations, such as engineering and architecture firms, commit to reducing maximum carbon emissions in delivering their projects. As such, commitment to maximise carbon reduction among the project team is the first significant attribute required from the beginning of goal setting throughout the refurbishment decision-making process.

This research demonstrates the accountability of team members in reducing carbon emissions for refurbishment projects. Client leadership is the key to promoting and inspiring other project participants to implement low carbon initiatives. The project manager is responsible for managing and monitoring carbon-reduction design and implementation. Engineers, architects, sustainability consultants and carbon specialists provide valuable input to create optimal refurbishment solutions that reduce operational and embodied carbon emissions. At the same time, cost advisors support prioritising cost-effective options. The participation of contractors, subcontractors and suppliers fills the gaps in understanding the implementation requirements of innovative designs and the carbon performance of construction materials and products. Extensive involvement of users alleviates the factors contributing to the "energy performance gap" (e.g., cases 1 and 2), including lack of accurate information at the design stage on occupancy profiles and user behaviours, underestimation of heating and cooling loads, inappropriate refurbishment solutions, ineffective building commissioning and maintenance. Therefore, accountability for producing optimal carbon-reduction solutions among the project team should be incorporated throughout the refurbishment process.

The timely involvement of the project team plays a pivotal role in reducing carbon emissions in building refurbishment. First, the early and active participation of team members, including clients, engineers, architects, cost advisors is critical for making carbon-reduced design decisions and achieving effective planning and delivery of the project (Winch, 2000; Chan et al., 2004; Kesidou & Sorrell, 2018). However, in comparison to previous observations, the empirical results from this research reveal that sustainability consultants and carbon specialists are also key actors who should be engaged from the early stage of the decision-making process. Their carbon knowledge and expertise can contribute significantly to identify potential carbon-saving solutions, consider the adoption of environmental certification schemes, undertake energy modelling, LCA analysis and verify carbon assessment results (e.g. cases 2 and 3). This has not been adequately recognised in the literature. Therefore, early consultant involvement is acknowledged as a key collaboration attribute to drive carbon-reduction initiatives in the refurbishment process. Second, the findings from all cases studied corroborates the findings of previous studies (e.g. Mollaoglu-Korkmaz et al. (2013)), emphasising that bringing in the contractors earlier in the process (e.g. detailed design) could benefit the consultant team in terms of constructability, waste management, and value engineering. However, we underline the contribution of early contractor involvement (e.g. case 1) in maximising embodied carbon reduction for refurbished buildings by providing input to resolve the issue of recycling and reusing existing construction materials and products. Third, one unexpected finding from cases 1 and 3 is that the important role of subcontractors and suppliers in reducing carbon emissions should not be neglected, particularly when low carbon design features are considered building innovation. The participation of these actors allows the consultant team to understand the requirements of implementing innovative designs (e.g. high-performance windows and facades) and technologies (e.g. HVAC, BMS, PV systems) and gain insight into the performance level and embodied carbon emissions of construction materials and products. Finally, the research suggests that the user group should be involved to identify the problems of the existing building at the starting point and provide input for the consultant team in generating appropriate refurbishment strategies. Taken together, three attributes demonstrating the timely involvement of the project team are (1) early consultant involvement to drive carbon-reduction initiatives, (2) early contractor involvement to improve carbon-reduction and (3) user involvement to bridge the performance gap.

The chapter's findings are also consistent with Kumaraswamy et al. (2005; Azari & Kim (2016) in reflecting the role of compatibility in collaboration and integration. In studied cases (e.g. cases 1 and 3), it is observed that the clients, engineers, architects, sustainability consultants, contractors, subcontractors, and suppliers have worked together on several building projects. They are familiar with each other through previous work and reputation. More importantly, involved parties are compatible with lifecycle carbon assessment approaches and processes. Thus, compatibility with lifecycle carbon assessment approaches and methods is a critical attribute in the design phase of the refurbishment process. The shared vision, compatibility, commitment, and integrity of team members create a trust-based collaborative environment for achieving targeted carbon performance and project outcomes; and facilitate long-term relationships, high levels of knowledge development and sharing between all parties.

Evolving from existing studies Azari & Kim (2016); Hosseini et al. (2016), this research further illustrates the joint operations of team members in producing carbon-reduction solutions. In all cases, many innovative ideas regarding carbon problems are generated during joint meetings. Team members collaboratively explore, create, and evaluate refurbishment alternatives based on discussions across relevant disciplines. Before making design decisions, life cycle carbon emissions and cost impacts are also discussed. Interestingly, the findings from this research demonstrate that higher levels of joint operations lead to higher performance outcomes in case 1. Empirical evidence has shown the highest integration level in the design process, which goes beyond joint meetings and discussions to joint working design model and project office that enhances effective face-to-face communication. Joint decision-making and problem-solving throughout the design process can help with carbon challenges, such as balancing the trade-off between the design options' operational and embodied carbon benefits and sourcing low-carbon materials.

Another important aspect to emerge from the analysis is information flow in the design process. Even though team members worked collaboratively to generate integrated design solutions, information flow barriers existed, especially regarding building performance and carbon assessment (e.g. case 2). BIM is considered necessary to increase the flow of information, create efficiency and reduce conflicts in refurbishment projects (Papadonikolaki & Wamelink, 2017). Besides the BIM model, advanced energy simulation and LCA tools are essential for carbon-related decision-making but require integrated information to function effectively and

efficiently. However, the project team often uses different toolkits and software to estimate building energy and carbon performance – a core part of each member’s deliverables. Our study suggests that all information, calculations, and assessment regarding energy modelling, building performance, and life cycle carbon emissions should be shared among team members. Everyone should have access to the same model, information, and calculations to ensure transparency and consistency in optimising the design and favour the sharing and development of carbon literacy rather than just the exchange, aggregation, and storage of information. Therefore, a centralised carbon data management system or a shared energy performance and LCA model or an integrated information system is needed to support the team’s effective collaboration and integration towards delivering ZCR.

9.6 Conclusion

This chapter explores collaboration and integration in delivering refurbishment projects that reduce life cycle carbon emissions. The investigation has identified how building stakeholders work collaboratively and interactively to reduce carbon emissions in the refurbishment process of three real-world case studies. The chapter uncovers the collaboration and integration process in three refurbishment projects that adopt similar and different approaches. Lessons learnt to improve collaboration and integration in future refurbishment projects are determined, which highlight the importance of organisational commitment, accountability and compatibility of team members, the timely involvement of key stakeholders, the joint operation in the design process, and a centralised and integrated information system.

A collaboration and integration framework for better delivery of ZCR projects is proposed based on the interactive analysis between the literature and empirical findings. The framework offers new insight into how building stakeholders collaborate to integrate carbon-reduction initiatives in the decision-making process for building refurbishment. It supports users in identifying who should be involved in each stage of the refurbishment process, their responsibilities, relationship and timely involvement, and key attributes required in an ideal process of collaboration and integration. It is acknowledged that every refurbishment project has a certain level of complexity. To what extent each building stakeholder is involved in each stage of the process also varies. Though the framework is developed based on best practices, its implementation can be different from one refurbishment project to another. Further research is required to refine and validate the proposed

framework with industry professionals and practitioners to strengthen its significant implications in integrating and collaborating in implementing refurbishment projects.

This chapter offers valuable insights into the current practices and challenges faced in collaboration and integration for building refurbishment. The findings are of interest to building stakeholders who wish to enhance their knowledge and experience to achieve zero-carbon objectives for refurbishment projects.

10 Chapter 10: Developing and validating a novel early-stage decision support framework towards zero carbon refurbishment of existing buildings in New Zealand

This chapter is based on the following manuscript. It is intended that the manuscript will be published, but it has not yet been submitted to a Journal.

Bui, T. T. P., MacGregor, C., Wilkinson, S. & Domingo, N. (2024). A novel early-stage decision support framework towards zero carbon refurbishment of existing buildings in New Zealand.

10.1 Abstract

Zero carbon refurbishment of existing buildings is vital to maximise carbon emissions reduction and alleviate the impacts of climate change. To better support decarbonisation decision-making in building refurbishment, there is a need for a new comprehensive decision support framework. Drawing on the findings from previous chapters, this chapter brings together the development and validation processes of a novel early-stage decision support framework towards zero carbon refurbishment of existing buildings in New Zealand (RefurbZC). The development of the framework was based on the critical analysis and interpretation of the literature review, preliminary study, and case study of university buildings in New Zealand, which integrate international best practices adopted to the local context and lessons learnt from real-life case studies. The framework was validated and refined using a focus group workshop with New Zealand building experts involved in the refurbishment process. The RefurbZC aims to provide a detailed guideline to use in the early stages of the refurbishment process, focusing on maximising whole-of-life carbon reduction. It helps to understand the refurbishment decision-making process, identify areas for integrating carbon-reduction initiatives, determine key factors and actors in driving carbon-reduction solutions, and promote stakeholder collaboration and integration in carbon-reduction building refurbishment. The presented framework contributes extensively to theoretical and practical knowledge of zero carbon refurbishment of existing buildings and offers a basis and foundation for future work in this research area.

10.2 Introduction

The impact of climate change has presented critical challenges over the last few decades (Seneviratne et al., 2016). Evidence has shown that global carbon emissions have continuously increased, from 22.5 billion tons in 1998 to 34.04 billion tons in 2018 (The World Bank, 2018). The Paris agreement in 2016 sought to limit the temperature increase from 1.5°C to 2°C above pre-industrial levels by 2050 (Rogelj et al., 2015). Responsible for one-third of global GHG emissions, the contributions of the building and construction industry are critical for carbon emission reduction. Refurbishing existing buildings offers a favourable opportunity to maximise carbon benefits in comparison with the construction of new buildings. For example, Hasik et al. (2019) compared the whole-building life cycle assessment (LCA) of refurbishment and new construction in the US. The case study demonstrates 53–75% environmental impact reductions when refurbishing rather than constructing a new building.

Successful zero carbon refurbishment for existing buildings can be attained if effective decisions are made throughout the refurbishment process. In reviewing the literature, decision-making is a major area of interest within the field of building refurbishment. Over the years, researchers have paid attention to the design and development of decision support tools, with a large and growing body of research focusing on developing multi-objective optimisation mechanisms to better support decision-making in selecting the best fit-for-purpose refurbishment options and alternatives (Jensen & Maslesa, 2015; Li & Froese, 2017; Gade et al., 2018; Serrano-Jiménez et al., 2021). The recent literature reviewed by Bui et al. (2021b) and Bui, Domingo, et al. (2022) has revealed that various practices, methods, approaches, and tools that support the decision-making process towards zero carbon building refurbishment are found in the literature. However, fewer scholars have been able to draw on systematic approaches where available mechanisms are integrated to support the decision-making process.

The first serious discussion and analysis of refurbishment decision support framework regarding energy efficiency, management, and sustainability emerged during the 2000s. Mickaityte et al. (2008) created the first conceptual sustainable refurbishment model for public buildings based on sustainable development principles, decision-making process considerations, and influencing factors. The proposed model was illustrated using a case study of building pollution mapping, which provided the pollution impact on human health to inform the

selection of refurbishment measures. Although the study offers an insight into the decision-making process, there is a lack of practical demonstration of this matter within the case study. Kolokotsa et al. (2009) later proposed a framework for building design and operational improvement by analysing various decision support methods for energy management and sustainability. However, this framework fails to address the strategic planning as well as method and tool selection, which provide the necessary information and resource support for refurbishment activities. The significance of this strategy is later illustrated in the study of Ma et al. (2012). The authors developed a systematic approach for sustainable building refurbishment by reviewing current research and development in the field. This approach has offered construction researchers and practitioners an adequate understanding of effectively implementing building refurbishment and promoting energy conservation and sustainability. In the same vein, Bhuiyan et al. (2015) generated a decision tree for social housing refurbishment from the literature to overcome the weakness of poor business cases. Nonetheless, these approaches focus on improving energy and operational carbon performance in the refurbishment process while the impacts of life cycle carbon emissions have been disregarded. Bui et al. (2021b) later addressed this issue, offering a new understanding of decision support tools for ZCR and suggesting a new theoretical decision support methodology based on a critical review. Yet, there has been little evidence on the practical implementation of this methodology in the construction industry, especially in adopting and integrating essential decision-support resources and tools throughout the refurbishment process. More importantly, there has been little discussion about how building stakeholders collaborate and integrate available practices, methods, approaches, and tools in the decision-making process towards successfully delivering building refurbishment projects towards zero carbon.

To address this knowledge gap, the empirical studies of Bui, Domingo, Wilkinson, et al. (2022); Bui, MacGregor et al. (2023); Bui, Wilkinson et al. (2023) were established to present an in-depth investigation into the decision-making process of three real-life building refurbishment case studies considering whole-of-life carbon reduction to assist in developing the decision support framework for better-delivering building refurbishment towards zero carbon in New Zealand. In the same vein, this chapter describes the development and validation processes of a novel early-stage decision support framework towards zero carbon refurbishment of existing buildings in New Zealand (RefurbZC).

This chapter starts with this introduction, which provides the research background and purpose. The following section presents the research design including the approaches to framework development and validation. The remaining parts of the paper report on the results and analysis of RefurbZC development, validation process and finalisation, followed by the framework application and implication critically discussed.

10.3 Research method

10.3.1 Framework development

The first objective of the chapter is to develop a novel early-stage decision support framework towards zero carbon refurbishment of existing buildings in New Zealand (RefurbZC). In reviewing the literature, it was acknowledged that primary data from interviews, case studies, focus groups, etc. or secondary data from existing literature could be used to develop a framework. For example, Le et al. (2018) generated a sustainable refurbishment framework for school buildings through a literature review. While Sweya et al. (2020) established a conceptual framework to measure resilience against floods for water supply systems using an expert-based approach. However, various methods using both primary and secondary data could be adopted to promote the reliability of the developed framework. For instance, Kesidou & Sorrell (2018) created an innovation implementation framework for supply chain integration in delivering low-carbon buildings, using a critical interdisciplinary literature review and case study approach. In a more integrated way, the literature review, focus group, expert interview, and case study approaches were adopted in Meng (2010) research to develop an assessment framework for construction supply chain relationships.

In this research, both primary and secondary data were applied to develop the novel early-stage decision support framework towards zero carbon refurbishment of existing buildings in New Zealand (RefurbZC). First, comprehensive literature reviews reported in the studies (Bui et al., 2021b, Bui, Domingo et al., 2022) identified a structure and critical components for the refurbishment decision-making process in the international context. Second, the findings from a preliminary study using semi-structured interviews with building experts regarding zero carbon refurbishment of existing buildings in New Zealand as well as an in-depth investigation into the decision-making process of three real-life building refurbishment case studies considering whole-of-life carbon reduction provided practical implications, zero-carbon relevant aspects and

areas of improvement in the refurbishment decision-making process in the New Zealand context. Third, as the RefurbZC framework was specifically designed to be applied within the New Zealand building and construction industry, lessons learnt from international practices were adapted in a way that is appropriate to the New Zealand circumstance. An additional literature review was also conducted to determine building refurbishment-related policies and guidelines required for building refurbishment in New Zealand. Through an interactive and critical analysis between primary and secondary data, the RefurbZC framework's main components and characteristics was generated.

After that, a semi-systematic literature review was conducted to select the most suitable model to categorise RefurbZC's main components and characteristics discovered from the literature review and empirical data. The lean philosophy, which originated from the Toyota Car Manufacturing Company as an innovative approach to increase efficiency, effectiveness, and productivity in construction projects, was adopted to develop the new RefurbZC. This approach was selected due to its popularity in design and engineering practices, particularly in implementing integrated project design and delivery solutions for construction projects (Babalola et al., 2019). It takes advantage of the technological solutions becoming available (e.g. BIM) and ensures that improvements in construction projects are considered as a holistic combination of people, processes, tools and technology, recognising the intrinsic requirement for all three of these aspects to be addressed in parallel (Owen et al., 2010).

The original lean-based sociotechnical systems model has three primary subsystems: 1) process, 2) people, and 3) tools and technology (Morgan & Liker, 2020). Collaboration is an important element of lean thinking in construction, facilitating the integration of different actors' competences and efforts in joint problem-solving (Eriksson, 2010; Babalola et al., 2019). However, collaboration attributes such as good communication, which are central to establishing a cohesive partnering team (Azari & Kim, 2016; Hosseini et al., 2016; Kesidou & Sovacool, 2019), have not yet been incorporated in lean-based sociotechnical systems model. In line with the findings from the study of Bui, MacGregor et al. (2023) which emphasised the key attributes defining the ideal collaboration and integration process in delivering building refurbishment towards zero carbon, this research extended the lean-based sociotechnical systems model by including the collaboration and integration

subsystem in the development of the RefurbZC framework. Thus, the application of the lean-based sociotechnical systems model in designing RefurbZC can be summarised as follows:

- **People:** Stakeholders and their timely involvement in the project.
- **Process:** Five steps and the sequences of the steps.
- **Tools and technology:** Tools and technology employed to deliver the tasks.
- **Collaboration and integration attributes:** Key attributes describing the ideal process of collaboration and integration to reduce carbon emissions for building refurbishment.

10.3.2 Framework validation

The RefurbZC validation aims to examine the developed framework in terms of its appropriateness, potential implementation, and areas of improvement. To achieve this aim, a focus group workshop was conducted with building experts involved in the refurbishment process to explore their expert knowledge and industry experience, critical reflections, and recommendations to ensure that the developed framework is applicable and generalisable to the industry practice. The focus group workshop was chosen as the most appropriate approach for this study due to the opportunity to guide product, program, service development and examine its effectiveness (Liamputtong, 2011; Hennink, 2013; Krueger, 2014). In particular, the focus group is useful to pilot-test the prototypes to fine-tune ideas, concepts or plans before implementing (Krueger, 2014). It is not only identifying the drawbacks of prototypes but, more importantly, understanding why these deficiencies exist, providing richer explanations of how to improve specific components compared to the quantitative validation approach (Hennink, 2013; Subiyakto et al., 2015). Moreover, the involvement of relevant experts in developing frameworks is key in optimising a buildings' environmental, energy and cost performance (Dauletbek & Zhou, 2022).

The focus group workshop was prepared, organised, and moderated based on the recommendations provided by (Krueger, 2014). In the planning stage, a focus group protocol including the purpose, background information, types of information needed, types of participants to be invited, questionnaires, the workshop structure and activities, number of groups to be conducted, plan of action, deliverables, timeline, and budget was developed. The protocol was then peer-reviewed and refined by academic researchers experienced with focus group discussions and familiar with the issue being studied.

The following stage purposively recruited participants based on their professional background, pertinent knowledge and reputation in the New Zealand building and construction industry. The participant selection criteria included (1) those who have worked within the New Zealand building and construction industry for at least five years, (2) those who have knowledge and expertise in sustainable design, construction, project delivery or related skills, (3) those with experience of carbon-reduction initiatives for building refurbishment projects. A professional networking platform, LinkedIn, was used to identify potential participants responsible for sustainability issues and/or those who experienced and/or led sustainable/green building projects within government agencies and construction firms. Participants received an invitation via email and were then asked to carefully read the project information, sign the written participant consent form following standard ethics protocols and confirm their attendance at the workshop. A panel of 11 experts representing various building stakeholders involved in the building refurbishment projects, including building clients/developers, projects managers, engineers, architects, sustainability and carbon consultants, cost advisors, contractors, and facilities managers, agreed to take part in the focus group discussions. The experts have been working for government agencies and construction/property companies of various sizes in New Zealand, specialising in sustainable construction and carbon reduction in building projects.

One week before the workshop, an information sheet was sent to all participants setting out pre-workshop and workshop agendas, research background, and an introduction to the developed framework. Participants were asked to read the information carefully, go through each step of the framework and think about the questions discussed during the workshop. In the implementation stage, the workshop was held virtually via Microsoft Teams on 22nd September 2022. The online workshop method was chosen because it greatly expands the pool of potential participants and adds considerable flexibility to the process of scheduling the time and date (Stewart & Shamdasani, 2017). Busy professionals and those located across the country, who might otherwise be unavailable for a face-to-face meeting, can often be reached through information technologies. In addition, there were also potential researcher benefits such as cost and time-savings due to the automatic and accurate capture of the discussion data (Tates et al., 2009; Stewart & Shamdasani, 2017). Not to mention COVID-19 impacts and restrictions, the use of virtual groups created a healthy and safe environment where participants

can contribute at their leisure and individual location (Dodds & Hess, 2021). Table 10-1 shows the participants demographics.

Table 10-1: Focus-group participants' profiles (Source: Authors)

Expert #	Position	Type of organisation
1	Lead Climate Mitigation Advisor	Local Government
2	Facilities Manager	State sector
3	Strategic Project Planner	State sector
4	Project Director	Project Management
5	Project Manager	Construction
6	Sustainability Engineer	Engineering Consulting
7	Sustainability Consultant	Environmental Consulting
8	Carbon Navigator	Engineering Consulting
9	Architect – Carbon Analyst	Architecture and Design
10	Architect – Sustainability	Architecture and Design
11	Architect	Architecture and Design

The workshop started with the moderator providing a brief presentation about the framework and its development. Next, participants were asked to introduce their interests and experience in the topic. Moving into the main parts of the workshop, two group discussions took place in the breakout rooms. The first discussion was for critically analysing, providing feedback and suggestions for improvement of the framework (e.g. what should be improved, changed, added, re-worded or clarified in the framework). The second discussion focused on the potential implementation of the framework. Participants were randomly allocated into three small focus groups for each debate, with each group having a unique colour code. An electronic Microsoft form indicating the instruction and questions was shared with each group for recording the answers. The groups were colour-coded into blue, green, and red groups and had a minimum of 3 and a maximum of 4 participants, respectively. After that, all participants returned to the common meeting room to share the group discussion results. The moderator then stimulated discussion between the participants by encouraging them to express their critical views and exchange opinions. The workshop was wrapped up with an online survey and a meeting Poll. The purpose of using the questionnaire in the end of the focus group was to quickly gather each participant's beliefs and opinions about the framework based on their experience and reflection on topics

discussed (Krueger & Casey, 2014). The questionnaire was developed using Qualtrics XM online survey and Microsoft forms platform. This short questionnaire consisted of two parts, aiming to gather participants' viewpoints on the potential implementation of the framework and their likelihood of applying it in their future work.

The virtual workshop was video recorded with permission from participants. Data were also recorded from electronic forms, surveys, hand-written notes, and memory. Transcriptions and notes were logged and coded in line with the developed framework for thematic analysis to yield qualitative results (O.Nyumba et al., 2018; Braun & Clarke, 2022). A qualitative data analysis software – Nvivo – was adopted to support a five-stage process of transcribing and preparing data, data organisation, data familiarisation, themes creation and assigning of codes, and data sorting to identify main themes in each category from the data obtained (Hoover & Koerber, 2009; Bazeley & Jackson, 2013). Even though qualitative data was mainly collected during the workshop, there were a few questions in the questionnaire survey that generated quantitative data. The quantitative data generated from these questionnaires had different scales of measurement including interval/ratios, ordinal, nominal and dichotomous. However, the main objective of the focus group was to capture views associated with the benefits and potential implementation of the framework. Therefore, a simple and meaningful data representation approach was given priority. Mostly, descriptive statistics were used in this research to analyse data related to different questions. Descriptive statistics describe or summarise data that include counts (numbers or frequency); proportions (percentages); measures of central tendency (the mean, mode and median) and measures of variation (range and standard deviation) (Fink, 2006). However, while analysing data from the questionnaire, computing counts (numbers or frequency) and proportions (percentages) were used as the appropriate method of reporting data. Therefore, the statistical analysis techniques considered in this study were non-parametric procedures. Moreover, all the quantitative data obtained in this research study was manually arranged with the support of Microsoft Excel, without using any quantitative data analysis software like SPSS.

10.4 Findings

10.4.1 An overview of RefurbZC development and validation

The RefurbZC was developed as a holistic decision support framework for building refurbishment projects. The main purpose of RefurbZC is to provide a detailed guideline to use in the early stages of the refurbishment process to reduce carbon emissions. The RefurbZC was designed to ensure that all relevant information is collected and considered logically, robustly, and consistently before making decisions. It helps to understand the refurbishment decision-making process, identify areas for integrating carbon-reduction initiatives, determine key factors and actors in driving carbon-reduction solutions, and promote stakeholder collaboration and integration in carbon-reduction building refurbishment. The developed framework can be used to formulate carbon-reduction objectives and deliverables for refurbishment projects and to enable focus on essential aspects for the primary decision makers. The developed framework can also be used as a collaboration and communication tool between different stakeholders and help in making evaluations based on expectations. The tool can monitor and evaluate the obtained results and provides the opportunity to evaluate alternative proposals. A copy of the developed framework before validation can be found in Appendix 5.

The RefurbZC's scope of work includes the major refurbishment of existing non-residential buildings which have been chosen to be refurbished. RefurbZC is a process-oriented framework that can be used by anyone with insight into the project. They are building stakeholders involved in the process of delivering or making decisions in the refurbishment, including but not limited to building clients, projects managers, engineers, architects, sustainability and carbon consultants, cost advisors, contractors, subcontractors, suppliers, facilities managers, and end-users. Although the final decision is made by building clients, this approach ensures that various perspectives, sources of information and interests are represented. It is recommended that decisions are made with input from all building stakeholders.

The findings from the framework validation have confirmed that the RefurbZC provides a consistent and comprehensive decision-making process that can be applied to every refurbishment project incorporating carbon reduction initiatives. It was thought that RefurbZC can encourage the uptake of building refurbishment, in which the carbon reduction goal is prioritised. With social cooperation being demanded, decision-makers

and their advisors tend to look for a holistic process to follow. As recognised by all experts participating in the focus group discussion, there are various ways that the RefurbZC could benefit users such as building clients, developers, project managers, architects, engineers, cost advisors, sustainability and carbon consultants, contractors, subcontractors, suppliers, and the user group (e.g. facilities managers and end-users). For example, all experts agreed that the framework offers valuable information supporting decision-making in the procurement and design of refurbishment projects by providing detailed guidance on what should be done regarding carbon reduction initiatives. According to over half of the participants, the framework could be adopted as a conversation starter with decision-makers which encourages carbon-reduction decisions to be made early in the refurbishment process. Another RefurbZC application could be a baseline and reference to ensure inclusive information and evidence provided by relevant stakeholders have been considered to make informed decisions, as indicated by most of the participants (80%). The framework was also acknowledged by experts #2 and #3 as a mechanism to support the post-occupancy evaluation in the operation stage. For example, the performance gaps related to energy use and high maintenance costs could be identified by understanding why particular decisions were made.

The survey distributed to all experts at the end of the workshop echoed their viewpoints on the potential implementation of the RefurbZC. The survey respondents were asked to rate the level of agreement with statements from 1 “strongly disagree” to 5 “strongly agree”. The results obtained from the survey are shown in Table 10-2, with the majority of respondents (above 90%) being either “agree” or “strongly agree” on the potential implementation and benefits of the RefurbZC to the industry practice. In addition, the Poll asked the respondents to indicate their likelihood of applying the framework in their future work. The Likert scale was used to weigh the response of the Poll respondents by setting the “definitely” as 5, the “probably” as 4, the “possibly” as 3, the “probably not” as 2 and the “definitely not” as 1. The Poll results reveal positive feedback on the potential adoption of the RefurbZC in future refurbishment projects, as shown in Figure 10-1.

Table 10-2: Survey results regarding RefurbZC potential implementation and benefits (Source: Authors)

RefurbZC potential implementation and benefits	Mean	Mode	Standard deviation
The framework could possibly help you understand the refurbishment decision-making process and requirements for reducing carbon emissions in certain activities	4.5	5	0.5
The framework could possibly help you identify areas for addressing carbon-related issues in the early stages of the refurbishment process	4.25	4	0.433
The framework possibly provides relevant information that supports your decision-making in reducing carbon emissions of building refurbishment	4	4	0.5
The framework could possibly help promote stakeholder collaboration in identifying carbon-reduction solutions for building refurbishment	4.25	4	0.433

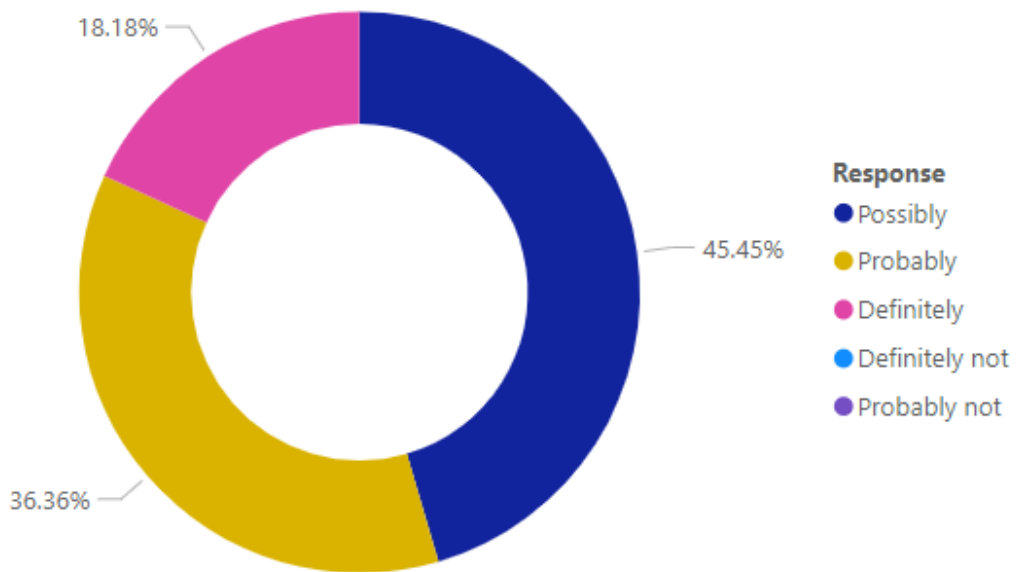


Figure 10-1: Results on the potential adoption of the RefurbZC in future refurbishment projects (Source: Authors)

However, several common views were established amongst experts regarding the need for further improvement of the developed framework. The detailed description of improvement suggestions and actions taken to modify the RefurbZC framework that catered for the experts' validation input and evaluation can be found in the Appendix 5. These findings have significant implications for improving the motion and efficacy

of decision-making process. Incorporating the findings from the focus group workshop with the critical reflection on the results of literature reviews, preliminary study and case studies reported in previous studies (Bui et al., 2021b; Bui, Domingo, et al., 2022; Bui, Domingo, Wilkinson, et al., 2022; Bui, MacGregor et al., 2023; Bui, Wilkinson et al. 2023), the following section describes the RefurbZC framework in its final form together with the discussion around the appropriateness of the specific elements of the RefurbZC.

10.4.2 RefurbZC finalisation

The high-level framework of the RefurbZC includes four components: people; process; tools and technology; collaboration and integration attributes, as demonstrated in Figure 10-2. The arrow presents the circular link between steps, demonstrating the continuous evaluation, reflection, and improvement throughout the process. The refurbishment decision-making process comprises five steps: (1) Building Condition Assessment; (2) Goal Setting; (3) Refurbishment Strategies; (4) Generation of Refurbishment Alternatives; (5) Performance Estimation and Evaluation. These steps align with design phases in NZCIC guidelines – New Zealand Building and Construction Industry Council to indicate a formal relationship between the steps of the framework and the actual project timeline. The low-level of the framework also includes four components: people, process, tools and technology, collaboration, and integration attributes that provides the comprehensive decision-making processes, decision points, additional guidance and lists of the information needed to inform decisions at each step. The following sub-sections outline the low-level of the framework in detail.

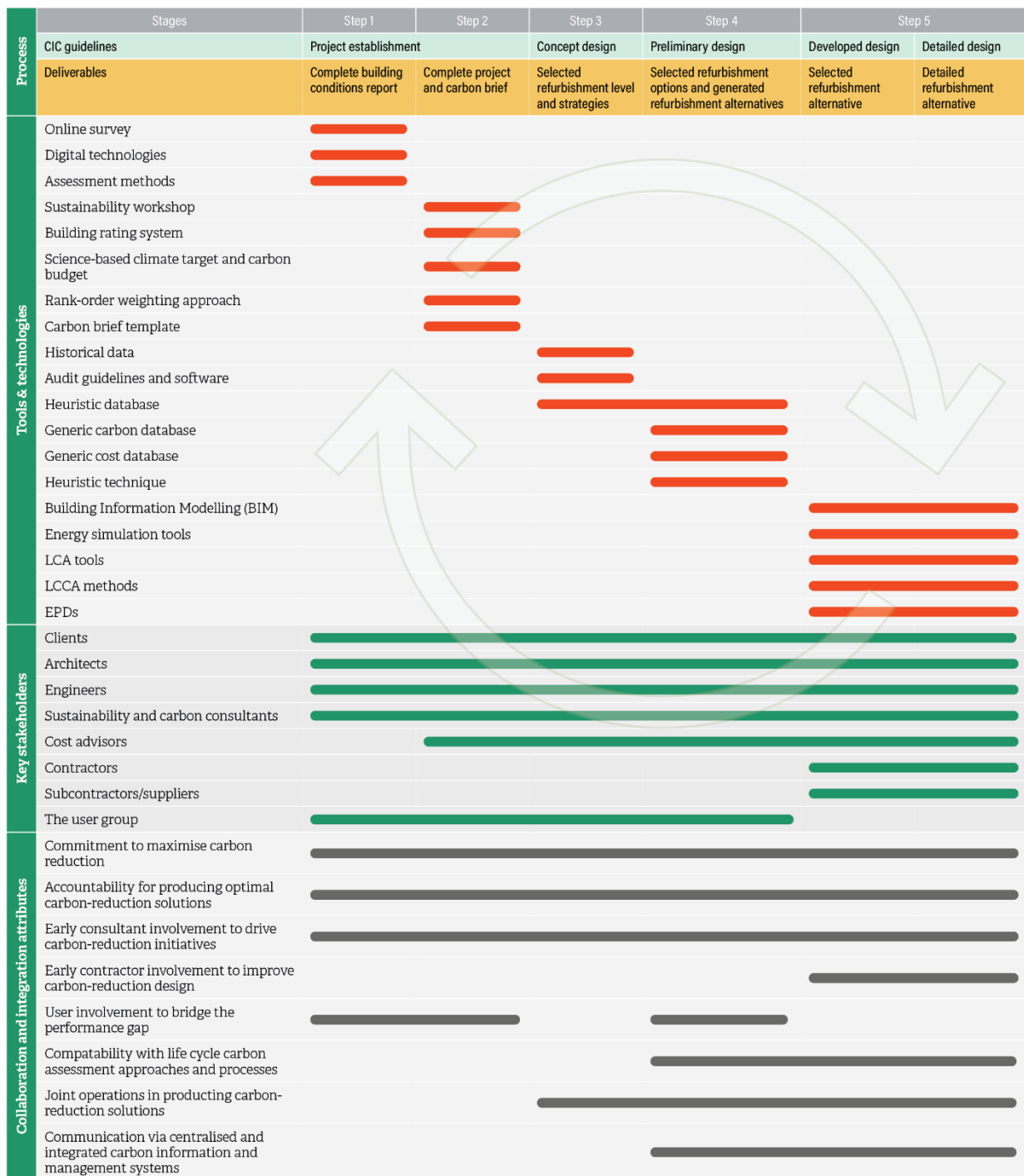


Figure 10-2: The high-level of five-step decision support framework (Source: Authors)

10.4.2.1 Step 1: Building condition assessment

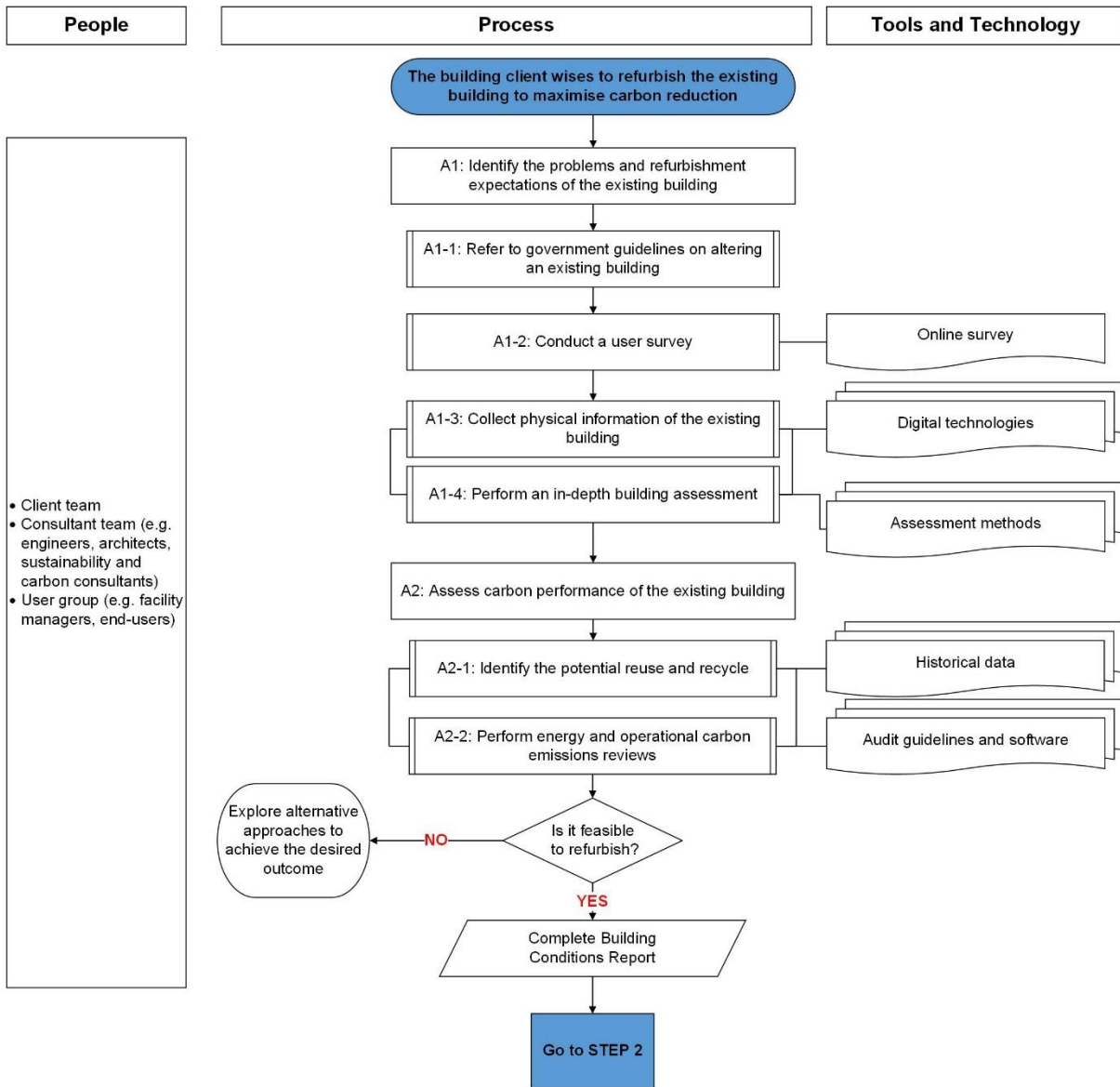


Figure 10-3: The low-level of decision support framework - Step 1 (Source: Authors)

The decision-making process begins with a building client wanting to refurbish an existing building to maximise carbon reduction. As suggested by experts participating in the focus group, having a carbon-reduction aspiration at the beginning of the process is important to enable the carbon-reduction focus throughout the process. Setting the carbon-reduction aspiration at first is also critical to draw an intention to carbon-targeted improvement areas for the existing building. Therefore, this important point has been added to the beginning of the process to clearly demonstrate the intention of the refurbishment.

Step 1 (A) of the framework is the building condition assessment. The building condition assessment is often used to recognise the degradation state of building components and services, identify system operational problems, and examine the building performance to determine whether the existing building can be refurbished. The assessment results are also used to identify appropriate refurbishment levels, strategies, and solutions later in the refurbishment process (Ma et al., 2012; Ferreira et al., 2013; Nielsen et al., 2016; Bui et al., 2021b; Bui, Wilkinson et al., 2023). The client team and the user group (e.g. facilities managers, end-users) are encouraged to be involved in Step 1. Subject to the resources and experience, client representatives and facilities managers can be responsible for undertaking activities in Step 1. However, the consultant team (e.g. engineers, architects, sustainability, and carbon consultants) is recommended to be involved in this step to help conduct an in-depth building condition assessment (Bui, Wilkinson et al. 2023; Bui, MacGregor et al. 2023).

Step 1 starts with activity A1, which is identifying the problems and refurbishment expectations of the existing building. First and foremost, the government guidelines on altering an existing building need to be reviewed to ensure the refurbishment meets the government requirements (A1-1) (MBIE, 2018). If the building is considered vulnerable to earthquakes, MBIE's EPB methodology for identifying and assessing earthquake-prone buildings should be followed (MBIE, 2017).

Next, the inclusion of conducting a user survey (A1-2) in Step 2 is highly recommended to better understand the building's operational and functional problems. The involvement of the user group provides perspectives on the area of improvement required in the refurbished building. It also helps the process of assessing building performance to be more targeted. Information about the user's activities and expectations could help determine appropriate refurbishment solutions in the later steps and bridge the performance gap in the post-refurbishment stage (Kesidou & Sorrell, 2018; Li et al., 2018; Bui et al., 2021b; Bui, Wilkinson et al. 2023). The findings from the focus group further support this idea, indicating that conducting user survey helps inform the scope of assessment work in the following activities, define project refurbishment objective, and target the building areas being assessed based on users' perspectives (#1, #2, #4, #10). However, this aspect has not been widely recognised in the current practice in New Zealand according to the majority of participants. Participant #6 explained that "the users have been using the building for years, and they could point out which parts of the building they like or dislike. That would help you look out for it in a different way. It is more valuable to have

the information from the users before the building assessment starts”. If the refurbished building accommodates new occupancy, the involvement of facilities managers is imperative to better understand the refurbishment expectation. Thus, the user group’s perspectives should be considered to help generate appropriate strategies for addressing the problems of the existing building. Figure 10-4 demonstrates an example of user survey results.

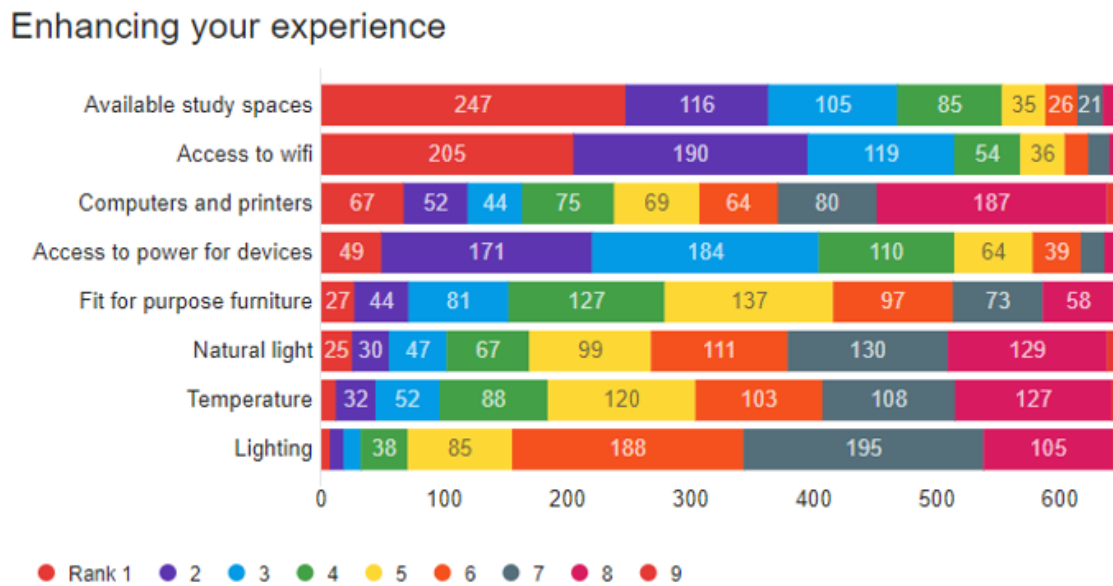


Figure 10-4: Example of user survey results (Source: Case study 2)

Following the results of the user survey, physical information about the existing building can be collected (A1-3), such as building location, building type, total building area, site orientation, gross floor area, occupancy, year built, type of construction, number of stories and other information about the existing building’s design and construction. At the same time, the client and consultant team can also perform a walk-in building assessment and generate a checklist providing a systematic registration of the degradation state of the building elements (A1-4) (Ma et al., 2012; Ferreira et al., 2013; Bui et al., 2021b; Bui, Wilkinson et al., 2023). The assessment checklist includes identified building problems, physical and functional building conditions, and the current state of structural elements, envelopes, services, and internal fittings. Each building item can be qualitatively ranked on a point system (Likert scale) from good to poor condition or a two-form system consisting of “yes – items to be upgraded” and “no – no change” (Bui, Wilkinson et al. 2023). Photography and video ought to be included for a visual demonstration. Using technologies such as 3D/Laser Scanner can

also help improve the site surveying and inspection by capturing and mapping the existing building information. This can later be integrated with the BIM model to enhance the accuracy of tracking information, improve data management, and increase productivity.

Table 10-3: Example of a systematic registration of the degradation state of the building components using a point system (Source: Authors)

Building elements/problems	Very poor (1)	Poor (2)	Average (3)	Good (4)	Excellent (5)
HVAC system		X The system is beyond its life expectation			
Lighting system				X The system operates in a good condition	
Indoor air quality	X Inadequate Ventilation				
Others					

Quantitative methods such as structural and material tests are recommended for assessing the existing building structure and materials, as reported in the case study (Bui, Wilkinson et al. 2023). This is because the existing building problems affect the achievement of project goals, especially carbon-reduction targets, which depended on different building typologies and aspects. For example, during the focus group discussion, participants #3, #5 and #8 indicated that it may not be able to achieve high embodied carbon reduction targets for earthquake-prone existing buildings due to the requirement of using a large amount of newly added construction materials and products to strengthen the building. In addition, participants #5 and #7 claimed that the most important assessment in Step 1 is the existing structural and material tests, which identify whether the existing building structure and materials could be retained. This benefits the carbon setting in terms of

determining how much existing material could be reused. This result, while not widely recognised in the literature, confirms the necessity of an in-depth analysis of existing building problems.

Table 10-4: Example of a systematic registration of the degradation state of the building components using a two-form system (Source: Case study 1)

HVAC system					
Areas	Ducted Preconditioned Outside Air	Ducted Return Air	Toilets AC and Exhaust	AC in Offices Teaching Spaces and Corridors	Full BMS Control
Level 1	Y	Y	Y	Y	Y
Level 2	Y	Y	Y	Y	Y
Level 3	Y	Y	N	Y	Y
Level 4	Y	Y	N	Y	Y

Note: Y: Yes – items to be replaced; N: No change

The following activity (A2) focuses on assessing the carbon performance of the existing building. Regarding embodied carbon emissions, the potential reuse and recycling of the existing structural elements, envelope, and internal fittings can be determined after assessing the current building condition (A2-2) (Bui, Wilkinson et al. 2023).

To determine the potential areas for improving energy efficiency and reducing operational carbon emissions, the client and consultant team can perform energy and operational carbon emissions (associated with energy and water use) reviews (A2-1) (Jaggs & Palmer, 2000; Xu et al., 2011; ASHRAE, 2011; Ma et al., 2012; Nielsen et al., 2016; Bui, Wilkinson et al., 2023). This can be done by carrying out basic energy performance reviews, including total annual energy consumption and heating, lighting, and electricity usage, from historical data such as and/or conducting energy bills or energy and operational carbon audits. The client and user group can provide the data collected from basic energy performance reviews, while the consultant team can be responsible for undertaking energy and carbon audits. The auditing guidelines are ASHRAE Handbook, AS/NZS 3598.1:2014 and the Ministry for the Environment’s “Measuring Emissions: Detailed Guide 2020”.

Energy and operational carbon audits are highly recommended to be carried out as the results of energy and carbon audits can be used later as a baseline/reference for the design improvement and comparing the building

before and after refurbishing. While this view has also been widely recognised in the literature (Ma et al., 2012; Ferreira et al., 2013; Bhuiyan et al., 2015; Nielsen et al., 2016), there has been little evidence of implementing energy and carbon audits in the current practices, as recognised in the findings of the case study (Bui, Wilkinson et al. 2023; Bui, MacGregor et al. 2023) and the focus group. A possible explanation for this was proposed by some experts during the focus group discussion. First, in the case of a major refurbishment, the design of the refurbished building could be changed, and the existing building services could be removed. Second, suppose the refurbished building was adaptively reused for different purposes (e.g. refurbishing a warehouse into an office building). In that case, the energy data collected in the pre-design stage might not be applicable for future use of the building. In addition, the audit accuracy can be subject to the availability of energy data, which have not been currently well-managed in the current practice in New Zealand. Therefore, it was suggested that this activity can only be done on condition of available budget and resources, the existing and future use of the refurbished building and data availability.

At the end of this step, the decision on whether to refurbish the existing building can be revised. If it is not feasible to refurbish the existing building, alternative approaches (e.g. change the use with minimum intervention, adaptation with a minor change, demolition, and redevelopment) should be explored to achieve the desired outcome. The project team is also expected to complete the Building Conditions Report, which includes a list of to-be-improved areas.

10.4.2.2 Step 2: Goal setting

Step 2 (B) of the framework is to set the right goal that meets the project requirements, budget, and expectations. Setting goals and criteria is an important point of the refurbishment process since the decision made in the following steps are adapted to these strategic and significant aspects (Ferreira et al., 2013; Bui et al., 2021b). The client team is mainly responsible for setting and prioritising the refurbishment goals and criteria. Subject to the client's experiences and resources, the consultant team (e.g. engineers, architects, sustainability, and carbon consultants) and cost advisors can be engaged to provide support in setting the right goal. The client may assemble the right project team members and appoint a leading consultant at this stage. The user group can also provide perspectives on the project goals (Bui, MacGregor et al. 2023).

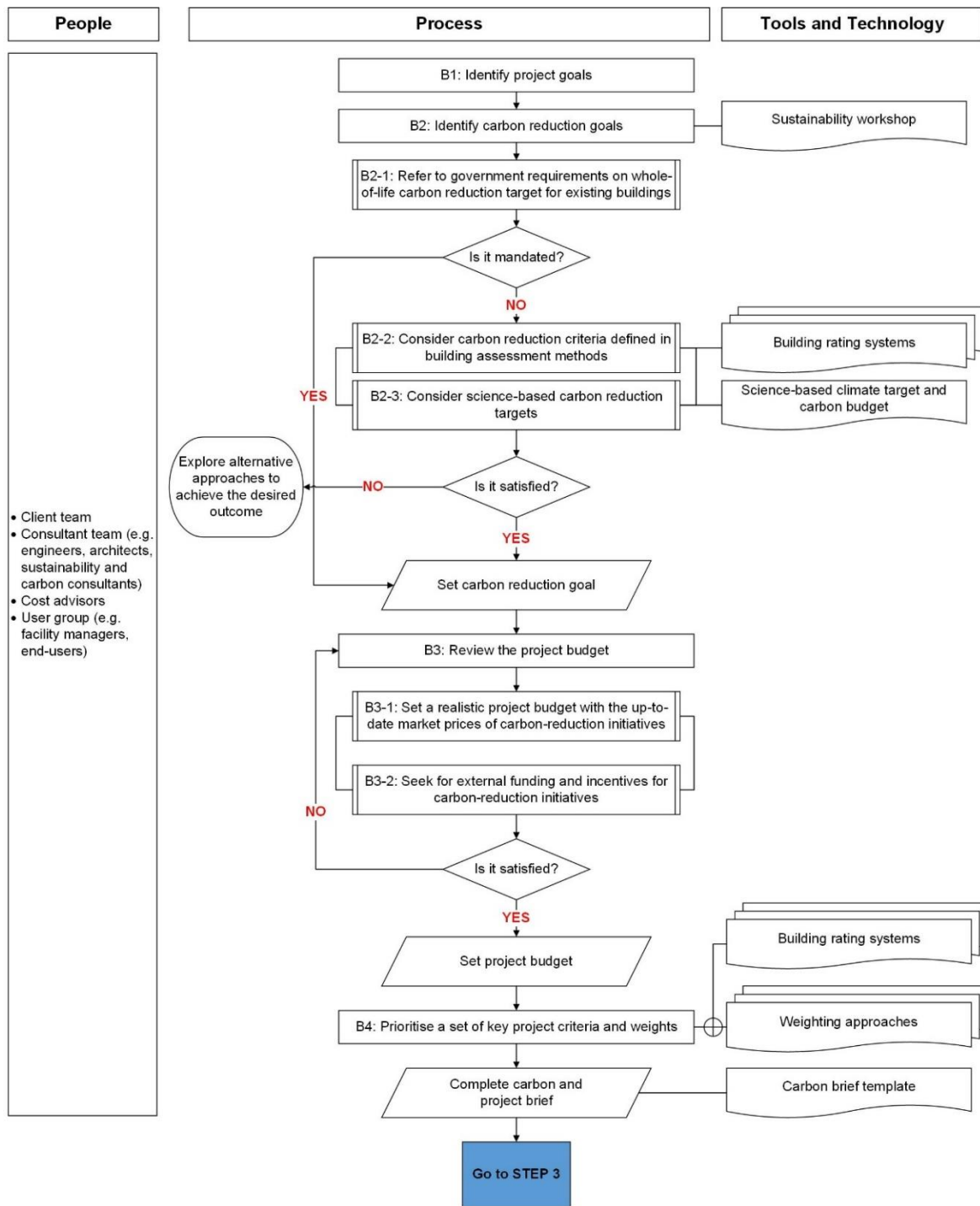


Figure 10-5: The low-level of decision support framework - Step 2 (Source: Authors)

The departure point of Step 2 is activity B1, where the client team first identifies the refurbishment project goal based on the organisation’s strategies, drivers, and values (Andresen, 2000; Ferreira et al., 2013; Nielsen et al., 2016; Bui, MacGregor et al., 2023). Table 10-5 demonstrates an example of determining refurbishment project goals.

Table 10-5: Example of determining project goals (Source: Case study 2)

Case study of a university building	Project goals
Organisation's strategies	Alignment with the organisation's Zero Carbon Plan
	Alignment with the organisation's Sustainability Strategy and UN Sustainability Development Goals
Project drivers and values	Community Benefits & Positive Environmental Impact
	Public, Students and Staff Visibility of Sustainability Initiatives
	The ability of the building to be re-purposed for low carbon
	Increasing student study capacity; creating modern fit-for-purpose student spaces; rationalising the print collection to free up space; seismic strengthening to bring the building up to the current Building Code

As maximising carbon reduction for the refurbishment project that aligns with the organisation's roadmap to achieve a net zero-carbon target is an aspiration, activity B2 is identifying the right carbon reduction goal for the refurbishment project. Subject to the client's resources and experience, a sustainability workshop should take place where the consultant team can be involved to support setting a whole-of-life carbon reduction target as a desirable outcome of the project (Bui, MacGregor et al. 2023). As agreed by experts taking part in the focus group, the sustainability workshop is a mechanism to enable the discussion around carbon reduction within the project team. The sustainability champion (e.g. sustainability managers/project managers from the client team and/or sustainability designers/consultants/advisors from the consultant team) can start the conversation on setting whole-of-life carbon reduction as a desirable project outcome. It was also acknowledged that the client and/or high-level decision makers in the client's organisation are key players in authorising carbon-reduction as a mandated goal for the project.

Activity B2 is presented as a hierarchy as suggested by experts during the framework validation process. The mandated option (B2-1) is following the New Zealand government's 'Building for Climate Change' programme, which sets legal minimum levels of operational efficiency and limits for embodied carbon in buildings (MBIE, 2020). The other options are volunteering, considering carbon reduction criteria defined in building rating systems (B2-2) and science-based whole-of-life carbon reduction targets (B2-3) (Bui, Wilkinson et al., 2023). The consultant team may assist the client in identifying the carbon reduction criteria

by pre-assessing the potential application of building rating systems and whole-of-life carbon reduction targets (Bui, MacGregor et al., 2023).

Indeed, there are some positive and negative benefits of each option that should be taken into account. It is important to note that building rating systems can be used early as a structured methodology to support the decision-making process by providing a direction for setting the goal, prioritising key criteria and specific areas of improvement, and potential design implications. The approved and recommended methods can be found in New Zealand Government Procurement (2021). The decision to include these rating systems to use early rather than to assess the finished building encourages the project team to incorporate the carbon-related design consideration throughout the process. However, these systems may not be fit-for-purpose due to being inflexible in design, laborious to include in the early stages, and limitations recognising the project values. There could be a tendency with the building rating systems to put a capital cost value on points and targeting points based on their cost rather than the value that criteria offered. Thus, the benefits of the design options need to be identified separately to align with the key project criteria during the design stages. These benefits can then be considered alongside the design requirements of rating systems rather than using these systems as a framework to inform design inclusions (Bui, Wilkinson et al., 2023).

Due to the limitation of some building rating systems on prioritising the maximum whole-of-life carbon reduction, it is important to consider the science-based carbon budget of New Zealand's buildings. For example, Bullen L. et al. (2021) calculated the carbon budget for New Zealand's office building sector, which is estimated as 2140 ktCO_{2eq}. This consideration helps establish a carbon benchmark for a comparative life-cycle carbon analysis to optimise the refurbishment design later in the process (Bui, Wilkinson et al., 2023). However, it also can be time-consuming and requires a lot of detailed information, such as the schedule of quantities, energy modelling, LCA, etc., which will be substantiated later in following steps. Furthermore, the climate target and carbon budget, as mentioned above, only apply to new buildings. A carbon budget for an individual building/whole existing building stock is expected to be estimated in future work. Thus, building rating systems and the climate target and carbon budget can be considered together to help achieve both sustainability and maximum carbon reduction goals.

After identifying the carbon reduction goal in B2, the question is whether the determined carbon goal is satisfied. If no, alternative approaches are explored to achieve the desired outcome. Otherwise, the outcome of this activity is to set a carbon reduction goal following one of the three mentioned options.

The process continues with activity B3, which is reviewing the project budget. The cost advisor should be involved in helping facilitate a better understanding of the cost and carbon-savings related to carbon-reduction initiatives across all aspects of the building and set a realistic project budget with up-to-date market prices (B3-1), as reported in the case study (Bui, Wilkinson et al., 2023) and the focus group. Simultaneously, the project team is encouraged to seek external funding and incentives for carbon-reduction initiatives (B3-2) (Bui, Wilkinson et al., 2023). It was suggested that a specific financial budget for carbon-reduction solutions can be specified in this step (Bui, Wilkinson et al., 2023). However, most experts participating in the focus group argued that the cost related to carbon-reduction solutions should already be included in the overall project budget rather than an additional cost for a specific carbon-reduction strategy. For example, experts #7 and #8 explained that “it is generally the first to get chopped, so easier if it sits within the overall project budget in the early stage”. This contrasting view can be related to potential bias from different building stakeholders’ perspectives. For instance, it is often acknowledged that carbon-reduction solutions are associated with higher cost from the client’s perspective. While from the consultant’s perspective, there are always ways to find carbon and cost-saving solutions in line with the project budget. Moving to the later steps, the carbon and cost-effective refurbishment options are further assessed, and the trade-offs between carbon and cost savings can be identified. Therefore, it is crucial to encourage the client to consider carbon-reduction initiatives and preserve the carbon targets as an aspirational goal in Step 2 without the cost constraints. Taken together, the specific financial budget for carbon-reduction solutions can be set but it should be within the overall project budget. The outcome of activity B3 is a set project budget. In the case of the limited budget against maximum carbon-reduction aspiration, the project team is still stimulated to proceed to the next steps, where detailed carbon-reduction solutions can be further identified and assessed.

Next, the client should prioritise key project criteria and weights (e.g. carbon, cost, energy, water, etc.) based on identified goals and budget (B4) (Wang et al., 2009; Nielsen et al., 2016). The user group should be engaged to provide information on the key project criteria for co-benefits for users, such as improving indoor air quality

(Kesidou & Sovacool, 2019; Rose et al., 2019; Bui et al., 2021b; Bui, Wilkinson et al., 2023). These criteria and weights are used later to assess the refurbishment solutions and performance. This can be done using a simple weighting approach (e.g. rank-order weighting) or a complex weighting approach (e.g. the analytical hierarchy process (AHP)) (Saaty, 1990; Arroyo et al., 2015), depending on the decision-makers' preferences, project drivers and values (Nielsen et al., 2016). Alternatively, the criteria and their weights in selected building rating systems can be followed (Ding, 2008; Ma et al., 2012). Trade-offs among key project criteria such as carbon and cost are inevitable in any design process. Even if comprehensive building rating systems are used, trade-offs must be made along the way. Figure 10-6 shows an example of prioritising the main project criteria using a simple rank-order weighting approach.

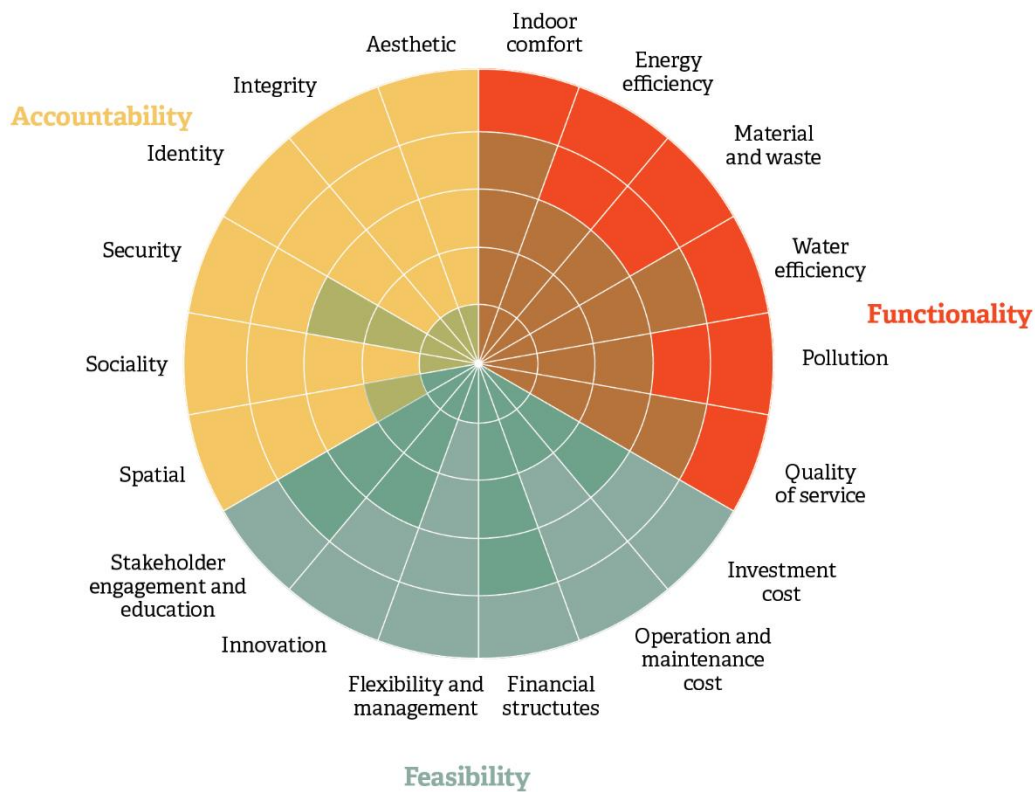


Figure 10-6: Examples of prioritising main project criteria (Scale of value: 0-5) (Kamari et al., 2017)

The outcome of Step 2 should be a complete carbon and project brief. The template and further guidance can be found in the New Zealand government guide to reducing carbon emissions in building and construction (New Zealand Government Procurement, 2021).

10.4.2.3 Step 3: Refurbishment strategies

The aim of Step 3 (C) is to establish the refurbishment level and strategies to achieve an overall long-term objective of building refurbishment projects. The client team is responsible for selecting the refurbishment level and refurbishment strategies. The consultant team (e.g. engineers, architects, sustainability and carbon consultants) and cost advisors could provide advice to support this decision (Bui, Wilkinson et al., 2023).

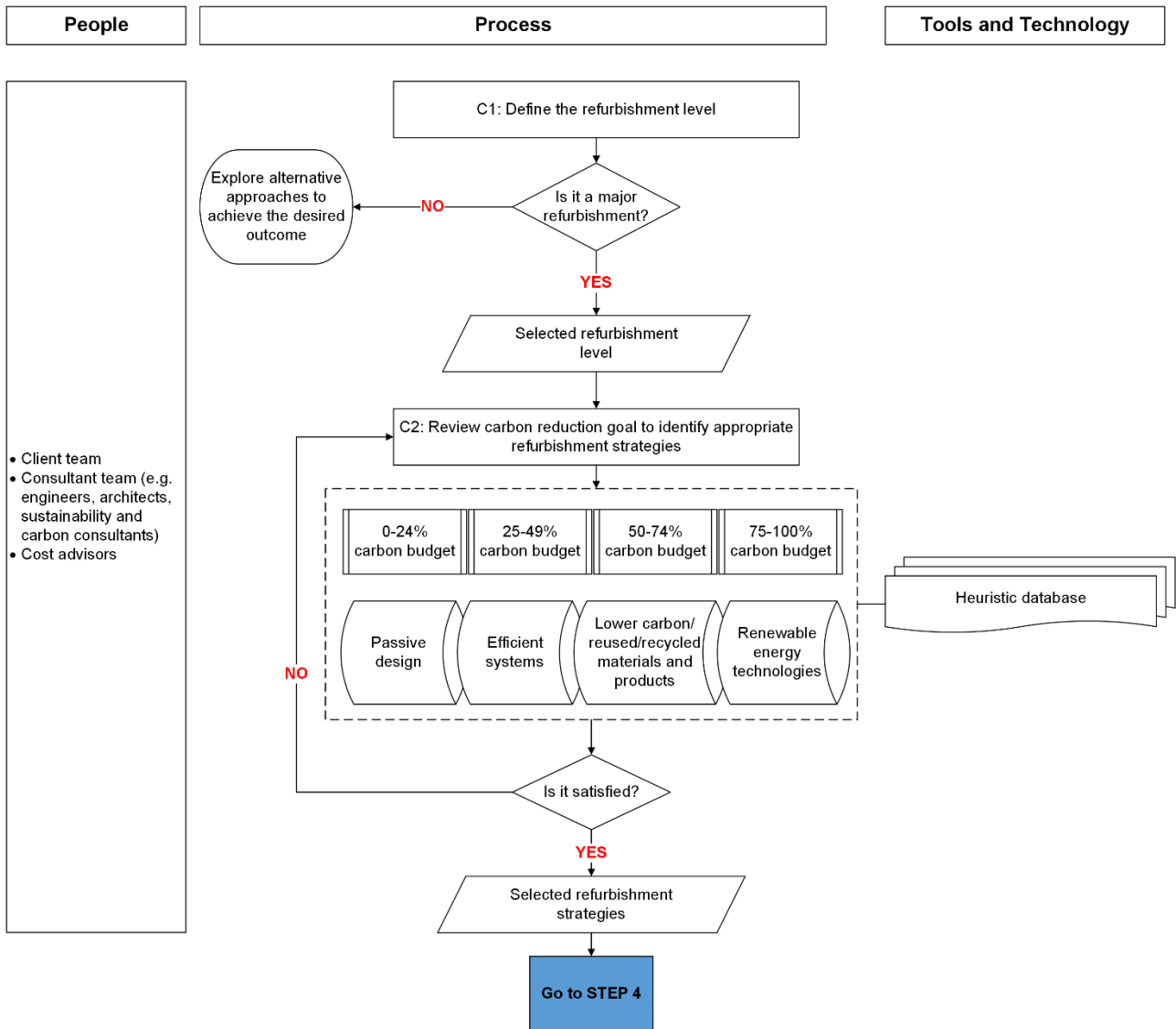


Figure 10-7: The low-level of decision support framework - Step 3 (Source: Authors)

The first activity (C1) is to define the refurbishment level based on the results of Step 1 and Step 2. According to experts participating in the focus group, there has been an inconsistent understanding of the difference between “major refurbishment” and “partial refurbishment” in the industry practice because of varying definitions and scope of work in New Zealand. The developed framework applies to major refurbishment

projects, therefore, the definition of “major refurbishment” is included to ensure transparency and consistency. Major refurbishment is defined as a significant modification and improvement to an existing building to bring it to an acceptable condition according to ISO 21931: 2010, EN 15978: 2011 and BREEAM: 2014. The refurbishment boundaries include the production of new components, transport of new elements, and construction as part of the refurbishment process, as well as waste management and end-of-life of the substituted and remaining existing building components (EN 15978: 2011; EN 15804:2012).

The decision on the refurbishment level should take the life-cycle cost and carbon emissions into account. This is because, in some cases, refurbishment focuses on upgrading certain building areas (e.g. upgrading building envelopes or building services), which may not resolve the problem of inefficient building operation in general. This could lead to a higher cost of ongoing maintenance and replacement and higher energy use and operational carbon emissions (Bui, MacGregor et al., 2023).

After selecting the refurbishment level, the next activity is reviewing the carbon reduction goal set in Step 2 to identify appropriate refurbishment strategies (C2). The carbon goal can be further broken down into classified levels (i.e. 0-24%, 25-49%, 50%-74%, and 75-100% carbon budget) (Bui et al., 2021b). This could help select corresponding refurbishment strategies, benchmark the alternatives, and optimise the design later in the process. Refurbishment strategies include passive design, efficient systems, lower carbon/reused/recycled materials and products, and renewable energy technologies (Xing et al., 2011; Jones et al., 2015; Loli and Bertolin, 2018; Bui, Wilkinson et al., 2023). Refurbishment strategies can be considered based on the heuristic database, such as previous project designs and case studies. However, there is a need for flexibility and freedom in selecting appropriate refurbishment strategies. This is because the consideration of the existing building condition and problems is the basis for developing refurbishment strategies. For example, passive design should be considered based on the physical conditions and capacities of the existing building. Renewable energy technologies can be regarded as long-term strategies for energy generation. However, performance assessment and feasibility studies are required to identify the trade-off between the advantages and disadvantages of these technologies (Bui, Wilkinson et al., 2023). The evaluation of refurbishment strategies can be done by the consultant team to support the client to make decisions (Bui, MacGregor et al., 2023). At the end of this step, the potential refurbishment strategies are selected.

10.4.2.4 Step 4: Generation of refurbishment alternatives

Step 4 (D) identifies different refurbishment options and alternatives. A refurbishment option means a design solution for addressing an existing building problem, such as upgrading the window and glazing system, installing a PV system, and adding wall insulation. A refurbishment alternative is a set of different refurbishment options, making the overall improvement of the refurbished building. The production of refurbishment options and alternatives usually involves the consultant team, including engineers, architects, and sustainability and carbon consultants. Cost advisors can take part to provide perspectives on cost-effective refurbishment options. Still, the client team is responsible for the approval. Optionally, the user group (e.g., facility managers, end-users) can be involved to provide input regarding their activities, behaviours, and ideal building features (Bui, MacGregor et al., 2023).

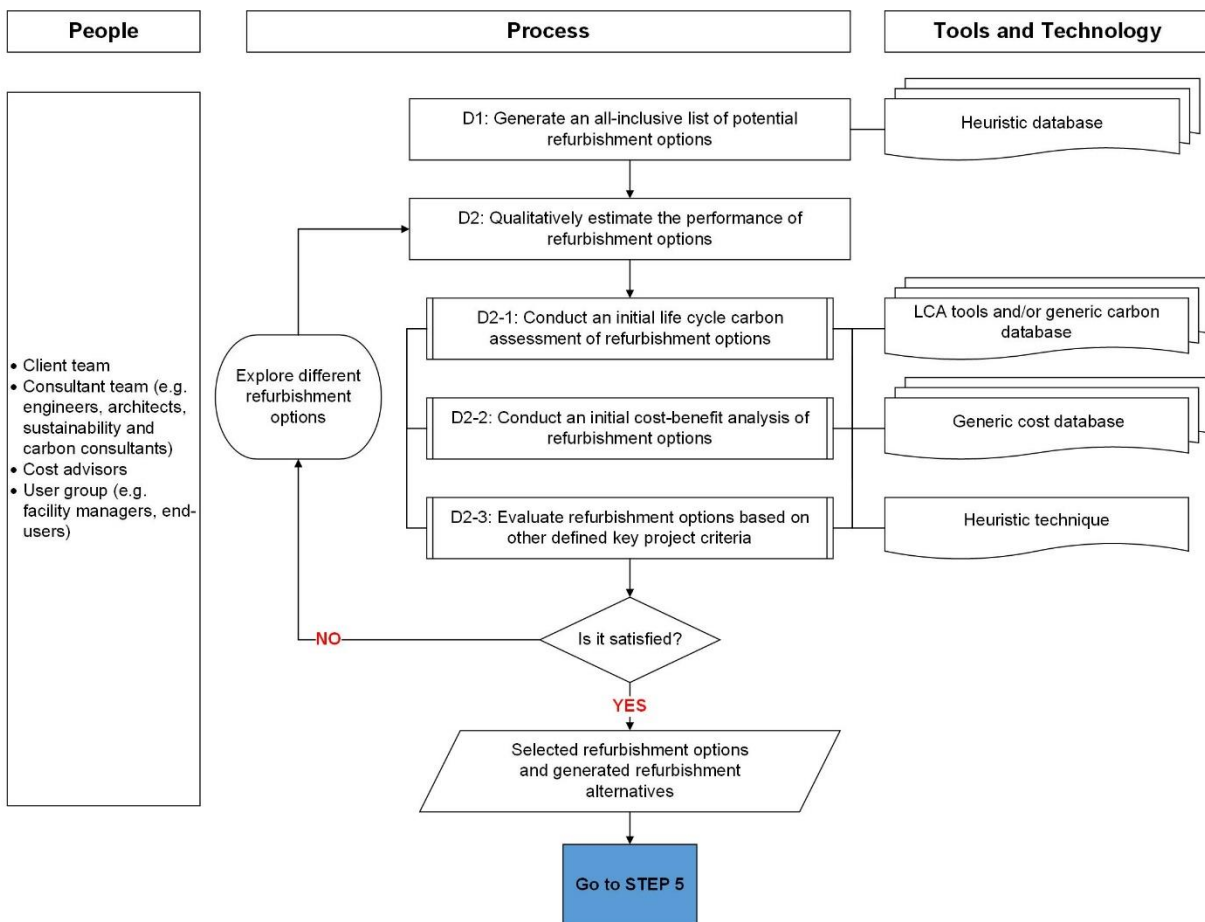


Figure 10-8: The low-level of decision support framework - Step 4 (Source: Authors)

To begin with, the consultant team generates an all-inclusive list of potential refurbishment options based on refurbishment strategies selected in step 3 (D1). The intention is to include all possible refurbishment options

in the decision-making at each design stage and encourage creativity and innovation in choosing refurbishment options. After that, the team could qualitatively estimate the performance of refurbishment options based on the key project criteria defined in step 1 (D2) (Bui, Wilkinson et al., 2023).




Sub-activities D2-1 and D2-2 are specific to addressing the whole-of-life carbon reduction goal. The consultant team conducts an initial life-cycle carbon assessment of refurbishment options to identify lower-carbon opportunities (D2-1). Sustainability and carbon consultants are key actors in identifying potential carbon-saving solutions (Bui, MacGregor et al., 2023). However, there might be a lack of information regarding the life-cycle carbon emissions of refurbishment options. Thus, initial carbon analysis should consider operational carbon emissions associated with energy use and initial embodied carbon emission related to the manufacture of building materials and products and the construction process (Module A1-A5 in building life cycle stages and modules BS EN 15978:2011). This can be done using available life cycle assessment tools and/or a generic carbon database (i.e., eTool, Tally, OneClick LCA, LCAQuick, LCAplay, CO₂NSTRUCT, CO₂MPARE, CO₂RE, EC3, etc.). At the same time, an initial cost-benefit analysis can be conducted using a generic cost database to determine lower-cost and lower-carbon refurbishment options of the best practices (D2-2). Cost advisors are accountable for identifying cost-effective opportunities (Bui, MacGregor et al., 2023). The refurbishment options are also evaluated based on other defined key project criteria (D2-3).

The results from the focus group corroborate that having the proposed sustainability and carbon-reduction register as shown in Table 10-6 is necessary to support decision-making. Indeed, it can help define the hierarchy of importance for each refurbishment option and their associated carbon impacts and benefits. The item can be ranked as a “must-have” or “nice-to-have”. This embraces the critical refurbishment options contributing significantly to carbon reduction that could eventually be removed later due to cost constraints.

If the considered refurbishment options meet the requirements and expectations, the project team selects a narrow set of possible options and generates refurbishment alternatives as the outcome of Step 4. Otherwise, different refurbishment options are explored, and the process is repeated from activity D2 until achieving the desired outcome.

Table 10-6: Example of qualitatively evaluating each refurbishment options (Source: Authors)

Ref	Refurbishment design options		Carbon emissions			Cost			Thermal comfort	Indoor air quality	Other criteria (n, n+1..., N)	Commentary	Status
	Item	Description	Operational carbon emissions	Initial embodied carbon emissions	Carbon payback period	Investment cost	Operation and maintenance cost	Investment payback period					
1	Upgrade window and glazing system	Double glazing with good g-value, Low-e coating and aluminium frames	Reduced energy use and operational carbon emissions	Aluminium frames and glazing can be high carbon-intensive	Operational carbon savings may not offset embodied carbon emissions	High	Medium	Less than 5 years	Improved thermal comfort	Improved indoor air quality	NA	<ul style="list-style-type: none"> • Slight reduction in visible light transmittance • Easy to implement but cannot be added later • Ongoing cleaning and maintenance 	A
2	Air Tightness Testing	Pressure tests the permeability of the building envelope post construction	Reduced energy use and operational carbon emissions	NA	NA	High	NA	5-10 years	Improved thermal comfort	Improved indoor air quality	NA	<ul style="list-style-type: none"> • Limited New Zealand capability at present • Need to procure accredited contractors from other countries such as Australia 	B

-  A: "Must have" option recommended to be included
-  B: "nice-to-have" option recommended to be included
-  C: "not-suggested" option

10.4.2.5 Step 5: Performance estimation and evaluation

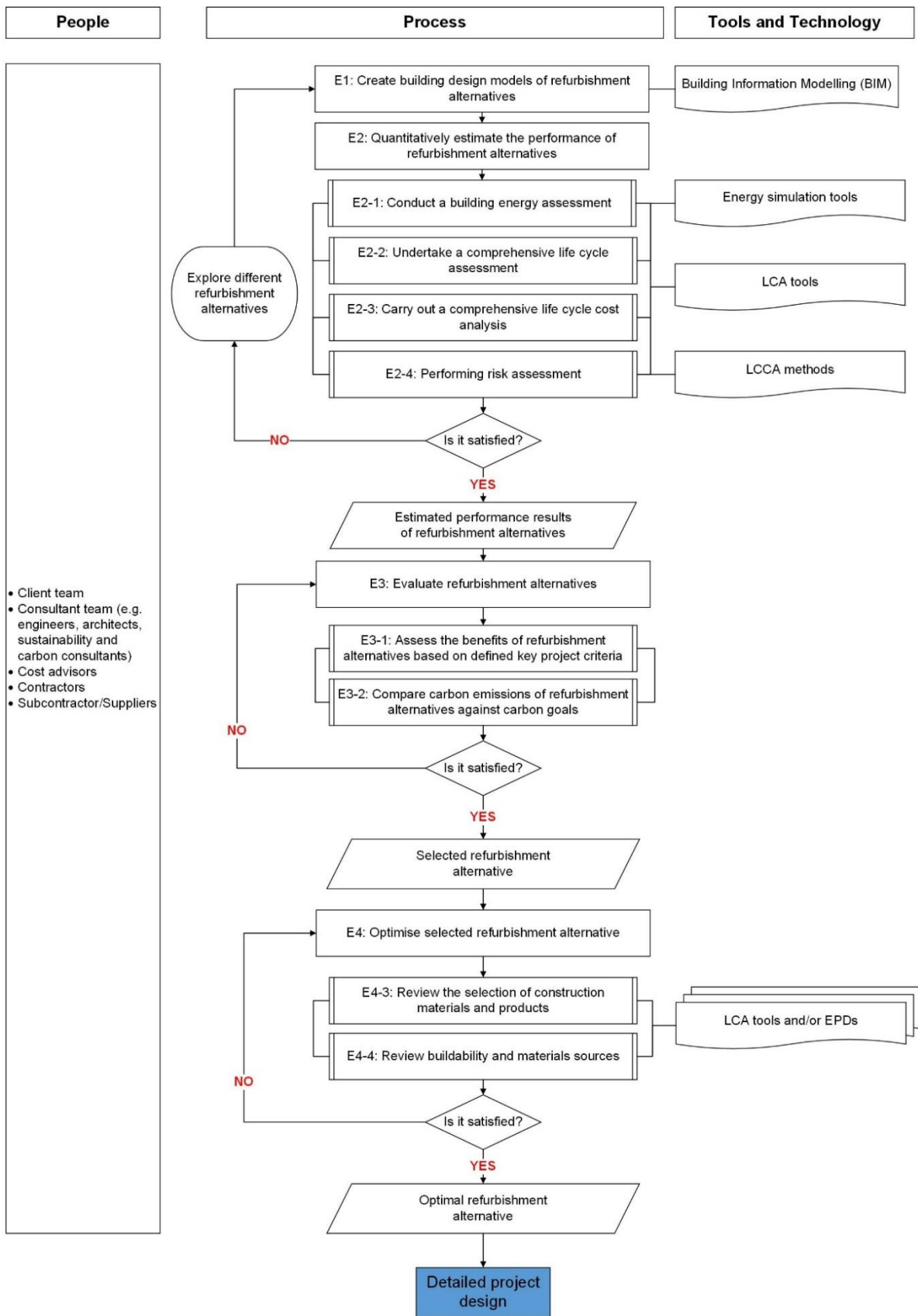


Figure 10-9: The low-level of decision support framework - Step 5 (Source: Authors)

Step 5 (E) aims to estimate and evaluate the performance of refurbishment alternatives. At this stage, different refurbishment alternatives can be assessed quantitatively based on the criteria for the project. As in step 4, the consultant team (e.g. engineers, architects, sustainability and carbon consultants) and cost advisors are mainly responsible for undertaking activities in step 5, while the client team is responsible for the approval. However, the involvement of contractors, subcontractors and suppliers also provides perspectives on the most appropriate refurbishment alternatives (Bui, MacGregor et al., 2023).

Step 5 starts with creating building design models using Building Information Modelling (BIM) (E1). The base case is the existing building, and the improved cases are based on the different alternatives of selected refurbishment options. BIM is recommended to support the whole-of-life carbon assessment using energy modelling and life cycle assessment in the following activities (Röck et al., 2018; Bui, Wilkinson et al., 2023; Bui, MacGregor et al., 2023). After that, the performance of refurbishment alternatives can be quantitatively estimated (E2). This estimation includes (E2-1) conducting a building energy assessment using energy simulation tools to evaluate building energy performance and operational carbon emissions, (E2-2) undertaking a comprehensive life cycle assessment to quantify whole-of-life carbon emissions of refurbishment alternatives using life cycle assessment tools, (E2-3) carrying out a comprehensive life-cycle cost analysis to calculate the life-cycle cost of refurbishment alternatives (Nielsen et al., 2016; Vilches et al., 2017; Bui et al., 2021b; Bui, Domingo, et al., 2022; Bui, Wilkinson et al., 2023).

As recommended by experts attending in the focus group, a risk assessment for refurbishment alternatives should be also included in step 5 (E2-4). Building refurbishment is subject to many factors, such as uncertainty in savings estimation, energy use measurements, weather forecasts, changes in energy consumption patterns, system performance degradations, etc. Furthermore, there are also uncertainties in undertaking LCA, such as insufficient carbon data of the product. These factors may lead to the investment in building refurbishment being highly uncertain. Risk assessment is, therefore, essential to provide decision-makers with sufficient confidence to select and determine the best refurbishment solutions (Ma et al., 2012). Architects, engineers, sustainability consultants and carbon consultants can work together to undertake energy modelling, LCA analysis and verifying carbon assessment results. Cost advisors are responsible for carrying out a cost-benefit

analysis that considers several indicators such as capital cost, annual savings, payback period, Net Present Value (NPV), and Internal Rate of Return (IRR) to prioritise cost-effective options (Bui, Wilkinson et al., 2023).

It is important to note that LCA tools can be used to assess the whole-of-life carbon emissions of buildings. However, it has several drawbacks, including the dependency on the quality and availability of data, affecting the accuracy of the assessment result. LCA tools may only consider the actual energy used during a certain period of production only. Considering the life span of a building, information related to energy load for the entire life span may not be available or not properly documented. This limitation can be solved using energy modelling to estimate the total energy gains and losses through building internal loads (Rasheed et al., 2019; Decano-Valentin et al., 2021). As such, energy modelling and LCA tools can be integrated to achieve the desired outcome.

The decision point at the end of activity E2 is to review the selection of refurbishment alternatives based on quantitative performance estimation results. Alternatively, different refurbishment alternatives are explored, and the process is repeated until achieving the desired outcome.

Next, activity E3 is to evaluate refurbishment alternatives by iteratively undertaking the following sub-activities. First, the benefits of refurbishment alternatives are assessed based on the performance estimation and the key project criteria identified in step 2 (E3-1). Table 10-7 demonstrates an example of evaluating refurbishment alternatives regarding economic and carbon performance indicators. Second, the quantified carbon emissions of refurbishment alternatives are compared to the carbon reduction goal (E3-2). The outcome of E3 is selecting the best refurbishment alternative.

Table 10-7: Comparison of the economic and carbon performance (Source: Authors)

Scenario	Description	Carbon					Cost				
		Annual energy use (kWh/m ² /yr.)	Annual operational carbon emissions (kg CO ₂ eq/yr.)	Annual operational carbon savings (kg CO ₂ eq/yr.)	Initial embodied carbon (kg CO ₂ eq)	Carbon payback period (year)	Life cycle carbon emissions (kg CO ₂ eq)	Annual energy cost savings (\$)	Investment cost (\$)	Operation and maintenance cost (\$)	Investment payback period (year)
Base case	Existing building										
1	Upgraded window and glazing										
2	Upgraded window and glazing, new mixed mode ventilation, new LED lighting										
3	Upgraded window and glazing, new mixed mode ventilation, new LED lighting, installed PV system										

Note:

Investment payback period (year) = Initial investment cost / Annual energy cost savings

Carbon payback period (year) = Initial embodied carbon / Annual operational carbon savings

After that, the selected refurbishment alternative is optimised (E4). This can be done by reviewing the selection of construction materials and products based on life cycle assessment tools and carbon data (e.g. Environmental Product Declaration (EPD)) (E3-3). The buildability and potential source of materials should also be reviewed (E3-4). While the consultant team work collaboratively to optimise the refurbishment alternative. The contractors, subcontractors and suppliers should be engaged to review buildability and waste management plans and provide detailed carbon data, potential sources, and performance requirements of construction materials and products (Bui, MacGregor et al., 2023).

It was thought that the process of estimating, evaluating, and optimising the refurbishment alternatives can be done iteratively (Nielsen et al., 2016). However, the results from the focus group recommended that the iterative process should be broken down into different parts as presented above. This is because a large amount of iterative analysis and design work may associate with high consultancy costs, preventing the consideration of carbon-reduction initiatives. As one expert indicated, “completing a full scale of comparative LCA iteratively throughout the process is a lot of work and very time- and cost intensive” (#8). It was agreed that considering the time and cost impacts of implementing the iterative process may lead to it not being done at all. Thus, the process has been divided into three parts with specific outcomes sought at each part.

At the end of Step 5, the optimal refurbishment alternative is selected as the output. After Step 5, the detailed project design should be generated, and the refurbishment process can continue with the construction and operation stages.

10.5 Discussion

This chapter set out to describe the development of a novel early-stage decision support framework towards zero carbon refurbishment of existing buildings in New Zealand (RefurbZC). The proposed framework was confirmed to provide decision-makers with a more systematic approach to making decarbonisation decisions for building refurbishment in New Zealand according to findings from a combination of extant literature review, preliminary study, case study and focus group.

The development of RefurbZC addresses the need for a comprehensive approach to measuring whole-of-life carbon reduction for building refurbishment. Traditionally, the primary objective of building refurbishment is

either bringing existing buildings up to current building codes and standards or improving building performance in terms of energy efficiency. For this reason, most comprehensive decision support frameworks have paid attention to improving operational carbon performance (Ma et al., 2012; Ferreira et al., 2013; Bhuiyan et al., 2015), leaving embodied carbon performance as a significant unaddressed issue. However, building refurbishment is associated with substantial embodied carbon emissions, mainly due to the use of energy-intensive construction materials (Zabalza Bribián et al., 2011; Pomponi et al., 2015; Ghose et al., 2017). Measures to promote energy efficiency refurbishment may not reduce overall carbon impacts (Ghose et al., 2017; Ghose et al., 2019; Ghose et al., 2020). Therefore, the RefurbZC, while evolving from previous comprehensive decision support frameworks, offers a standardised process guideline to address the carbon performance of building refurbishment in terms of both operational and embodied carbon emissions.

Unlike prior comprehensive decision support frameworks developed in (Dalla Mora et al., 2018; Serrano-Jiménez et al., 2021), the RefurbZC expands knowledge by providing an advanced step-by-step process for assessing decarbonisation decisions for building refurbishment. It has brought a new understanding of applying lean philosophy by integrating the collaboration and integration attributes to the lean-based sociotechnical systems model that originally includes people, processes, tools, and technology (Morgan & Liker, 2020) in order to support decision-making from a holistic point of view. Although the final decision is made by building clients, the RefurbZC ensures that various perspectives, sources of information and interests are represented. It is also recommended that decisions be made based on input provided by building stakeholders, including but not limited to project managers, engineers, architects, sustainability and carbon consultants, cost advisors, contractors, subcontractors, suppliers, facilities managers, and end-users. To provide holistic carbon-reduction solutions for building refurbishment, the RefurbZC promotes the collaboration between key stakeholders and their interconnection with available decision-support resources and tools. It illustrates the influence and interconnectedness between the key actors and factors. Having discussions among the project team on zero-carbon aspiration and commitment, which criteria to include to select fit-for-purpose refurbishment solutions, along with in-depth discussions of their meaning, advantages and disadvantages regarding whole-of-life carbon emissions and how they are prioritised against other criteria (i.e. capital cost value) in the early stages of refurbishment projects, aligns with the concept of Value-Focus Thinking (Keeney, 1996), which emphasises

the preferred values of the decision-makers involved, and the creation of relevant refurbishment solutions based on these values (Olsson et al., 2016; Kamari et al., 2017; Gade et al., 2018; Bui et al., 2021b). In summary, the RefurbZC not only is about shifting the discussion from individual variables to synergies across the decision-making process but also seeks to enable knowledge development and sharing between all parties and long-term relationships beyond a refurbishment project.

Most prior decision support mechanisms identified in the literature apply multi-objective optimisation processes and integrated simulation tools to determine the most optimal refurbishment alternatives (Jafari & Valentin, 2017; Kamari et al., 2019; Napoli et al., 2020). These mechanisms are limited to theoretical contexts that lack clear evidence of performance improvement in practice. Authors (e.g. Lu & Lai, (2020); Aste et al., (2022); Too et al., (2022); Bui, Domingo et al., (2022)) call for research to move away from stimulation studies to develop detailed frameworks designed in collaboration with key stakeholders' perspectives (e.g. clients, designers, contractors, and the user group) as reliable references for evaluating the building performance. To develop decision support mechanisms facilitating performance improvement in real life, it is important to identify existing challenges to reducing whole-of-life carbon emissions in the refurbishment decision-making process and potential opportunities for improvement. Thus, the development of RefurbZC considers the strengths and limitations of various academic decision support tools and frameworks as well as addresses key challenges identified by industry experts. Accordingly, the RefurbZC provides a structured framework that includes the suitable adoption of different tools, methods, and mechanisms to encourage concerted actions by industry actors towards maximising whole-of-life carbon reduction in the refurbishment decision-making process. It clarifies when, why and how these tools, methods and mechanisms should be used to assess whole-of-life carbon aspects along the refurbishment process to achieve the desired outcome and reduce performance gap issues. The framework also guides users on the various evaluation criteria to be considered at each step of the decision-making process. Taken together, the RefurbZC is a theoretical and practical construct that extends the theoretical knowledge and bridges the gap between theory and practice, offering a basis and foundation for future work in this research area.

Decision-making on carbon-reduction initiatives in practice for building refurbishment is a complex process involving the analysis of multiple interactions between various existing and new building components. The

process of identifying the most optimal decarbonisation refurbishment alternatives comprises the reconciliation of project objectives, budget, available refurbishment design and technologies, carbon assessment approaches and expertise. Despite concerted attempts by researchers to develop various decision support tools to address this multiple-objective trade-offs (Hu, 2018; Rabani et al., 2020; Kamari et al., 2021), there is a lack of clear research-based evidence on how to deploy these tools in practice. Approaches proposed in literature often demand building professionals' capacity and capability to undertake integrated simulation-based decision support tools, which may not be feasible in practice. Take the New Zealand case as an example. The lack of carbon data and literacy throughout the New Zealand building and construction industry leads to ambiguous and inconsistent life cycle carbon assessment. Adopting complex decision support systems incorporating multi-objective optimisation factors to generate the most fit-for-purpose refurbishment alternative is challenging for industry practitioners. Not to mention, the constraints associated with additional consultancy costs for adopting complex systems for whole-of-life carbon assessment are significant barriers to stimulating decision-making in implementing carbon-reduction initiatives. These challenges appear to be global issues for the building and construction industry. Since there is no step-by-step method with detailed guidelines to better deliver ZCR projects, the RefurbZC provides industry practitioners with robust information, expectations, and desired outcomes at well-defined decision points.

The RefurbZC seeks to enable the best practice that is reasonably ambitious compared to the current industry practice. Since the framework is addressing different stakeholder groups, it has been developed to be easy to understand and simple to use. Alongside with step-by-step decision flowcharts, narrative that outlines what, why and how actions should be taken to reduce carbon emissions in building refurbishment is included in every step. Primary users of RefurbZC might be clients, developers, project managers, facilities managers, who want to better understand the refurbishment decision-making process, identify areas for integrating carbon-reduction initiatives as well as human resources and mechanisms required to achieve carbon-reduction initiatives. Architects, consultants, cost advisors, and contractors might use RefurbZC as a reference for strategy illustrations, carbon and cost assessment, and comparisons of different carbon-reduction proposals. One of the advantages of RefurbZC is that it can be used as a communication tool between clients/developers/project managers/facilities managers and architects/consultants/cost advisors/contractors to

manage the different expectations and values as well as to show to which degree the carbon-reduction objectives have been met. The RefurbZC provides all relevant information such as people, process, tools and technology, collaboration and integration attributes that should be considered logically, robustly, and consistently to better make decarbonisation decisions. However, in practice, the inclusion of every aspect demonstrated in the RefurbZC may vary from one refurbishment project to another, depending on the project requirements, client's resources, and expectations. For example, sometimes, using LCA tools to assess carbon performance of refurbishment options is not seriously considered because assumptions made about outcomes or preferences are so strong that refurbishment options are selected without in-depth analysis. The carbon literacy and expertise as well as budget for life-cycle carbon assessment of refurbished buildings may also be limited. In other cases, the refurbishment options are determined by thorough consideration of all information and evidence. Even though, the implementation of the RefurbZC differentiates from a case-by-case basis, it still offers a comprehensive guide based on best practices for reducing carbon emissions in the refurbishment process, where the impact of the decision can be critically evaluated, and the decisions made with in-depth analysis may necessarily be the most appropriate ones in terms of carbon reduction.

Taking cognisance of critical discussion and recommendation highlighted in this research regarding implementing zero carbon refurbishment, it is noted that the following key aspects should be considered when adopting the RefurbZC in any refurbishment project. First, the carbon-reduction goals and suitable refurbishment proposals can be tailored and embedded in different refurbishment strategies with a certain number of actions, which can be altered depending on each case. Second, the adoption of climate target and carbon budget, carbon benchmarking, carbon accounting and scope of work (i.e. LCA boundaries for building refurbishment), carbon databases, as well as building rating systems, energy modelling and LCA tools, should be well-defined for robust whole-of-life carbon assessment and benchmarking. Third, knowledge development and sharing in carbon literacy is necessary for successfully delivering building refurbishment towards zero carbon since the process of assessing carbon emissions requires both heuristic knowledge and practical experience in carbon performance estimation. Carbon-reduction initiatives must be addressed throughout the refurbishment decision-making process, and the process will be made only if all involved stakeholders are engaged and understand theory and practice. Last but not least, organisational and project team commitments

towards delivering carbon-reduction goals for refurbishment projects are crucial for generating a trust-based collaborative environment for achieving targeted carbon performance and overall project outcomes. Establishing partnering relationships among the project participants will assist in cooperatively mitigating carbon impacts across the value chain.

10.6 Conclusion

In summary, this chapter presents the development, validation, and finalisation of the state-of-the-art decision support framework – RefurbZC – as a major result of this PhD thesis. The framework unpacks the activities and decarbonisation decisions to be made in the refurbishment process as a step-by-step decision flowchart. It supports the involved building stakeholders to better understand the refurbishment decision-making process and requirements for reducing carbon emissions in certain activities, identify areas for addressing carbon issues in the early stages of the refurbishment process, determine relevant information and key factors and actors in driving carbon-reduction solutions, and promote stakeholder collaboration and integration in carbon-reduction building refurbishment. The presented framework contributes significantly to theoretical and practical knowledge and offers a basis and foundation for future work in this research area.

11 Chapter 11: Summary and recommendations and future research

11.1 Introduction

This chapter presents key findings from the research and original research contribution, and outlines recommendations for future research. The chapter first summarises the fulfilment of the research aim and objectives, followed by the highlights of the original research contribution. Subsequently, the chapter acknowledges limitations of this research and provides insights into future studies to promote the wider uptake of zero-carbon initiatives for the refurbishment of existing buildings within the building and construction industry.

11.2 Fulfilment of research aim and objectives

This thesis aimed to improve the decision-making towards zero carbon refurbishment of existing buildings in New Zealand. The following seven objectives were formulated to achieve the research aim:

- Objective 1: To explore the current practice of zero carbon buildings worldwide
- Objective 2: To assess the global development and implementation of building refurbishment towards zero carbon
- Objective 3: To examine the adoption of zero carbon buildings in New Zealand
- Objective 4: To investigate the development and implementation of building refurbishment towards zero carbon in New Zealand
- Objective 5: To examine the current decision-making process for reducing whole-of-life carbon emissions of building refurbishment in New Zealand
- Objective 6: To develop and validate a novel decision support framework towards zero carbon refurbishment of existing buildings in New Zealand

A summary of how this thesis achieved each research objective is outlined in the subsequent sections.

11.2.1 Objective 1

The literature review on zero carbon buildings in the international context presented in Chapter 2 revealed that considering both embodied and operational carbon impacts is critical to maximising carbon reduction in a building throughout its life cycle. An overview of the concept of ZCBs has identified various ZCBs definitions across the globe, as well as the importance of climate targets and carbon budgets. One significant finding was that the design and construction of buildings towards zero carbon should aim to maximise whole-of-life carbon reduction, which is aligned with the carbon budget representing “allowable” emissions that can occur between now and 2050 to mitigate global warming.

In reviewing the literature on strategies for maximising carbon reduction in buildings, it was realised that improving building energy performance is the most effective and available measure to reduce operational carbon emissions for buildings, which can be done by adopting the systems integration of design strategies (i.e. passive design, energy efficiency, and renewable energy technologies). However, operational carbon emissions have gradually decreased due to the implementation of energy efficiency systems and technologies, leading to increased embodied carbon emissions. More importantly, the electricity grid is becoming greener, with some advanced economies targeting 100% energy sourced from renewable energy by 2030. Thus, the central focus should be on minimising embodied carbon emissions from materials and products rather than improving energy efficiency. Besides that, three strategies for reducing embodied carbon emissions are: (1) reducing the number of needed materials throughout the entire life cycle, (2) substituting traditional materials for alternatives with lower environmental impacts, and (3) reducing construction stage impact. The most substantial strategy is the retaining of existing buildings. Further investigation into the importance of building refurbishment in the context of ZCBs showed that refurbishing existing buildings offers greater carbon-saving benefits than constructing new buildings, mainly due to the reuse of building parts and elements and utilisation of recycled materials.

11.2.2 Objective 2

Research objective 2 was addressed in Chapter 3 and Chapter 4. The semi-systematic literature review on the global development and implementation of building refurbishment towards zero carbon discovered critical suggestions for future work, including the need for:

- a holistic multi-objective methodology considering whole-of-life carbon, economic factors, co-benefits and other impacts;
- empirical research on how available methods, tools and systems regarding multi-objective optimisation processes are adopted to support the decision-making process in the current industry practice;
- an investigation on stakeholder collaboration in the decision-making process towards delivering ZCR projects;
- establishing the availability of embodied carbon quantities; and
- conducting whole-of-life carbon performance assessment.

In addition, the findings from the critical review offered a new understanding of decision support tools for zero carbon refurbishment. It also proposed a novel theoretical decision support framework for future zero carbon refurbishment decision-making tools developed to better support building stakeholders in the refurbishment process. The findings also called for a detailed investigation of the decision-making process for building refurbishment towards zero carbon in the industry practice to develop a state-of-the-art decision support framework based on theoretical and practical knowledge.

11.2.3 Objective 3

Research objective 3 was outlined in Chapter 5 and Chapter 6 of this thesis. The examination of ZCBs adoption in the New Zealand context divulged an insight into the current practices and policy implications for the uptake of ZCBs in New Zealand. The results from the preliminary study showed that New Zealand's building and construction industry is in the early stage of transiting to a net-zero carbon built environment, with key actions being focused on devising a way for the industry to implement ZCBs. Central and local governments' initiatives on ZCBs, including revising building policies and regulations, have been underway while industry-leading construction firms started creating roadmaps to achieve the carbon target by 2050 and rethinking the design and construction practices. The findings have also revealed the differences in the carbon performance of New Zealand's buildings because of the use of different rating systems and calculating tools. Challenges and issues to implementing ZCBs in New Zealand were also identified and discussed. The critical challenges to implementing and delivering ZCBs are financial issues, the shortage of knowledge, capacity and capability,

the lack of legislation, and cultural barriers. Of these, low capacity and capability, lack of knowledge and skills in carbon literacy, low carbon data efficiency, and slow-to-innovate appeared to be global issues towards ZCBs implementation. It was suggested that delivering buildings towards zero carbon can be successful if adopting well-defined and deliberate building policies, integrated building design and construction processes, knowledge development and sharing, as well as established partnering relationships among building stakeholders with accessible resources and support mechanisms.

11.2.4 Objective 4

Research objective 4 was answered in Chapter 7 of this study. It presents a specific investigation into the development and implementation of building refurbishment towards zero carbon in New Zealand. The findings revealed the current practices in selecting refurbishment design opportunities to lower carbon emissions of building refurbishment, with the existing priority on reducing operational rather than whole-of-life carbon emissions. Moreover, New Zealand's building stakeholders faced many challenges in integrating carbon reduction in their decision-making practices in different areas of the pre-design and design stages of the refurbishment process. These barriers include the following:

- inexplicit carbon goal setting leading to several barriers affecting the design decisions regarding carbon benchmarking, the trade-off between cost and carbon performance, identification and performance assessment of refurbishment solutions;
- ineffective building condition assessment due to the inadequate existing building data and the lack of user guidelines and methods for building condition assessment;
- deficient and incomprehensive relevant whole-of-life carbon information to support the decision-making; and
- inconsistent and ambiguous carbon-calculation guidelines and benchmarks.

Consistent with the knowledge gap in the international context, the findings emphasised the need for a further in-depth investigation into the decision-making process of real-life building refurbishment case studies considering whole-of-life carbon reduction in order to develop a comprehensive decision support framework that provides a detailed guideline to better-delivering ZCR.

11.2.5 Objective 5

The fifth objective was to examine the current decision-making process for reducing whole-of-life carbon emissions of building refurbishment in New Zealand. This objective was fulfilled in Chapter 8 and Chapter 9 of this thesis. The findings from three real-life cases studied broadly helped determine the parameters and characteristics that apply to developing the novel decision support framework. Lessons learnt for improved implementation of building refurbishment towards zero carbon were also identified as follows:

- There is a need to effectively use building rating systems to integrate sustainability and carbon performance criteria, the client’s requirements and stakeholder values into the refurbishment process;
- Whole-of-life carbon reduction targets for existing buildings are required for the carbon benchmark and the optimisation of the refurbishment design;
- The implication of the specific financial budget for carbon-reduction initiatives is highlighted;
- The consideration of implementing flexible, appropriate and long-term refurbishment designs and strategies is required;
- The significance of key aspects in delivering refurbishment projects towards zero carbon, including holistic design reports, ECI approach, government funding and incentives, and supply chain and data availability, is uncovered; and
- The importance of collaboration and integration among building stakeholders involved in the decision-making process is emphasised with associated key attributes to the successful delivery of ZCR, including:
 - a) the commitment to maximise carbon reduction, accountability for producing optimal carbon-reduction solutions;
 - b) early consultant involvement in driving carbon-reduction initiatives;
 - c) early contractor involvement in improving carbon-reduction design;
 - d) user involvement in bridging the performance gap;
 - e) compatibility with lifecycle carbon assessment approaches and processes;
 - f) joint operations in producing carbon-reduction solutions; and
 - g) communication via centralised and integrated carbon information and management systems.

11.2.6 Objective 6

Chapter 10 of this thesis provided a response to the sixth objective, playing an important role in achieving the research aim. The key findings emerged from the research were embedded in the state-of-the-art decision support framework – RefurbZC. The five-step framework consists of two levels: high level and low level; four components: people, process, tools and technology, collaboration and integration attributes; as well as additional guidance and lists of the information needed to inform decisions at each step. It was developed to provide decision-makers with a more systematic approach to making decarbonisation decisions for building refurbishment in New Zealand using a combination of extensive literature review, preliminary study, case study and focus group. The RefurbZC, while considering an all-inclusive perspective from building stakeholders involved in the refurbishment process, expands the theoretical knowledge by offering a new standardised step-by-step process guideline to address the whole-of-life carbon performance of refurbished buildings. Throughout the development and validation processes, it was confirmed that applying the RefurbZC in the industry practice is beneficial to improve the decision-making towards zero carbon refurbishment of existing buildings. It supports the decision makers and their advisors to better understand the refurbishment decision-making process and requirements for reducing carbon emissions in certain activities, identify areas for addressing carbon-related issues in the early stages of the refurbishment process, determine relevant information key factors and actors in driving carbon-reduction solutions, and promote stakeholder collaboration and integration towards successfully delivering ZCR projects.

11.3 Original research contribution

This thesis contributes to the existing body of theoretical and practical knowledge on zero carbon refurbishment of existing buildings. It focuses on improving the decision-making towards zero carbon refurbishment of existing buildings in New Zealand. Several key contributions made by this research have not been found in previous research studies. The contributions of this study are outlined and discussed below.

11.3.1 Theoretical implications

This thesis has significant theoretical implications in at least four major respects. First, the research emphasises the need for measuring whole-of-life carbon reduction for building refurbishment. The findings from this

research reveal that the primary objective of building refurbishment is either bringing existing buildings up to current building codes and standards or improving building performance in terms of energy efficiency. For this reason, most studies in the field of zero carbon refurbishment have only focused on improving operational carbon performance of existing buildings, leaving embodied carbon performance as a significant unaddressed issue. However, the refurbishment of existing buildings is associated with substantial embodied carbon emissions, mainly due to the use of energy-intensive construction materials. For example, the refurbishment often improves energy efficiency by upgrading building services, accounting for a considerable amount of embodied carbon emissions of Mechanical, Electrical and Plumbing (MEP) and tenant improvement (TI) components. Therefore, measures to promote energy efficiency refurbishment may not reduce whole-of-life carbon impacts. Not to mention, the carbon impacts of the production of new components, transport of new components, construction as part of the refurbishment process, waste management and end-of-life of the substituted and remaining existing building components should be also considered when undertaking life cycle carbon assessment of refurbished buildings. Thus, the study suggests that the refurbishment of existing buildings should aim to reduce operational and embodied carbon emissions throughout the life cycle of the refurbished building.

Second, this thesis expands the understanding of the refurbishment process. It explains the interrelationship between building condition assessment and goal setting and proposes refurbishment strategies to be included in the process. According to the existing literature, setting the right goals, objectives, and criteria is often the starting point of the refurbishment process since all following phases are adapted to these strategic and significant aspects. However, the building condition assessment can be done before the goal setting to reveal the actual state of the building, and thus its refurbishment requirements, the site's advantages and disadvantages, and the appropriate refurbishment solutions. The findings from this study provides better support for the conceptual premise that the results of building condition assessment assist in setting realistic carbon goals and establishing appropriate refurbishment strategies. This is because it offers a better understanding of the existing building's energy and carbon performance and potential reused and recycled building materials. At the same time, setting the carbon-reduction aspiration at first is also critical to draw an intention to carbon-targeted improvement areas in the building condition assessment process. Thus, the study

proposes that the starting point of the refurbishment process is having a high carbon-reduction aspiration. Then, a building condition assessment is conducted, and the results are used to define the specific carbon goal as well as inform suitable refurbishment strategies. Furthermore, the refurbishment process found in the literature does not comprise a refurbishment strategies stage. This critical stage is included in the development of the new decision support framework in this thesis that should be considered before generating refurbishment solutions.

Third, the thesis has brought a new understanding of applying lean philosophy by integrating the collaboration and integration attributes to the lean-based sociotechnical systems model that originally included people, processes, tools and technology in order to support decision-making from a holistic point of view. To provide holistic carbon-reduction solutions for building refurbishment, the study promotes the collaboration between key stakeholders and their interconnection with decision-support mechanisms. It illustrates the influence and interconnectedness between the key actors and factors in the decision-making process. The following collaboration and integration attributes developed in this study that are integrated in different steps of the decision-making process, have not been recognised in the existing literature: (1) commitment to maximise carbon reduction, (2) accountability for producing optimal carbon-reduction solutions, (3) early consultant involvement to drive carbon-reduction initiatives, (4) early contractor involvement, (5) user involvement to bridge the performance gap, (6) comparability with life cycle carbon assessment approaches and processes, (7) joint operation in producing carbon-reduction solutions, and (8) communication via centralised and integrated carbon information and management system. Moreover, the findings from this study further support the idea of applying the concept of Value-Focused Thinking introduced by Keeney (1996) in the decision-making process. The study findings suggest that having discussions among the project team on zero-carbon aspiration and commitment, the criteria to select fit-for-purpose refurbishment solutions, along with in-depth analysis of their meaning, advantages, and disadvantages regarding whole-of-life carbon emissions is critical. The carbon-reduction criteria should be prioritised against other project criteria (i.e. capital cost value) in the early stages of refurbishment projects based on the preferred values of the building stakeholders involved in the process, and the refurbishment solutions should be created based on these values. In summary, various stakeholders' perspectives and interests as well as sources of information should be represented and considered throughout the refurbishment process to make the most appropriate decision. Shifting the discussion from

individual variables to synergies across the decision-making process enables knowledge development and sharing between all parties and long-term relationships beyond a refurbishment project, leading to the uptake of zero carbon refurbishment of existing buildings in the wider industry.

Last but not least, this research sheds a new light into the development of decision support mechanisms that facilitate carbon performance improvement in building refurbishment. The study suggests that existing decision support mechanisms are limited to theoretical contexts that lack clear evidence of performance improvement in practice. The new decision support mechanisms should be designed in collaboration with key stakeholders' perspectives (e.g. clients, designers, contractors, and the user group) and existing challenges faced in the refurbishment decision-making process to reducing whole-of-life carbon emissions as reliable references for evaluating the carbon performance of refurbished buildings. Thus, the development of the novel RefurbZC in this study considers the strengths and limitations of various academic decision support tools and frameworks as well as addresses key challenges identified by industry experts. Accordingly, it provides a structured framework that includes the suitable adoption of different tools, methods, and approaches to encourage concerted actions by industry actors towards maximising whole-of-life carbon reduction in the refurbishment decision-making process. This result extends the theoretical knowledge and bridges the gap between theory and practice, offering a basis and foundation for future work in zero carbon refurbishment research area.

11.3.2 Practical implications

The results of this research make several contributions to the current industry practices. In particular, the novel decision support framework for building refurbishment towards zero carbon developed in this thesis addresses the gap in lacking step-by-step method with detailed guidelines to better deliver zero carbon refurbishment projects in New Zealand and international contexts. It was developed based on the critical analysis and interpretation of theoretical propositions found in the literature and best practices identified in the industry. It provides a comprehensive decision-making process with robust information, expectations, and desired outcomes at well-defined decision points that can be implemented in every refurbishment project incorporating carbon reduction initiatives. It offers step-by-step guidelines for building stakeholders to follow from the beginning of the refurbishment process. The RefurbZC comprises flowcharts and diagrams with detailed

activities to help building stakeholders visualise where they are in the process, who should be involved in each step, where carbon expertise is required, what factors are considered in each decision point, where carbon analysis and assessment is required, what inputs are needed, what available support mechanisms are, what expected outcomes are. Taking cognisance of the shortcomings of the current industry practice in reducing carbon emissions, key aspects and recommendations have also been proposed in this study when adopting the RefurbZC in any refurbishment project. The potential implementation of the RefurbZC framework has been confirmed by industry experts through an explicit validation process. The framework can be demonstrated in a more concise form such a guideline or industry report disseminated through professional bodies and institutions such as BRANZ where the New Zealand industry practitioners can have easy access to the framework.

The research findings provide a clear and structured way to effectively assess the building condition. In observing the current industry practice, the building condition is assessed mostly against the performance requirements of the New Zealand Building Code or beyond the Code with the focus on improving energy efficiency, which do not include carbon performance metrics and benchmarks. Furthermore, there has been little evidence of implementing energy and operational carbon emissions audits to determine the potential areas for improving energy efficiency and reducing operational carbon emissions according to the findings from the case study and the framework validation. The research fills this gap by suggesting the incorporation of energy and operational carbon emissions audits in the building condition assessment process, subject to the current and future use of the existing building and data availability. In addition, the research findings recognise the importance of conducting user survey to better assess the existing building condition and problems, but it has not been broadly implemented in the current practice. Therefore, it is suggested to incorporate this vital activity in the building condition assessment process to better understand the building's operational and functional problems. The research emphasises involvement of the user group to provide perspectives on the area of improvement required in the refurbished building. It also helps the process of assessing building performance to be more targeted. Information about the user's activities and expectations could help determine appropriate refurbishment solutions in the later steps and bridge the performance gap in the post-refurbishment stage.

The research outcome offers a new understanding of whole-of-life carbon goal setting that has not been established in the industry practice. According to empirical findings, the carbon goal setting in the current New Zealand industry practices is inexplicit, leading to several barriers affecting the design decisions about carbon benchmarking, such as the trade-off between cost and carbon performance as well as identification and performance assessment of refurbishment solutions. In addition, the building rating systems have often been used to define carbon reduction goals for building refurbishment in New Zealand, even though these rating systems are limited to whole-of-life embodied carbon reduction targets and assessment. To address this shortcoming, the study provides a transparent and logical way to carefully establish carbon reduction targets, considering the current government initiatives on whole-of-life carbon reduction for buildings, building rating systems and science-based climate target and carbon budget. It is recommended that building rating systems and the climate target and carbon budget can be considered together to help achieve both sustainability and maximum carbon reduction goals. The study findings also suggest that the whole-of-life carbon budget, specific embodied carbon reduction targets and calculation methods should be established specifically for the refurbishment of existing buildings rather than using the similar references and approaches for new buildings. This is due to the scope of life cycle carbon assessment of refurbished buildings differing from that of new buildings. Furthermore, the sustainability workshop and carbon brief proposed in this research are acknowledged as important mechanisms to regulate carbon reduction goals in building refurbishment.

A new conception of setting financial budget for carbon reduction initiatives is also demonstrated in this research. It is indicated that financial issues including cost-driven industry, the perception of high initial investment in low-carbon construction products and technologies, and lack of financial incentives are amongst the most significant challenges to delivering buildings towards zero carbon in New Zealand. In addition to the carbon budget, a financial budget set in the early stage, may be needed for carbon-reduction solutions to avoid unexpected additional costs (i.e. carbon specialist consultation, energy modelling and life cycle assessment fees) and enable the strategic consideration of lower carbon options tailor to meet the budget. However, the financial budget for carbon-reduction solutions could also be seen as business-as-usual rather than additional costs for specific carbon-reduction strategies, which may present the motivation to target carbon-reduction initiatives for building refurbishment from the beginning of the refurbishment process. Whereas the actual

carbon- and cost-effective refurbishment options are assessed later in the process where the trades-offs between carbon and cost savings can be identified. Therefore, the study recommends that the financial budget should be presented as an element already included in the project budget to prevent the client's resistance to the commitment with a high carbon-reduction goal. Government funding and incentives are also essential to assist in promoting carbon-reduction initiatives and achieving the required carbon performance targets with the reduced financial payback period.

In terms of refurbishment strategies, the study suggests a more flexible way in implementing passive design, efficient services systems and renewable technologies compared to the existing literature and current industry practice. For example, instead of applying a hierarchical approach towards zero carbon refurbishment, which prioritises refurbishment strategies in the following order: (1) retrofit fabrics, (2) more efficient equipment, (3) micro generation. These strategies should be identified simultaneously and appropriately to the physical condition of the existing building and project budget. Moreover, performance assessment and feasibility studies are required to show the trade-offs between the advantages and disadvantages of renewable technologies before making the decision to overcome public perception. Other important strategies found in this study include prioritising local materials, using low-carbon materials, maximising reused and recycled materials of existing buildings, which should be considered to reduce embodied carbon emissions. It is also important to note that the selection of refurbishment strategies should be aligned with the defined carbon reduction goals in the earlier stage.

This research contributes to the existing industry practice by providing a new insight into refurbishment solutions' carbon performance analysis and evaluation in both qualitative and quantitative ways. In practice, refurbishment options are usually selected using experience, heuristics, lessons learnt from global case studies, qualitative estimation of carbon performance, consulting and partnering with other project team members. However, the study finding proposes the adoption of several simple LCA tools (e.g. LCAPlay), complex LCA tools (e.g. LCAquick, eTool) and carbon database tools (e.g. CO₂NSTRUCT), which provide genetic carbon impacts of different building elements, to better assess initial life cycle carbon performance. Moreover, the proposed example of qualitatively evaluating each refurbishment options in this study is confirmed as necessary mechanism to support decision-making. This embraces the critical refurbishment options

contributing significantly to carbon reduction that could eventually be removed later due to cost constraints. The study also recommends a new approach that is benchmarking carbon emissions impacts of refurbishment alternatives against carbon reduction goals rather than a reference building, which is often used in the current LCA practices. The choice of the reference building determines to some extent the carbon performance of the selected building design. For example, the building is x% better than the reference building, which is usually a standard building that meets the minimum requirements of the Building Code. Therefore, the real test should be how the refurbished building performs against its carbon budget or the aim to achieve near or zero carbon emissions. A carbon payback analysis to identify trade-off carbon benefits between embodied and operational carbon emissions should also be considered alongside with financial payback analysis. This aspect has been demonstrated by proposing the example for comparing the economic and carbon performance of refurbishment alternatives.

The study promotes collaboration and integration approach towards successfully delivering building refurbishment towards zero carbon, which have not been well-established in the current practice. It demonstrates the relationship among building stakeholders participating in the decision-making process as well as proposes their timely involvement and key attributes required to effectively collaborate. Client leadership is the key to promoting and inspiring other project participants to implement low-carbon initiatives. The project manager is responsible for managing and monitoring carbon-reduction design and implementation. Engineers, architects, sustainability consultants and carbon specialists provide valuable input to create optimal refurbishment solutions that reduce operational and embodied carbon emissions. At the same time, cost advisors support prioritising cost-effective options. The participation of contractors, subcontractors and suppliers fills the gaps in understanding the implementation requirements of innovative designs and the carbon performance of construction materials and products. Extensive involvement of users alleviates the factors contributing to the “energy performance gap”, including lack of accurate information at the design stage on occupancy profiles and user behaviours, underestimation of heating and cooling loads, inappropriate refurbishment solutions, ineffective building commissioning and maintenance. The commitment, accountability, timely involvement, compatibility, joint operation, and communication among team members create a trust-based collaborative environment for achieving targeted carbon performance and project

outcomes; and facilitate long-term relationships, high levels of knowledge development and sharing between all parties.

11.4 Research limitations

While the findings in this study have provided solutions, guidance, and recommendations for shifting ZCBs adoption and improving decision making in ZCR of existing buildings, there exists some noticeable limitations surrounding the thesis. This section identifies the limitations of this thesis and suggests how these should be addressed in future studies.

First, the empirical data collection is limited to the New Zealand building and construction industry. Therefore, the research results should be reassessed and reanalysed to be adapted to other countries. The UK, Australia, and New Zealand could learn lessons from each other because of their similar traits in terms of building legislation and regulation. However, as New Zealand is an advanced high-income economy with its unique geography, the research findings may be of interest to other comparable economies (e.g. Denmark) or developing economies. Even though the proposed framework was developed based on the best international and local practices, it may not be able to be completely generalised to a different context. However, the knowledge can be transferred to other research, such as using the same methodology to build frameworks that are applicable to the situation in other countries.

Secondly, the outcomes of this research are not free from adverse methodological effects such as research bias. The choice of qualitative research approach, mainly with the use of interviews, is context specific. There was an attempt to draw the best possible sample for the research, including 17 preliminary interviews, 23 case study interviews and 11 focus-group interviews, given that a limited number of participants who have knowledge and experience in zero carbon and sustainability field as well as the COVID-19 impacts and restrictions over the research period. The sample size was confirmed within the required research limits to achieve saturation points. There could also be possibilities of bias based on the respondent's opinion as well as the researcher bias. However, careful measures were taken to ensure validity and reliability in each study stage. Additionally, the study is bound by the limitations related to the research circumstances, for instance, the access to the research setting, availability of participants and real-life case studies, data confidentiality, asymmetry of data obtained from the case studies and localism of the data. However, the author has been explicit in presenting

the research circumstances, the nature of the data, the analytical process, and the interpretation. The evidence was also collected by triangulating methods.

Thirdly, from the beginning of this research, the major sampling population represented clients, architects, engineers, and quantity surveyors since they are the key drivers in making decisions on zero-carbon initiatives. Although the perspectives of the contractor and the user group (i.e. facilities managers) were considered, their representatives only made up a minor sampling population. The research findings emphasised the important role of subcontractors and suppliers in reducing carbon emissions. However, these acknowledgements mostly came from the client and consultant team. The difference in the professional representation may have little or no influence on the study findings as the findings align with the existing literature within the building and construction industry. Yet, further research should add subcontractors and suppliers to the list of potential participants owing to their key role in providing the performance level and embodied carbon emissions of construction materials and products.

Last but not least, the decision support framework has several limitations. Even though there is a requirement to develop a framework to support decision-making in reducing carbon emissions for non-residential building refurbishment, the developed framework was based only on data collected from university buildings. Not to mention, the decision-making process and the characteristics of the university and other public buildings may differ from those owned by the private sector. It was due to the limited real-life building refurbishment case studies in New Zealand. The RefurbZC provides all relevant information such as people, process, tools and technology, collaboration and integration attributes that should be considered logically, robustly, and consistently to better make decarbonisation decisions for building refurbishment. However, in practice, the inclusion of every aspect demonstrated in the RefurbZC may vary from one refurbishment project to another, depending on the project requirements, client's resources, and expectation. Even though, the implementation of the RefurbZC differentiates from a case-by-case basis, it offers a comprehensive guide based on best practices and its flexibility to be customised in specific case for reducing carbon emissions in the refurbishment process, where the impact of the decision can be critically evaluated, and the decisions made with in-depth analysis may necessarily be the most appropriate ones in terms of carbon reduction.

11.5 Recommendations for future research

There are interesting opportunities for future research based on the constraints worked with to accomplish this thesis. In order to facilitate wider adoption of the RefurbZC framework, future work could conduct longitudinal case studies to compare the implementation of the RefurbZC framework in different building typologies. Findings from the case studies could also support the continuous improvement of the framework as well as showcase the benefits of the framework implementation, promoting zero-carbon initiatives within the building and construction industry.

This research advances the knowledge and understanding of the decision-making towards ZCR of existing buildings and its complexities. It is research that creates further directions of enquiry on various decision points in the overall process. Further areas of work are suggested as follows:

- Calculation and proposals of the carbon budget of the existing building stock and/or an individual existing building to support the process of carbon accounting and benchmarking in building refurbishment projects.
- Exploration of different refurbishment options in terms of carbon and cost savings as well as other potential co-benefits, considering different building typologies, the location of buildings, and the size of buildings.
- Investigation of various refurbishment alternatives that align with achievement levels of carbon budget (i.e. 0-24%, 25-49%, 50%-74%, and 75-100% carbon budget), considering different building typologies, the location of buildings, and the size of buildings.
- Studies to address the disconnections and gaps between as-design, as-built and post-occupancy performance and discover how decisions made during the early stage of the refurbishment process could be disseminated to the construction process of refurbished buildings and post-occupancy evaluation.

12 Reference

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13 Appendices

13.1 Appendix 1: Preliminary study schedule

PRELIMINARY INTERVIEW SCHEDULE

Research Project: Towards Zero Carbon Refurbishment of Existing Buildings in New Zealand

Introduction

Building refurbishment is a complex undertaking cutting across different technical fields and facing challenges in incorporating zero carbon targets, and many decisions are made throughout the refurbishment process. This research aims to improve the decision-making towards zero-carbon refurbishment for New Zealand's existing buildings. The research results are expected to provide construction professionals with current practices and an interdisciplinary guide to better reduce carbon emissions for refurbishment projects. The study contributes significantly to the New Zealand construction industry transitioning to net zero carbon by 2050.

The aim of this interview is to explore the current practices of reducing carbon emissions in building projects in New Zealand, with a specific focus on the refurbishment of existing buildings. This interview seeks to gather information from respondents based on their knowledge and experience in order to identify areas for improvement towards implementing building projects towards zero carbon.

Agenda

Participant information	5 minutes
The current practices of designing and constructing buildings towards zero carbon	25 minutes
The current practices of refurbishing existing buildings towards zero carbon	25 minutes
Further thoughts	5 minutes
Total	1 hour

Interview questions

Participant information

1. Could you please introduce yourself?

2. Could you tell me about your company and what do you do at your company?
3. For how many years have you worked within the New Zealand construction industry?
4. What types of building projects do you usually take part in? What is your typical project role?

The current practices of designing and constructing buildings towards zero carbon

1. What is your thought about zero carbon target for the building sector (e.g. net zero carbon by 2050).
2. What do you think about zero carbon build and what does that mean to your building projects?
3. What do you know about zero carbon build and how it is changing the building process?
4. How does zero carbon build have impacts on you and your company?
5. Does your company have any plan to address zero carbon target in their projects?
6. What do you think about the challenges and incentives regarding zero carbon build?
7. What are the difficulties that you and your company are facing regarding zero carbon build?
8. Which support do you need to plan and implement zero carbon build?

The current practices of refurbishing existing buildings towards zero carbon

1. My project is about building refurbishment; do you have any comments to make about refurbishing existing buildings to reduce carbon emissions?
2. Do you have any examples of the refurbishment of existing buildings in New Zealand? What are the current practices of reducing carbon emissions?
3. I am looking at how to make good decisions during the process of refurbishing existing buildings. What do you think it is a good process to use?
4. What decisions might you make about refurbishing to reduce carbon emissions?
5. What problems may come up against?
6. Which support do you need to make an informed decision to reduce carbon emission?
7. Is there any tools or procedures have been used to support decision making?

Further thoughts and follow-up questions (if applicable)

1. Is there anything else you would like to add about any of the topics discussed?

Thank you very much for participating in this study.

13.2 Appendix 2: Case study schedule

CASE STUDY INTERVIEW SCHEDULE

Research Project: Towards Zero Carbon Refurbishment of Existing Buildings in New Zealand

Introduction

Building refurbishment is a complex undertaking cutting across different technical fields and facing challenges in incorporating zero carbon targets, and many decisions are made throughout the refurbishment process. This research aims to improve the decision-making towards zero-carbon refurbishment for New Zealand's existing buildings. The research results are expected to provide construction professionals with current practices and an interdisciplinary guide to better reduce carbon emissions for refurbishment projects. The study contributes significantly to the New Zealand construction industry transitioning to net zero carbon by 2050.

This interview aims to investigate the current decision-making process for reducing carbon emissions of building refurbishment in New Zealand. This interview explores the decision-making process of three real-life building refurbishment case studies considering whole-of-life carbon reduction to assist in developing the decision support framework for better-delivering building refurbishment towards zero carbon.

Agenda

Participant information	5 minutes
Project brief, the refurbishment process and involved participants	10 minutes
The decision-making process and carbon-reduction decisions	40 minutes
Further thoughts	5 minutes
Total	1 hours

Interview questions

Participant information

1. Can you introduce yourself, your position and your role in the project?
2. How many years have you been working in the construction industry?

Project brief, the refurbishment process and involved participants

1. Can you tell me briefly about the project, the refurbishment process and how have you been involved in that process?
2. If possible, can you send me relevant project documentation (e.g. sustainable strategy reports, sustainability plans, site investigation reports, building performance reports, energy efficiency reviews, sustainable design briefs, building condition assessment reports, drawings, design specifications, study reports)?

The decision-making process and carbon-reduction decisions

Stakeholders	Main Questions
Clients	<ol style="list-style-type: none"> 1. What are priorities for the refurbished building? What are the specific goals? 2. Are there any carbon-reduction goals for the refurbished building? 3. In terms of carbon-reduction/sustainability, what are the key drivers and considerations in getting the refurbished building commissioned and delivered? 4. What are decision making criteria/factors affecting the decision making in early stages of choosing refurbishment design opportunities? 5. What are the resources/tools/practices that support you to make carbon-reduction/sustainability decision? 6. From your experience, what kind of advice/required people that need? 7. Are there any answers or information you have difficulty with to get when you have to make carbon-reduction/sustainability decisions? 8. What are the challenges you found in the process concerning sustainability/carbon reduction? 9. What support do you need to be able to make better decision in relation to carbon reduction/sustainability? 10. Is integrated design process applied in this project? How this approach supports the decision making in terms of carbon reduction/sustainability? (optional)

-
11. What do you think about ECI in the refurbishment process? Would it help to improve the process and reduce carbon emissions further?
 12. What should be improved in the refurbishment process in terms of carbon reduction specifically/sustainability in general?
 13. What are the lessons-learnt that you get from this project?

Engineers &
Architects

1. How were the building conditions assessed before choosing potential refurbishment design options, and at what level?
 2. Was energy auditing implemented to identify areas with energy savings potential and provide the information needed in building performance assessment?
 3. Can you tell me briefly about the process of carbon analysis (operational carbon and whole-of-life carbon) for refurbished building (e.g. What are tools/resources/practices? How did carbon specialists/consultants support the consultant team in the process?)
 4. Were different refurbishment design packages/options/scenarios/levels considered for refurbished building? Which specific design elements were included in each of them?
 5. How were carbon emissions (operational carbon and whole-of-life carbon) measured for refurbished building?
 6. What were the embodied/whole-of-life carbon emissions calculated for refurbished building? (optional)
 7. What are the challenges you find in the process concerning cost and sustainability/carbon reduction?
 8. What are uncertainty factors in relation to sustainability/carbon reduction should be considered in the process and when selecting refurbishment options?
 9. Was there any risk assessment in the refurbishment process?
-

-
10. What do you think would help inform the client's decision making related to carbon reduction/sustainability? (optional)
 11. What do you think about ECI in the refurbishment process? Would it help to improve the process and reduce carbon emissions further?
 12. Are there any answers or information you and/or your team have difficulty getting in relation to carbon reduction/sustainability?
 13. Are there any carbon-reduction/sustainability tensions that occurred during the decision-making process that you witnessed? (optional)
 14. What should be improved in the refurbishment process in terms of carbon reduction specifically/sustainability in general?
 15. What are the lessons-learnt in terms of carbon reduction/sustainability that you get from this project?

Quantity
Surveyors

1. Is life cycle cost analysis considered in the process? (e.g. maintenance cost)
 2. Are there any economic analysis methods that have been used?
 3. Are there any cost-benefit analysis tools that have been used?
 4. Are there any other the resources/tools/practices that support you in the cost estimating process? (optional)
 5. Are there any carbon reduction/sustainability tensions that occurred during the decision-making process that you witnessed? (optional)
 6. What do you think would help inform the client's decision making? (optional)
 7. What are uncertainty factors in relation to cost and sustainability/carbon reduction should be considered in the process?
 8. What are the challenges you find in the process concerning cost and sustainability/carbon reduction?
 9. What do you think about ECI in the refurbishment process? Would it help to improve the costing process?
-

-
10. Are there any answers or information you have difficulty getting in relation to cost and sustainability/carbon reduction?
 11. What should be improved in the refurbishment process in terms of carbon reduction specifically/sustainability in general?
 12. What are the lessons-learnt in terms of carbon reduction/sustainability that you get from this project?

Contractors

1. What is your thought about carbon emissions in the refurbishment process?
 2. What are the challenges you find in the process concerning sustainability/carbon reduction?
 3. What do you think about ECI in the refurbishment process? Would it help to improve the costing process?
 4. Are there any answers or information you have difficulty getting in relation to sustainability/carbon reduction?
 5. What should be improved in the refurbishment process in terms of carbon reduction specifically/sustainability in general?
 6. What are the lessons-learnt in terms of carbon reduction/sustainability that you get from this project?
-

Further thoughts and follow-up questions (if applicable)

1. Specific questions applied for each case study.
2. Is there anything else you would like to add about any of the topics discussed?
3. Follow-up questions via emails/phones.

Thank you very much for participating in this study.

13.3 Appendix 3: Focus group schedule

13.3.1 Appendix 3.1. Workshop Information Sheet (WIS)

WORKSHOP INFORMATION SHEET (WIS)

Research Project: Towards Zero Carbon Refurbishment of Existing Buildings in New Zealand

Workshop: Carbon Reduction for Building Refurbishment in New Zealand

Research background

Achieving net-zero greenhouse gas (GHG) emissions is crucial to diminishing catastrophic climate change impacts. New Zealand needs to maximise carbon reduction in the design and construction of buildings to meet the net-zero carbon target by 2050. In particular, there is a need to implement carbon-reduction refurbishment strategies for the existing building stock rather than demolishing and rebuilding. This is often more difficult than new builds because the refurbishment process is influenced by constraints and limitations, such as project objectives, budget, available building techniques and user expectations. It may be challenging to manage clients' requirements with the need to focus on zero carbon strategies. International research suggests that successful zero carbon refurbishment for existing buildings can be achieved if effective decisions are made throughout the process. However, little research and initiatives have been undertaken regarding carbon reduction decision-making in building refurbishment in New Zealand. This research aims to improve the decision-making towards zero carbon refurbishment of New Zealand's existing buildings. The research objectives are:

1. To examine the planning and implementation of building refurbishment towards zero carbon worldwide.
2. To investigate the current decision-making process for reducing carbon emissions of building refurbishment in New Zealand.
3. To develop and validate a carbon-reduction decision support framework for building refurbishment in New Zealand.

As a result of the study, a “*Carbon-reduction decision support framework for building refurbishment in New Zealand (RefurbZC)*” has been developed based on the critical analysis and interpretation of international best practices and investigation of New Zealand’s building refurbishment case studies. The research results are expected to provide construction professionals with current practices and an interdisciplinary guide to better reduce carbon emissions for refurbishment projects. The study contributes significantly to the New Zealand construction industry transitioning to net zero carbon by 2050.

Pre-workshop agenda

Before attending the workshop, please ensure that you complete the checklist below:

1. You are asked to carefully read the research background, introduction to the developed framework (RefurbZC) and additional explanation.
2. You are asked to go through each step of the framework and think about the following questions:
 - Is there anything missing? If so, what is your suggestion for improvement?
 - Is there anything that does not make sense to you? If so, what is your suggestion for improvement?
 - Who should be involved in each step of the framework? (e.g. clients/developers, project managers, architects, engineers, cost advisors, sustainability and carbon consultants, contractors, subcontractors/suppliers, facilities managers, end-users, etc.)
 - Is this framework something you could apply to your work? If so, why? If not, why?
 - Would this framework benefit your work? If so, in what way?
 - Based on your experience/expertise, what do you think are the challenges in implementing this framework? How could these challenges be mitigated?
 - Do you have further suggestions to improve this framework?

Workshop agenda

Time: 10am – 12pm

Date: Thursday 22nd September 2022

Location: MS Teams

Note: The meeting room will open at 9:50 am on Thursday, 22nd September 2022. Feel free to open MS Team and “join” the workshop 5 minutes before the scheduled time.

Time	Session	Description
10:00 am - 10:10 am	Introduction	Arrivals and welcome.
10:10 am - 10:25 am	Warm-up	Opening question.
10:25 am - 10:45 am	Group discussion 1	Discussing five steps of the developed framework.
10:45 am - 11:00 am	Joint discussion 1	Providing feedback about five steps of the developed framework.
11:00 am - 11:10 am	Morning tea	Networking.
11:10 am - 11:25 am	Group discussion 2	Discussing the potential implementation, benefits, challenges and suggestions for improvement of the developed framework.
11:25 am - 11:40 am	Joint discussion 2	Providing feedback about the potential implementation, benefits, challenges and suggestions for improvement of the developed framework.
11:40 am - 11:45 am	Questionnaire survey	Completing a survey.
11:45 am - 12:00 pm	Closing	Ending Poll question. Further thoughts and follow-up activities.

13.3.2 Appendix 3.2. Workshop Activities

13.3.2.1 Appendix 3.2.1. Activity 1: Group discussion 1

20/02/2023, 08:07

Workshop_ZC_22Sep_Group discussion 1

Workshop_ZC_22Sep_Group discussion 1

To-do list in breakout rooms

1. Please nominate a group representative who will:
 - Open the form and share it on the screen.
 - Write down the group answers.
2. Please go through each step of the developed framework, discuss the questions in the MS form together and record your group answers.
3. Please save a copy of your group response after submitting the MS form.

• Required

1. What is your group name? *

- Blue 1
- Red 1
- Green 1

2. Is there anything missing in each step? If so, what is your suggestion for improvement? *

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3. Is there anything that does not make sense to you in each step? If so, what is your suggestion for improvement? *

4. Who should be involved in each step of the framework? (e.g. clients/developers, project managers, architects, engineers, cost advisors, sustainability and carbon consultants, contractors, subcontractors/suppliers, facilities managers, end-users, etc.). Please list the stakeholders who you think should be involved in each step and their responsibility. *

This content is neither created nor endorsed by Microsoft. The data you submit will be sent to the form owner.



13.3.2.2 Appendix 3.2.2. Activity 2: Group discussion 2

20/02/2023, 08:18

Workshop_ZC_22Sep_Group discussion 2

Workshop_ZC_22Sep_Group discussion 2

To-do list in breakout rooms

1. Please nominate a group representative who will:
 - Open the form and share it on the screen.
 - Write down the group answers.
2. Please go through each step of the developed framework, discuss the questions in the MS form together and record your group answers.
3. Please save a copy of your group response after submitting the MS form.

* Required

1. What is your group name? *

- Blue 2
- Red 2
- Green 2

2. Is this framework something you could apply to your work? If so, why? If not, why? *

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3. Would this framework benefit your work? If so, in what way? *

4. Based on your experience/expertise, what do you think are the challenges in implementing this framework? How could these challenges be mitigated? *

5. Do you have further suggestions to improve this framework? *

This content is neither created nor endorsed by Microsoft. The data you submit will be sent to the form owner.



13.3.2.3 Appendix 3.2.3. Activity 3: Survey

**A FOLLOW-UP SURVEY ON THE VALIDATION OF CARBON-REDUCTION
DECISION SUPPORT FRAMEWORK FOR BUILDING REFURBISHMENT IN NEW
ZEALAND**

Dear participants,

Thanks for attending the workshop and contributing the research project.

I would greatly appreciate if you would complete this follow-up survey. Your feedback will be highly valued.

The questionnaire survey will take about 5 minutes of your time to complete. The information collected will be kept confidential and will only be used for research purposes.

This research project has been evaluated by peer review and judged to be low risk - Ethics Notification Number: 4000023526. The researcher named in this questionnaire is responsible for the ethical conduct of this research.

If you require clarification and any further information, please do not hesitate to contact:

Thao Bui (Alice)

Email: T.Bui@massey.ac.nz

Thank you for your valuable time!

By clicking the button below, you acknowledge:

Your participation in the study is voluntary. You are 18 years of age. You are aware that you may choose to terminate your participation at any time for any reason.

- I consent, begin the study.
- I do not consent; I do not wish to participate.

Q1: Based upon your examination of the developed framework and guidance document, to what extent do you agree or disagree with the following statements?

Please choose **ONLY one** option.

	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree	Not sure
The structure of the proposed framework is clear.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
The contents presented in the framework are clear.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
It is easy to follow the processes and sub-processes of the framework.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
The relationship and links between steps are clear.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Additional guidance and lists of the information provided at each step are clear.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
The framework could possibly help you understand the refurbishment decision-making process and requirements for reducing carbon emissions in certain activities.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
The framework could possibly help you identify areas for addressing carbon-related issues in the early stages of the refurbishment process.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
The framework possibly provides relevant information that support your decision making in reducing carbon emissions of building refurbishment.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
The framework could possibly help promote stakeholder collaboration in identifying carbon-reduction solutions for building refurbishment.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Q2: Do you have any other comments on the developed framework that you would like to share with us?

We thank you for your time spent taking this survey.

Your response has been recorded.

13.3.2.4 Appendix 3.2.4. Activity 4: Poll

LIVE Poll: Record name ; Results shared

What is the likelihood you would support the use of the framework in your future work?

- Definitely
- Probably
- Possibly
- Probably not
- Definitely not

[Submit Vote](#)

13.4 Appendix 4: Examples of participant information sheets and consent forms used in this study

13.4.1 Participant information sheet

PARTICIPANT INFORMATION SHEET (PIS)

Project: Towards zero carbon refurbishment of existing buildings in New Zealand

You have been identified as a key player in the “*Towards zero carbon refurbishment of existing buildings in New Zealand*” research project. This PIS sets out why we are doing the study, what your participation would involve, what the benefits and rights you might be, and what would happen after the study ends.

Research introduction

Building refurbishment is a complex undertaking cutting across different technical fields and facing challenges in incorporating zero carbon targets, and many decisions are made throughout the refurbishment process. This research aims to improve the decision-making towards zero-carbon refurbishment for New Zealand’s existing buildings. The research results are expected to provide construction professionals with current practices and an interdisciplinary guide to better reduce carbon emissions for refurbishment projects. The study contributes significantly to the New Zealand construction industry transitioning to net zero carbon by 2050.

As a result of the study, a “*Carbon-reduction decision support framework for building refurbishment in New Zealand*” has been developed. The framework provides a detailed guideline to use in the early-stage refurbishment process. It is designed to ensure that all relevant carbon information is collected and considered logically, robustly and consistently. The scope of work includes non-residential existing buildings that have been decided to be refurbished. The framework consists of five steps considered in the pre-design and design stages of the refurbishment process, including (1) goal setting, (2) building diagnostics, (3) refurbishment strategies, (4) generation of refurbishment alternatives, and (5) performance estimation and evaluation. Information related to People, Process, Tools and Technology are considered in each step. Additional guidance and lists of the necessary information to inform decisions at each step are also provided.

Workshop procedures

The workshop aims to validate and refine the developed framework. The invitation will be sent to building stakeholders in New Zealand, including but not limited to building clients, projects managers, engineers, architects, sustainability consultants, quantity surveyors, contractors, and facilities managers. If you accept the invitation, a copy of the developed framework and an agenda will be sent to you before the workshop.

The workshop will take place online (MS Team) for two hours. All participants will also be sent a poll to select the most suitable time and date.

The workshop will be recorded, transcribed, and analysed by the named researchers only, who will safeguard the data. The transcriptions will not be included in the study without your consent. Your identity will not be revealed in the transcripts, and analysis, except with your permission. Based on the analysis, written reports will be prepared, which may be published in various formats as study findings. The data collected will be destroyed within five years after the completion of this research project.

Participant's Rights

You are under no obligation to accept this invitation. If you decide to participate, you have the right to:

- decline to answer any particular question; withdraw from the study (specify timeframe);
- ask any questions about the study at any time during participation;
- provide information on the understanding that your name will not be used unless you permit the researcher;
- be given access to a summary of the project findings when it is concluded.
- ask for the recorder to be turned off at any time during the workshop.

If you agree to participate in this study, you will be asked to sign the Consent Form. You will be given a copy of the PIS and the Consent Form.

This project has been evaluated by peer review and judged to be low risk. Consequently, it has not been reviewed by one of the University's Human Ethics Committees. The researcher(s) named below are responsible for the ethical conduct of this research.

If you have any concerns about the conduct of this research that you wish to raise with someone other than the researcher(s), please contact Prof Craig Johnson, Director, Research Ethics, telephone 06 356 9099 x 85271, email humanethics@massey.ac.nz". The researchers named in this document are responsible for the ethical conduct of this research.

If any queries arise, please get in touch with the research team:

Thao Thi Phuong Bui (Alice) PhD Candidate and Tutor in Construction, School of Built Environment, College of Science, Massey University, email: T.Bui@massey.ac.nz

Prof. Suzanne Wilkinson Associate Dean Research, College of Sciences, College of Sciences, Massey University, email: S.Wilkinson@massey.ac.nz

Dr. Niluka Domingo Senior Lecturer in Quantity Surveying, School of Built Environment, College of Sciences, Massey University, email: N.D.Domingo@massey.ac.nz

Dr. Casimir MacGregor Principal Social Scientist, BRANZ, email: casimir.macgregor@branz.co.nz

Thank you for your time and your kind support!

13.4.2 Consent form

CONSENT FORM

Project: Towards zero carbon refurbishment of existing buildings in New Zealand

You have been provided with project information and the workshop procedure by reading the Participant Information Sheet. This form acknowledges your agreement to attend the workshop and your permission for the workshop to be recorded.

During the workshop, you may ask to stop recording to make comments off the record. Results will not be published in any form that allows the identification of individuals or organisations without permission.

You are free to refuse to answer any question and to withdraw your participation at any time without needing to provide any explanation for your decision. In this event, the researcher will destroy all data from any withdrawing participant.

Signature: _____ **Date:** _____

CONFIDENTIALITY AGREEMENT

I, Thao Thi Phuong Bui, agree to keep confidential all information concerning the project. I will not retain or copy any information involving the project for any other use than this research's purpose.



Signature: _____ **Date:** ____11/08/2022____

13.5 Appendix 5: Introduction to RefurbZC

The decision support framework (RefurbZC) aims to provide a detailed guideline to use in the refurbishment process to reduce carbon emissions. It helps to understand the refurbishment decision-making process, identify areas for integrating carbon-reduction initiatives, determine key factors and actors in driving carbon-reduction solutions, and promote stakeholder collaboration and integration in carbon-reduction building refurbishment. This RefurbZC is designed to ensure that all relevant information is collected and considered logically, robustly, and consistently before making decisions. The RefurbZC's scope of work includes the major refurbishment of non-residential existing buildings that have been decided to be refurbished. This framework can be used by building stakeholders involved in the process of delivering or making decisions in building refurbishment, including but not limited to building clients, projects managers, engineers, architects, sustainability and carbon consultants, cost advisors, contractors, subcontractors, suppliers, facilities managers, and end-users. Although the final decision is made by building clients, this approach ensures that various perspectives, sources of information and interests are represented. It is recommended that decisions are made with input from all building stakeholders.

Figure 1 below demonstrates a high level of decision support framework, which includes four components: people, process, tools and technology, collaboration and integration attributes. The lower level of the framework comprises of the detailed decision-making processes, additional guidance and lists of the information needed to inform decisions at each step. The contents of each step are linked through a coding system (numbering system), which correlates activities and sub-activities in the process.

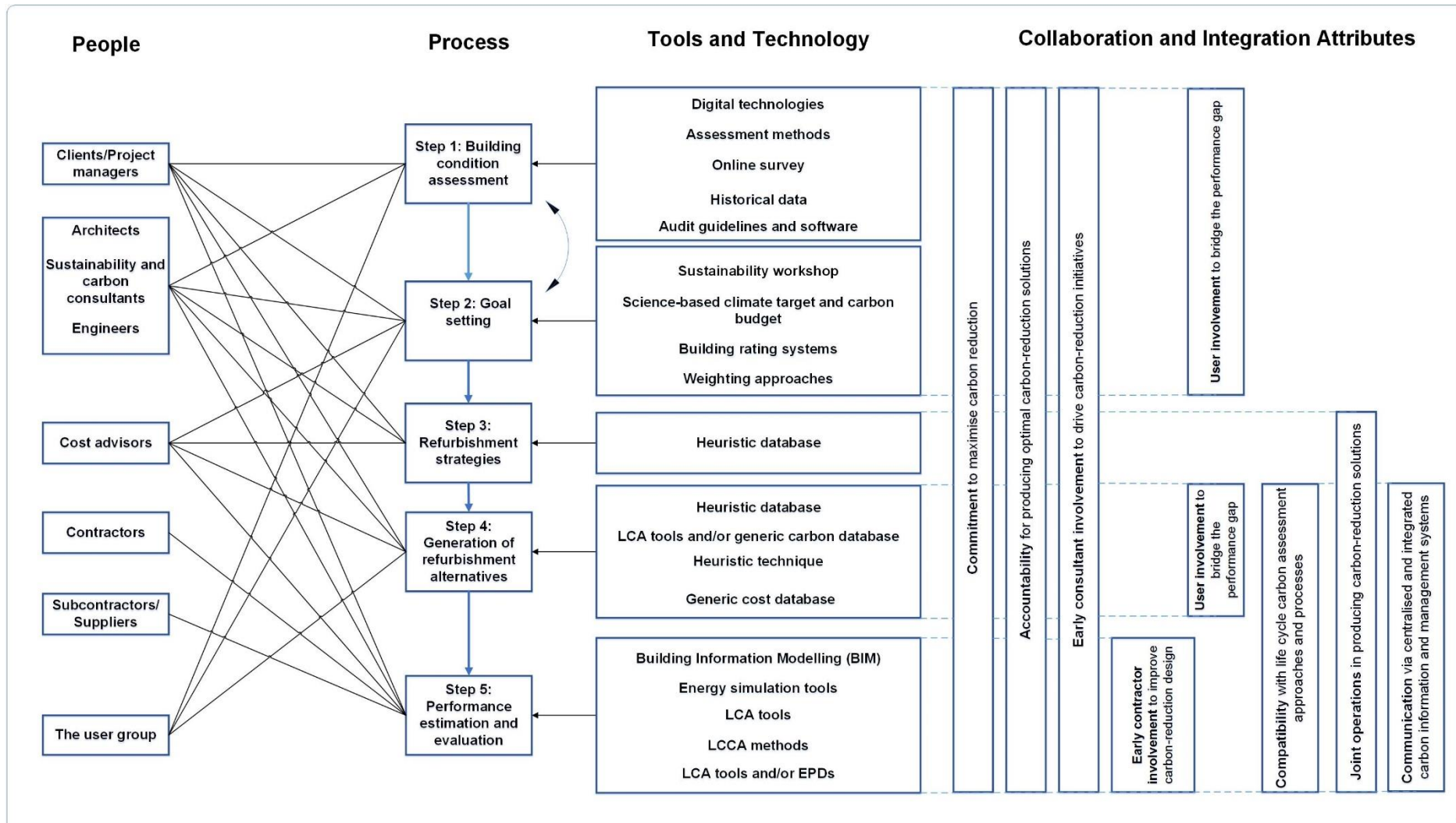


Figure 1: High level of five-step decision support framework (Source: Authors)

Step 1: Building condition assessment (A)

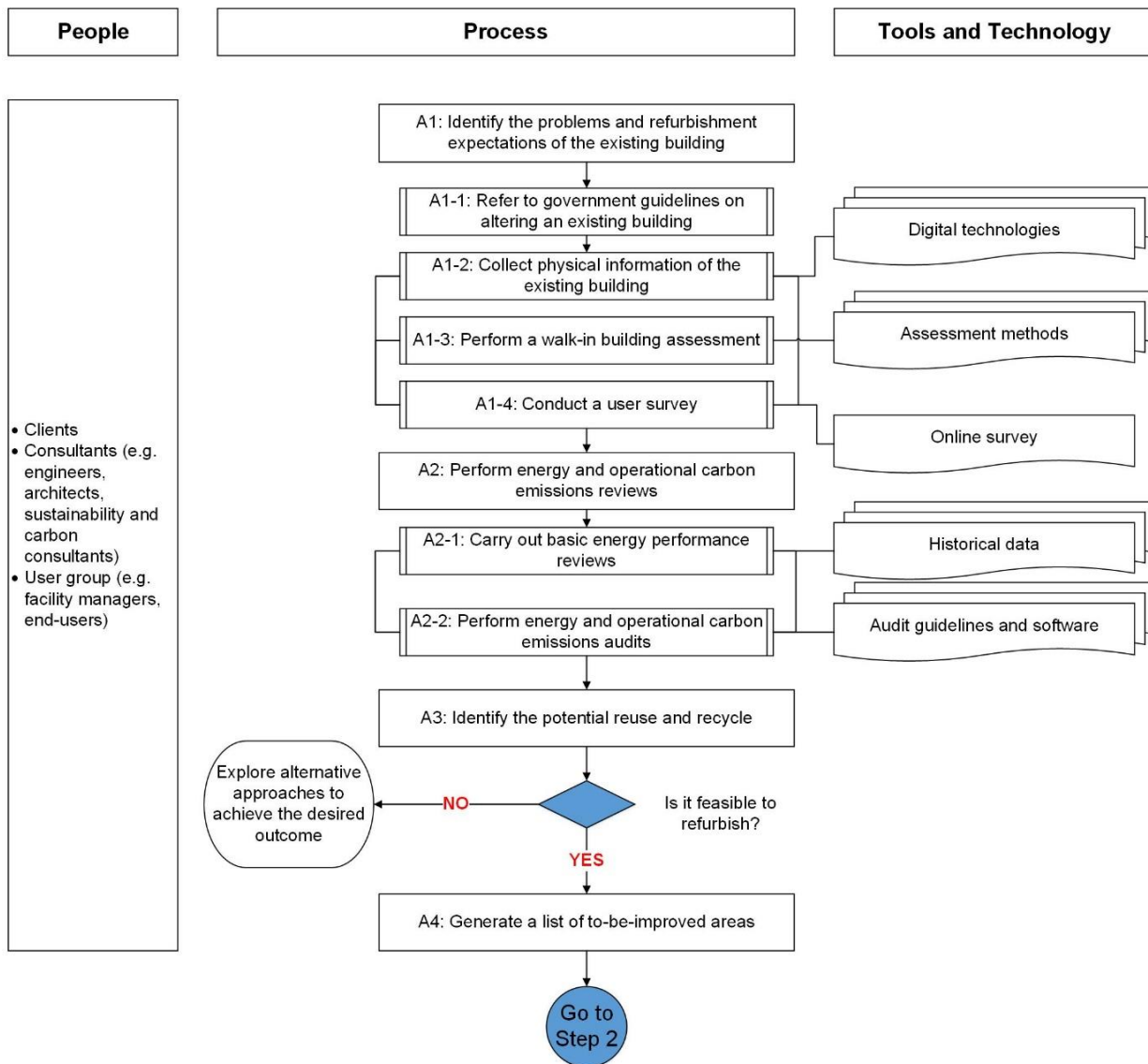


Figure 2: Low level of decision support framework - Step 1 (Source: Authors)

The departure point of the decision-making process is that the building client wishes to refurbish the existing building to maximise carbon reduction. Step 1 (A) of the framework is the building condition assessment. The building condition assessment is often used to recognise the degradation state of building components and services, identify system operational problems, and examine the building performance to determine whether the existing building can be refurbished. The assessment results are also used to identify appropriate refurbishment levels, strategies, and solutions later in the refurbishment process. The client team and the user group (e.g. facilities managers, end-users) are encouraged to be involved in step 1. Subject to the resources and experience, client representatives and facilities managers can be responsible for undertaking activities in

step 1. However, the consultant team (e.g. engineers, architects, sustainability and carbon consultants) is recommended to be involved in this step to help conduct an in-depth building condition assessment.

Step 1 starts with activity A1, which is identifying the problems and refurbishment expectations of the existing building. First and foremost, the government guidelines on altering an existing building need to be followed to ensure the refurbishment meets the government requirements (A1-1) (MBIE, 2018). If the building is considered vulnerable to earthquakes, MBIE’s EPB methodology for identifying and assessing earthquake-prone buildings should be followed (MBIE, 2017). Next, physical information about the existing building can be collected (A1-2), such as building location, building type, total building area, site orientation, gross floor area, occupancy, year built, type of construction, number of stories and other information about the existing building’s design and construction.

Table 1: Example of a systematic registration of the degradation state of the building components using a point system (Source: Authors)

Building elements/problems	Very poor (1)	Poor (2)	Average (3)	Good (4)	Excellent (5)
HVAC system		X The system is beyond its life expectation			
Lighting system				X The system operates in a good condition	
Indoor air quality	X Inadequate Ventilation				
Others					

The client and consultant team also perform a walk-in building assessment and generates a checklist providing a systematic registration of the degradation state of the building elements (A1-3). The assessment checklist includes identified building problems, physical and functional building conditions, and the current state of

structural elements, envelopes, services, and internal fittings. Each building item can be qualitatively ranked on a point system (Likert scale) from good to poor condition or a two-form system consisting of “yes – items to be upgraded” and “no – no change” (see Tables 1 and 2). Quantitative methods such as structural and material tests are recommended for assessing the existing building structure and materials.

Photography and video should be included for a visual demonstration. Using technologies such as 3D/Laser Scanner is recommended to help improve the site surveying and inspection by capturing and mapping the existing building information. This can later be integrated with the BIM model to enhance the accuracy of tracking information, improve data management, and increase productivity.

Table 2: Example of a systematic registration of the degradation state of the building components using a two-form system (Source: Case study 1)

HVAC system					
Areas	Ducted Preconditi oned Outside Air	Ducted Return Air	Toilets AC and Exhaust	AC in Offices Teaching Spaces and Corridors	Full BMS Control
Level 1	Y	Y	Y	Y	Y
Level 2	Y	Y	Y	Y	Y
Level 3	Y	Y	N	Y	Y
Level 4	Y	Y	N	Y	Y

Note: Y: Yes – items to be replaced; N: No change

In some cases, the client team can conduct a user survey (A1-4) to better understand the building’s operational and functional problems. The involvement of the user group provides perspectives on the area of improvement required in the refurbished building. Information about the user’s activities and expectations could help determine appropriate refurbishment solutions in the later steps and bridge the performance gap in the post-refurbishment stage.

The following activities (A2 and A3) focus on carbon performance. To determine the potential areas for improving energy efficiency and reducing operational carbon emissions, the client and consultant team can perform energy and operational carbon emissions (associated with energy and water use) reviews (A2). This

comprises basic energy performance reviews (A2-1), including total annual energy consumption and heating, lighting, and electricity usage, from historical data such as energy bills and energy and operational carbon emissions audits (A2-2). The client team can conduct the basic energy performance reviews, while the consultant team can be responsible for energy and carbon audits. The auditing guidelines can be referred to as ASHRAE Handbook, AS/NZS 3598.1:2014 and the Ministry for the Environment's "*Measuring Emissions: Detailed Guide 2020*". B2-2 is highly recommended to be carried out as the results of energy and carbon audits can be used later as a baseline/reference for the design improvement and comparing the building before and after refurbishing. However, this can only be done if available budget and resources exist.

Regarding reducing embodied carbon emissions from newly-added construction materials and products, the potential reuse and recycling of the existing structural elements, envelope, and internal fittings should be identified (A3). At the end of this step, the project team is expected to generate a list of areas that need improvement (A4).

Step 2: Goal setting (B)

Step 2 (B) of the framework is to set the right goal that meets the project requirements, client's budget and expectations. Setting goals and criteria is an important point of the refurbishment process since the decision made in the following steps are adapted to these strategic and significant aspects. This step can be done by the client team, who is mainly responsible for setting and prioritising the refurbishment goals and criteria. Subject to the client's experiences and resources, the consultant team (e.g. engineers, architects, sustainability and carbon consultants) and cost advisors can be engaged to provide support in setting the right goal. The client may assemble the right project team members and appoint a leading consultant at this stage. The user group can also provide perspectives on the project goals.

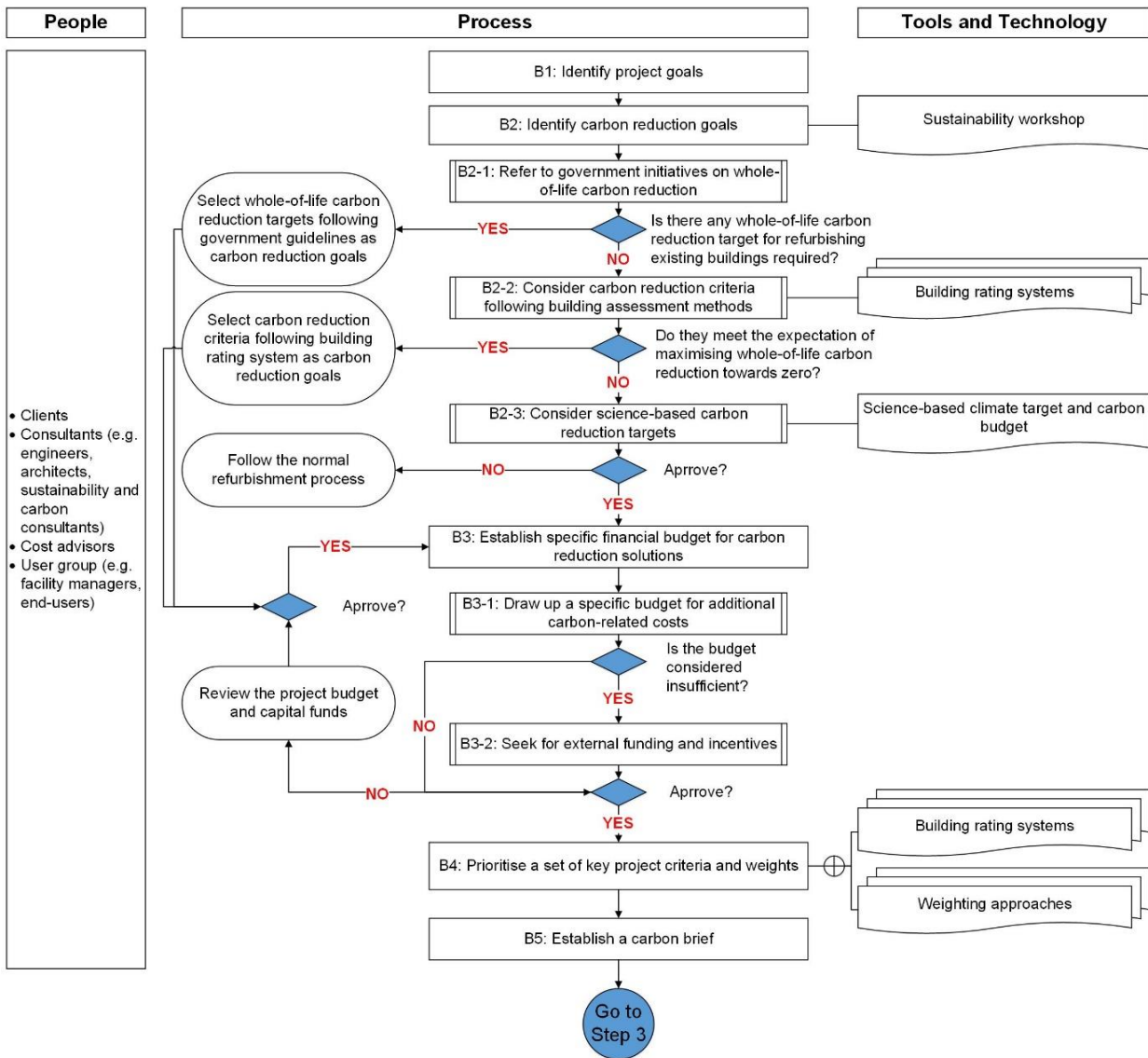


Figure 3: Low level of decision support framework - Step 2 (Source: Authors)

The departure point of step 2 is activity B1, where the client team first identifies the refurbishment project goal based on the organisation's strategies, drivers, and values. Table 3 demonstrates an example of determining refurbishment project goals. Suppose one of the project goals is maximising carbon reduction for the refurbishment project that aligns with the organisation's roadmap to achieve a net zero-carbon target. In that case, the team can proceed to activity B2, which is identifying the right carbon reduction goal for the refurbishment project. Subject to the client's resources and experience, a sustainability workshop is suggested to be taken place where the consultant team can be involved to support setting whole-of-life carbon reduction targets as a desirable outcome of the project.

Table 3: Example of determining project goals (Source: Case study 2)

Case study of a university building	Project goals
Organisation's strategies	Alignment with the organisation's Zero Carbon Plan
	Alignment with the organisation's Sustainability Strategy and UN Sustainability Development Goals
Project drivers and values	Community Benefits & Positive Environmental Impact
	Public, Students and Staff Visibility of Sustainability Initiatives
	The ability of the building to be re-purposed for low carbon
	Increasing student study capacity; creating modern fit-for-purpose student spaces; rationalising the print collection to free up space; seismic strengthening to bring the building up to the current Building Code

For activity B2, the first choice (B2-1) is following the New Zealand government's "Building for Climate Change" programme, which might legally set minimum levels of operational efficiency and limits for embodied carbon in buildings (MBIE, 2020). The other options are volunteering, considering carbon reduction criteria defined in building rating systems (B2-2) and science-based whole-of-life carbon reduction targets (B2-3). Indeed, there are some positive and negative benefits of each option that should be taken into account. The consultant team can help the client identify the carbon reduction criteria and pre-assess the potential application of building rating systems and whole-of-life carbon reduction targets.

It is important to note that building rating systems can be used early as a structured methodology to support the decision-making process by providing a direction for setting the goal, prioritising key criteria and specific areas of improvement, and potential design implications. The approved and recommended methods can be found in New Zealand Government Procurement (2021). The decision to include these rating systems to use early rather than to assess the finished building encourages the project team to incorporate the carbon-related design consideration throughout the process.

However, these systems might be inflexible in design, time-consuming to include at the early stages, and limited to recognising the project values. There could be a tendency with the building rating systems to put a capital cost value on points and target points based on their cost rather than the value that criteria offered. Thus, the benefits of the design options need to be identified separately to align with the key project criteria during the design stages. These benefits can then be considered alongside the design requirements of rating systems rather than using these systems as a framework to inform design inclusions. Due to the limitation of some building rating systems on prioritising the maximum whole-of-life carbon reduction, it is important to consider the science-based climate target and carbon budget of New Zealand's buildings (Bullen L. et al., 2021). This consideration helps establish a carbon benchmark for a comparative life-cycle carbon analysis to optimise the refurbishment design later in the process. However, it also can be time-consuming and requires a lot of detailed information, such as the schedule of quantities, energy modelling, LCA, etc., which will be demonstrated later in the following steps. Furthermore, the climate target and carbon budget, as mentioned above, apply to new buildings. A carbon budget for an individual building/whole existing building stock is expected to be estimated in future work. It is recommended that building rating systems and the climate target and carbon budget can be considered together to help achieve both sustainability and maximum carbon reduction goals.

Moving on now to consider activity B3, which is recommended to establish a specific financial budget for carbon reduction solutions. It is thought that this financial budget is often not considered in the current industry practices, leading to unexpected costs for carbon reduction solutions and limiting the consideration of lower carbon options later in the process. Thus, drawing up a budget for additional consultancy costs regarding whole-of-life carbon assessment, such as energy modelling, life cycle assessment, and possible investment costs for low-carbon materials, products, and green technologies (B3-1), and seeking external funding and incentives (B3-2) are crucial. The project budget and capital funds need to be reviewed if the budget is still considered insufficient for carbon reduction solutions. In the case of the limited budget against maximum carbon-reduction aspiration, it is encouraged to proceed to the next steps, where detailed carbon solutions can be further identified and assessed. The consultant team can assist the client in proposing the financial budget for carbon solutions.

Next, the client should prioritise key project criteria and weights (e.g. carbon, cost, energy, water, etc.) based on identified goals and budget (B4). The user group should be engaged to provide information on the key project criteria for co-benefits for users, such as improving indoor air quality. These criteria and weights are used later to assess the refurbishment solutions and performance. This can be done using a simple weighting approach (e.g. rank-order weighting) or a complex weighting approach (e.g. the analytical hierarchy process (AHP)), depending on the decision-makers' preferences, project drivers and values. Alternatively, the criteria and their weights in selected building rating systems can be followed. Trade-offs among key project criteria such as carbon and cost are inevitable in any design process. Even if comprehensive building rating systems are used, trade-offs must be made along the way. Figure 4 shows an example of prioritising the main project criteria using a simple rank-order weighting approach.

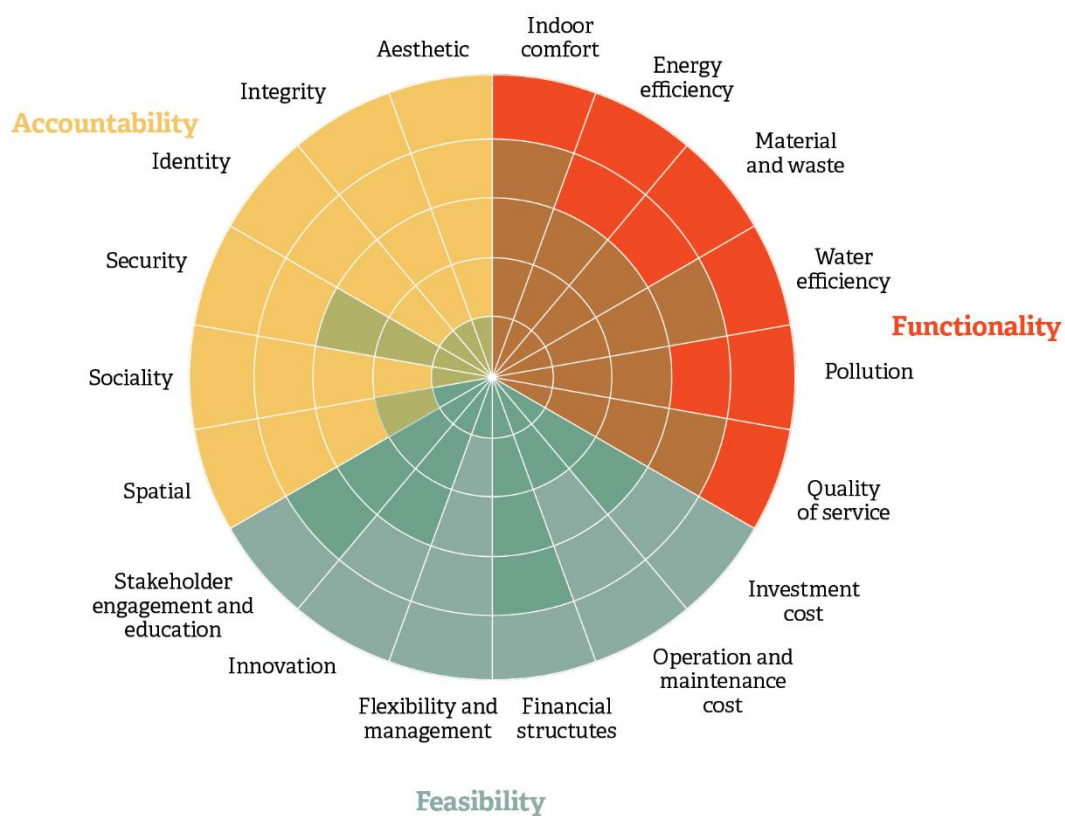


Figure 4: Examples of prioritising main project criteria (Scale of value: 0-5) (Kamari et al., 2017)

The last activity in step 2 is establishing a carbon brief as part of the project brief, which can be done by the client team (B5). The template and further guidance can be found in the New Zealand government guide to reducing carbon emissions in building and construction (New Zealand Government Procurement, 2021).

It is important to note that step 2 can be done before step 1. Assessing the building performance in step 1 after having set up project goals in step 2 will make the process of identifying improvement areas more targeted.

Step 3: Refurbishment strategies (C)

The aim of step 3 (C) is to establish the refurbishment level and strategies to achieve an overall long-term objective of building refurbishment projects. The client team is responsible for selecting the refurbishment level and refurbishment strategies. The consultant team (e.g. engineers, architects, sustainability and carbon consultants) and cost advisors could provide advice to support this decision-making.

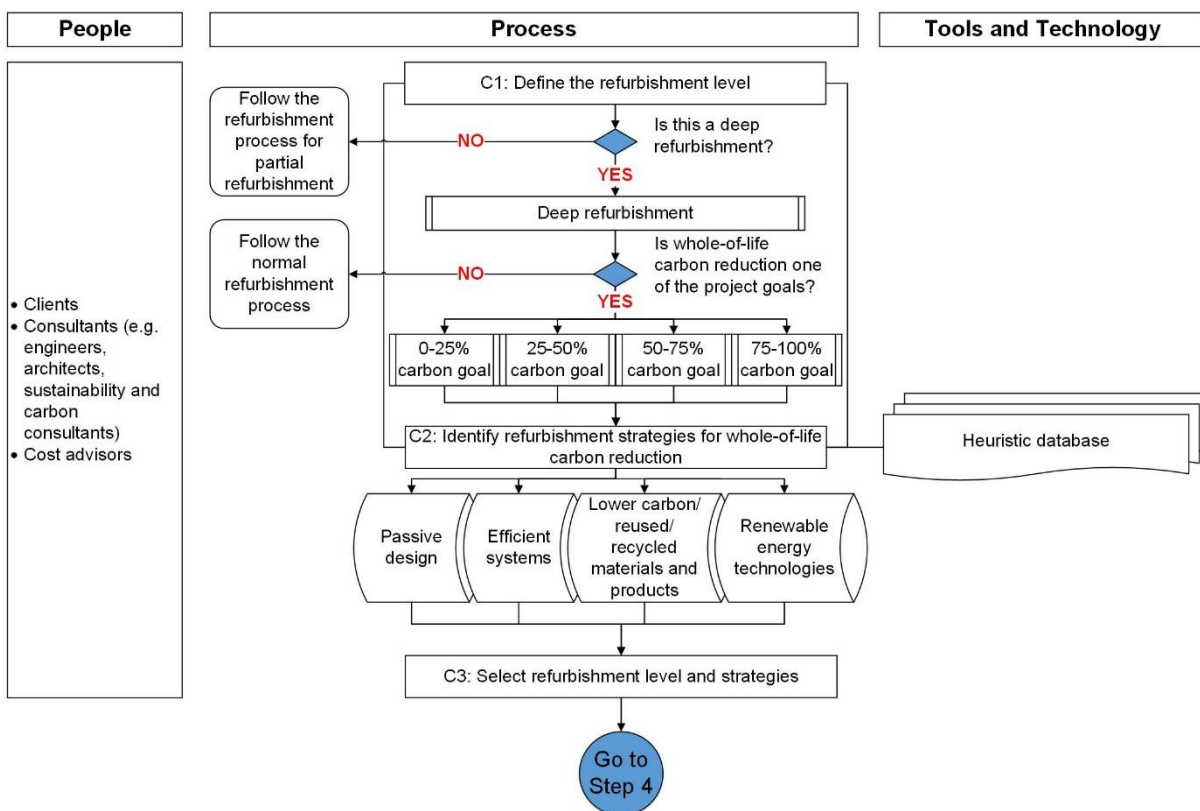


Figure 5: Low level of decision support framework - Step 3 (Source: Authors)

The first activity (C1) is to define the refurbishment level (e.g. partial or deep) based on the results of step 1 and step 2. As mentioned in the scope of work, the developed framework applies to major refurbishment projects. The decision on the refurbishment level should take the life-cycle cost and carbon emissions into

account. This is because, in some cases, partial refurbishment focuses on upgrading certain building areas (e.g. upgrading building envelopes or building services), which may not resolve the problem of inefficient building operation in general. This could lead to a higher cost of ongoing maintenance and replacement and higher energy use and operational carbon emissions. In this activity (C1), if one of the project goals is whole-of-life carbon reduction, the level of major refurbishment can be classified based on carbon goal setting in step 2. This could help select suitable refurbishment strategies, benchmark the alternatives, and optimise the design later in the process.

Together with activity C1, activity (C2) is to identify refurbishment strategies to reduce whole-of-life carbon emissions. These include passive design, efficient systems, lower carbon/reused/recycled materials and products, and renewable energy technologies. Refurbishment strategies can be considered based on design databases and case studies. However, there is a need for flexibility and freedom in selecting appropriate refurbishment strategies. This is because the consideration of the existing building condition and problems is the basis for developing refurbishment strategies. For example, passive design should be considered based on the physical conditions and capacities of the existing building. Renewable energy technologies can be regarded as long-term strategies. However, performance assessment and feasibility studies are required to identify the trade-off between the advantages and disadvantages of these technologies. The evaluation of refurbishment level and strategies can be done by the consultant team to support the client make decisions. At the end of this step, the client team select the refurbishment level and potential refurbishment strategies (C3).

Step 4: Generation of refurbishment alternatives (D)

Step 4 (D) identifies different refurbishment options and alternatives. A refurbishment option means a design solution for addressing an existing building problem, such as upgrading the window and glazing system, installing a PV system and adding wall insulation. A refurbishment alternative is a set of different refurbishment options, making the overall improvement of the refurbished building. The production of refurbishment options and alternatives usually involves the consultant team, including engineers, architects, and sustainability and carbon consultants. Cost advisors can take part to provide perspectives on cost-effective refurbishment options. Still, the client team is responsible for the approval. Optionally, the user group (e.g.

facility managers, end-users) can be involved to provide input regarding their activities, behaviours and ideal building features.

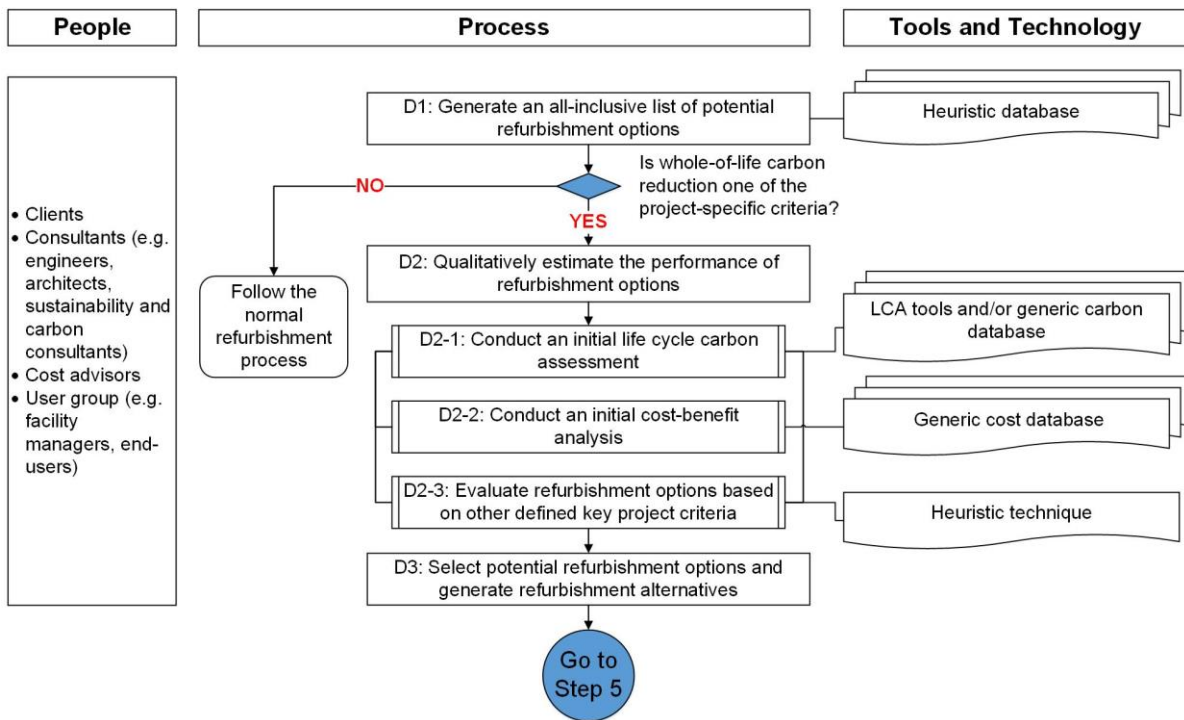


Figure 6: Low level of decision support framework - Step 4 (Source: Authors)

To begin with, the consultant team should generate an all-inclusive list of potential refurbishment options based on refurbishment strategies selected in step 3 (D1). The intention is to include all possible refurbishment options in the decision-making at each design stage and encourage creativity and innovation in choosing refurbishment options. After that, the team could qualitatively estimate the performance of refurbishment options based on the key project criteria defined in step 1 (D2). Table 4 represents an example of assessing each refurbishment option.

Table 4: Example of qualitatively evaluating each refurbishment options (Source: Authors)

Ref.	Refurbishment options	design	Carbon emissions			Cost			Energy efficiency	Thermal comfort	Indoor air quality	Other criteria (n, n+1..., N)	Commentary
	Item	Description	Operational carbon emissions	Initial embodied carbon emissions	Carbon payback period	Investment cost	Operation and maintenance cost	Investment payback period					
1	Upgrade window and glazing system	Double glazing with good g-value, Low-e coating and aluminium frames	Reduced energy use and operational carbon emissions	Aluminium frames and glazing can be high carbon-intensive	Operational carbon savings may not offset embodied carbon emissions	High	Medium	Less than 5 years	Improved energy efficiency	Improved thermal comfort	Improved indoor air quality	NA	<ul style="list-style-type: none"> • Slight reduction in visible light transmittance • Easy to implement but cannot be added later • Ongoing cleaning and maintenance
2	Air Tightness Testing	Pressure test the air permeability of the building envelope post construction	Reduced energy use and operational carbon emissions	NA	NA	High	NA	5-10 years	Improved energy efficiency	Improved thermal comfort	Improved indoor air quality	NA	<ul style="list-style-type: none"> • Limited New Zealand capability at present • Need to procure accredited contractors from other countries such as Australia

Sub-activities D2-1 and D2-2 are specific to addressing the whole-of-life carbon reduction goal. The consultant team conducts an initial life-cycle carbon assessment to identify lower-carbon refurbishment options (D2-1). Sustainability and carbon consultants are key actors in identifying potential carbon-saving solutions. However, there might be a lack of information regarding the life-cycle carbon emissions of refurbishment options. Thus, initial carbon analysis can consider operational carbon emissions associated with energy use and initial embodied carbon emission related to the manufacture of building materials and products and the construction process (Module A1-A5 in building life cycle stages and modules BS EN 15978:2011). This can be done using available life cycle assessment tools and/or a generic carbon database. At the same time, an initial cost-benefit analysis can be conducted using a generic cost database to determine lower-cost and lower-carbon refurbishment options of the best practices (D2-2). Cost advisors are accountable for identifying cost-effective options. After evaluating potential refurbishment options based on other defined key project criteria (D2-3), the project team.

Step 5: Performance estimation and evaluation (E)

Step 5 (E) aims to estimate and evaluate the performance of refurbishment alternatives. At this stage, different refurbishment alternatives can be assessed quantitatively based on the criteria for the particular project. As in step 4, the consultant team (e.g. engineers, architects, sustainability and carbon consultants) and cost advisors are mainly responsible for undertaking activities in step 5, while the client team is responsible for the approval. However, the involvement of contractors, subcontractors and suppliers also provides perspectives on the most appropriate refurbishment alternatives.

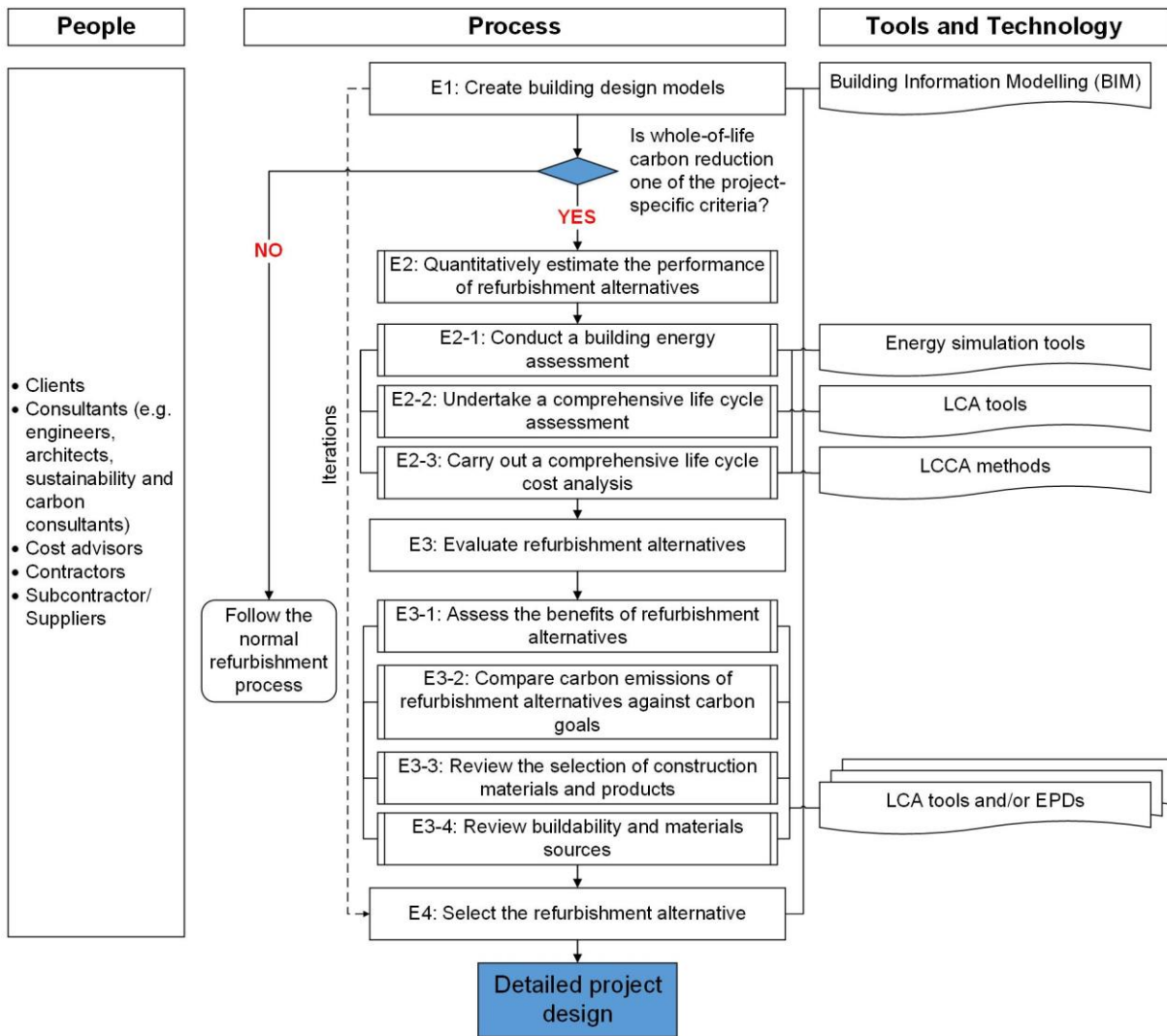


Figure 7: Low level of decision support framework - Step 5 (Source: Authors)

Step 5 starts with creating building design models using Building Information Modelling (BIM) (E1). The base case is the existing building, and the improved cases are based on the different alternatives of selected refurbishment options. BIM is recommended to support the whole-of-life carbon assessment using energy modelling and life cycle assessment in the following activities. After that, the performance of refurbishment alternatives can be quantitatively estimated (E2). This estimation includes (E2-1) conducting a building energy assessment using energy simulation tools to evaluate building energy performance and operational carbon emissions, (E2-2) undertaking a comprehensive life cycle assessment to quantify whole-of-life carbon emissions of refurbishment alternatives using life cycle assessment tools and (E2-3) carrying out a comprehensive life-cycle cost analysis to calculate the life cycle cost of refurbishment alternatives. Architects, engineers, sustainability and carbon consultants can work together to undertake energy modelling, LCA

analysis and verifying carbon assessment results. Cost advisors are responsible for carrying out the life cycle cost analysis to prioritise cost-effective options.

It is important to note that LCA tools can be used to assess the whole-of-life carbon emissions of buildings. However, it has several drawbacks, including the dependency on the quality and availability of data, affecting the accuracy of the assessment result. LCA tools may only consider the actual energy used during a certain period of production only. Considering the life span of a building, information related to energy load for the entire life span may not be available or not properly documented. This limitation can be solved using energy modelling to estimate the total energy gain and losses through building internal loads. As such, it is recommended to integrate energy modelling and LCA tools to achieve a desirable outcome.

Next, activity (E3) is to evaluate refurbishment alternatives by iteratively undertaking the following sub-activities. First, the benefits of refurbishment alternatives are assessed based on the performance estimation and the key project criteria identified in step 2 (E3-1). Table 5 demonstrates an example of evaluating refurbishment alternatives regarding economic and carbon performance indicators. Second, the quantified carbon emissions of refurbishment alternatives are compared to the carbon reduction goal and the areas where the design can be optimised are identified (E3-2). Third, the selection of construction materials and products is reviewed to select the lowest carbon options based on life cycle assessment tools and carbon data (e.g. Environmental Product Declaration (EPD)) (E3-3). Last but not least, the buildability and potential materials sources should also be reviewed (E3-4). While the consultant team work collaboratively to evaluate refurbishment alternatives. The contractors, subcontractors and suppliers should be engaged to review buildability and waste management plans and provide detailed carbon data, potential sources, and performance requirements of construction materials and products.

At the end of step 5, the optimal refurbishment alternative is selected (E4). Notably, the activities in step 5 are iterative, where refurbishment alternatives are continuously estimated and evaluated. After step 5, the refurbishment process can continue with the detailed project design, construction, operation.

Table 5: Comparison of the economic and carbon performance (Source: Authors)

Scenario	Description	Carbon					Cost				
		Annual energy use (kWh/m ² /yr.)	Annual operational carbon emissions (kg CO ₂ eq/yr.)	Annual operational carbon savings (kg CO ₂ eq/yr.)	Initial embodied carbon (kg CO ₂ eq)	Carbon payback period (year)	Life cycle carbon emissions (kg CO ₂ eq)	Annual energy cost savings (\$)	Investment cost (\$)	Operation and maintenance cost (\$)	Investment payback period (year)
Base case	Existing building										
1	Upgraded window and glazing										
2	Upgraded window and glazing, new mixed mode ventilation, new LED lighting										
3	Upgraded window and glazing, new mixed mode ventilation, new LED lighting, installed PV system										






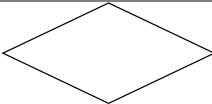

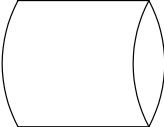
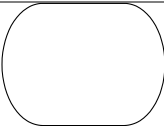




Note:

Investment payback period (year) = Initial investment cost / Annual energy cost savings

Carbon payback period (year) = Initial embodied carbon / Annual operational carbon savings

13.6 Appendix 6: Improvement measures for RefurbZC

13.6.1 Flow chart symbols and meaning

Symbols	Meaning
	Indicates the beginning of the process
	Indicates an activity in the process
	Indicates a sub-activity in the process
	Indicates single input/data/mechanism/tool/technology
	Indicates multiple input/data/mechanism/tool/technology
	Indicates decisions
	Indicates output/results/outcomes
	Indicates database
	Indicates an alternative activity
	Indicates AND/OR
 	Indicates the decision direction
	Indicates sub-activities that can be done simultaneously

13.6.2 Revisions required to improve the RefurbZC

General improvement	<ul style="list-style-type: none">✓ The clarity of the RefurbZC should be improved (i.e. clear direction and input/output, eliminating unnecessary activities and decisions to make the RefurbZC more comprehensive and user-friendly, using consistent terminology)✓ The iterative process in step 5 should be broken down into different parts with specific outcomes✓ Aligning the high level of RefurbZC with project timeline and phases in NZCIC guidelines – New Zealand Building and Construction Sector Council✓ The whole refurbishment process from the beginning to the post-occupancy should be circular instead of linear
Specific improvement	<ul style="list-style-type: none">✓ The starting point could be having a carbon-reduction aspiration at the beginning of the process✓ A1-4 should be placed after A1-1✓ A2-1 and A2-2 should be combined✓ The cost related to carbon-reduction solutions (B3-1) should be seen as business as usual rather than an additional cost for a specific carbon-reduction strategy✓ A need for the condition for applying activity B2 (i.e. determining the existing and future use of the refurbished building and data availability)✓ The scope of life cycle carbon analysis in D2-1 needed to be clearer (i.e. conducting initial life cycle carbon assessment of refurbishment options)✓ Risk assessment for refurbishment alternatives in step 5 should be included✓ The decision direction should not be back to following the normal refurbishment process from step 3 forwards



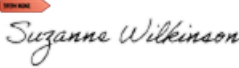
13.6.3 Actions taken to improve the appropriateness of the RefurbZC

Actions taken to refine the RefurbZC	Proposed steps	Proposed components	Refined steps	Refined components
<ul style="list-style-type: none"> ✓ Inserted “the building client wishes to refurbish the existing building to maximise carbon reduction” as the starting point ✓ Moved and changed A1-4 to A1-2 “conduct a user survey” ✓ Renamed A2 to “assess carbon performance of the existing building” ✓ Combined A2-1 and A2-2 and changed to A2-2 “perform energy and operational carbon emissions reviews” ✓ Included the conditions for applying activity A2-2 (i.e. determining the existing and future use of the refurbished building and data availability) in the additional guideline ✓ Changed A3 to A2-1 “identify the potential reuse and recycle” ✓ Changed A4 to outcome of step 1 “complete Building Conditions Report” 	Step 1	<ul style="list-style-type: none"> A1 A1-1 A1-4 A1-2 A1-3 A2 A2-1 A2-2 A3 A4 	Step 1	<ul style="list-style-type: none"> The starting point A1 A1-1 A1-2 A1-3 A1-4 A2 A2-2 A2-1 Outcome of step 1
<ul style="list-style-type: none"> ✓ Removed decision points between B2-2 and B2-3 ✓ Added outcome of carbon goal setting “set carbon reduction goal” ✓ Reworded B3 to “review the project budget” ✓ Renamed B3-1 to B3-1 “set a realistic project budget with the up-to-date market prices of carbon-reduction initiatives” ✓ Inserted outcome of reviewing the project budget “set project budget” ✓ Deleted “follow the normal refurbishment process” 	Step 2	<ul style="list-style-type: none"> B1 B2 B2-1 B2-2 B2-3 B3 	Step 2	<ul style="list-style-type: none"> B1 B2 B2-1 B2-2 B2-3 Outcome of carbon goal setting B3


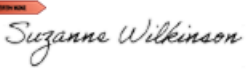
✓ Inserted “explore alternative approaches to achieve the desired outcome” as an alternative		B3-1		B3-1
		B3-2		B3-2
✓ Changed A5 to outcome of step 2 “complete carbon and project brief”				Outcome of reviewing the project budget
		B4		B4
		B5		Outcome of step 2
✓ Removed the unnecessary decision point between C1 and C2	Step 3	C1	Step 3	C1
✓ Deleted “follow the normal refurbishment process”				Outcome of refurbishment level selection
✓ Inserted “explore alternative approaches to achieve the desired outcome” as an alternative		C2		C2
✓ Added outcome of refurbishment level selection “selected refurbishment level”				Outcome of step 3
✓ Reworded C2 “review carbon reduction goal to identify appropriate refurbishment strategies”				
✓ Changed C3 to the outcome of step 3 “selected refurbishment strategies”				
✓ Removed the decision point between D1 and D2	Step 4	D1	Step 4	D1
✓ Deleted “follow the normal refurbishment process”		D2		D2
✓ Reworded D2-1 to “conduct an initial life cycle carbon assessment of refurbishment options”		D2-1		D2-1
		D2-2		D2-2
✓ Reworded D2-2 to “conduct an initial cost-benefit analysis of refurbishment options”		D2-3		D2-3
		D3		Outcome of step 4
✓ Inserted “explore different refurbishment options” as an alternative				
✓ Added a decision point after D2				

✓ Inserted a column in Table 7-6 to provide the ranking for each refurbishment option using traffic light system or namely “must-have” and “nice-to-have”				
✓ Changed D3 to the outcome of step 4 “selected refurbishment options and generated refurbishment alternatives”				
✓ Removed the decision point between E1 and E2	Step 5	E1	Step 5	E1
✓ Removed and replaced the iteration with appropriate decision points		E2		E2
✓ Deleted “follow the normal refurbishment process”		E2-1		E2-1
✓ Inserted E2-4 “performing risk assessment” in the tools and technology component		E2-2		E2-2
		E2-3		E2-3
✓ Inserted “explore different refurbishment alternatives” as an alternative				E2-4
✓ Added outcome of performance estimation “estimated performance results of refurbishment alternatives”				Outcome of performance estimation
✓ Added outcome of refurbishment alternative selection “selected refurbishment alternative”		E3		E3
		E3-1		E3-1
✓ Changed former E4 to the outcome of step 5 “optimal refurbishment alternative”		E3-2		E3-2
✓ Inserted later E4 “optimise selected refurbishment alternative”				Outcome of refurbishment alternative selection
✓ Changed E3-3 to E4-3 “review the selection of construction materials and products”				E4
		E3-3		E4-3
✓ Altered E3-4 to E4-4 “review buildability and materials sources”		E3-4		E4-4
		E4		Outcome of step 5



13.7 Appendix 6: Statement of contribution

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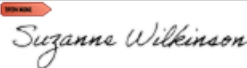
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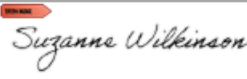
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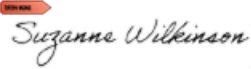
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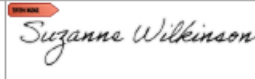
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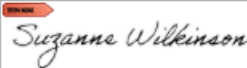
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