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The Development of a Decision-Support Tool (DST) for Selecting Best-fit Zero-Carbon Building Materials; The Case of New Zealand Building Industry

A thesis submitted in fulfilment of the requirements for the degree of

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Construction

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by

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Abstract

The construction sector plays a critical role in national and global decarbonisation efforts due to its substantial contribution to greenhouse gas emissions, particularly through the embodied carbon of building materials. In New Zealand, while policy initiatives such as the Zero Carbon Act 2019 and the Building for Climate Change programme signal a strong commitment to net-zero emissions by 2050, practical mechanisms to support early-stage zero-carbon material selection remain limited. Material choices are often fragmented, experience-driven, and constrained by incomplete or inconsistent data, highlighting the need for structured and evidence-based decision support.

This doctoral research addresses this gap by establishing a multi-criteria decision-support framework for zero-carbon material selection in the New Zealand construction industry. Guided by a pragmatic research philosophy, the study adopts a sequential mixed-methods and design science research approach to integrate empirical evidence, expert judgement, and artefact development.

The research is structured across five interconnected phases. First, a scoping review identifies common zero-carbon and low-carbon building materials relevant to the New Zealand context, including timber-based systems, straw bale, rammed earth, adobe, cork, stone, and earth-based materials. Second, a PRISMA-aligned systematic literature review synthesises international and local evidence on material performance and selection criteria. Third, a national survey of construction stakeholders is analysed using descriptive statistics, one-sample tests, and structural equation modelling to identify and weight key material selection factors, namely cost-effectiveness, durability, buildability, embodied carbon, availability, and aesthetics. Fourth, a qualitative SWOT analysis evaluates these criteria to capture contextual constraints, risks, and implementation considerations. Finally, the integrated findings are operationalised into a digital multi-criterion DTS.

The study makes theoretical, methodological, and practical contributions by reframing zero-carbon material selection as a multi-dimensional decision problem, demonstrating a replicable mixed-method design science approach, and delivering a validated, practitioner-oriented DTS tailored to New Zealand conditions. The research supports more transparent, defensible, and context-sensitive material selection decisions and contributes to advancing zero-carbon construction practice in New Zealand.

Dedication

To my beloved mother, and my father, in loving memory,
whose unwavering love, sacrifices, and support have formed the foundation of my journey. Your guidance, encouragement, and belief in me have been a constant source of strength throughout my life.

This work is dedicated to you, with my deepest gratitude, respect, and love.

Ali Hashemi Araghi

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List of Peer-reviewed Publications

This thesis comprises eight chapters, each originating from a research article that has been published, accepted, or submitted to reputable peer-reviewed journals. Apart from minor editorial and formatting adjustments, the chapters are presented largely in their original manuscript form.

Publication 1 (*Chapter 3):* Common Zero-Carbon Building Materials in New Zealand

This chapter is based on the following published work:

- Araghi, A.H., Rasheed, E., Vishnupriya, V., Seadon, J. (2024). Zero-Carbon Building Materials for the 2050 Net-Zero Emissions in New Zealand Construction Industry: Benefits and Limitations. In: Rotimi, J.O.B., Shahzad, W.M., Sutrisna, M., Kahandawa, R. (eds) Advances in Engineering Project, Production, and Technology. EPPM 2023. Lecture Notes in Mechanical Engineering. Springer, Cham. https://doi.org/10.1007/978-3-031-56878-7_13

Publication 2 (*Chapter 4):* Zero-Carbon Building Materials in the New Zealand Context: A Systematic Literature Review. This chapter is based on the following published work:

- Araghi, A. H., Rasheed, E. O., Vishnupriya, V., & Seadon, J. (2025). Zero-carbon building materials in New Zealand context: a systematic literature review. *Discov Appl Sci* **7**, 544. https://doi.org/10.1007/s42452-025-06564-7

Publication 3 (*Chapter 5):* Factors Influencing Sustainable Building Material Selection in New Zealand. The content of this chapter is extracted from:

- Araghi, A. H., Rasheed, E. O., Vishnupriya, V., & Seadon, J. (2025). Identifying Key Factors Influencing the Selection of Sustainable Building Materials in New Zealand. *Sustainability*, *17*(20), 9071. https://doi.org/10.3390/su17209071

Publication 4 (*Chapter 6):* SWOT-Based Evaluation of Zero-Carbon Building Material Selection Criteria. This chapter synthesises a systematic qualitative SWOT analysis of six zero-carbon material selection criteria (cost-effectiveness, durability, buildability, embodied carbon, availability, and aesthetics). The content of this chapter is extracted from:

- Araghi, A. H., Rasheed, E. O., Vishnupriya, V., & Seadon, J. (2026). Strengths, Weaknesses, Opportunities, and Threats of Zero-Carbon Materials in New Zealand: A

Literature Review, International Conference on Digital Frontiers in Buildings and Infrastructure (DFBI2026) (Under Review)

Publication 5 (*Chapter 7):* Development and Delphi Validation of a DTS for Zero-Carbon Material Selection in New Zealand. This chapter presents the MCDM-based DST framework, Streamlit implementation, sensitivity analysis, and three-round Delphi validation with 14 experts. The content of this chapter is extracted from:

- Araghi, A. H., Rasheed, E. O., Vishnupriya, V., & Seadon, J. (2026). A Multi-Criteria Decision Tool for Zero-Carbon Material Selection: Development and Evaluation, CivilEng, Under Review (R2)

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Abbreviations

BRANZ – Building Research Association of New Zealand

BREEAM – Building Research Establishment Environmental Assessment Method

CO_2 – Carbon Dioxide

CO_2-eq – Carbon Dioxide Equivalent

Delphi – Delphi Method for Expert Consensus

DST – Decision-Support Tool

EECA – Energy Efficiency and Conservation Authority (New Zealand)

GHG – Greenhouse Gas

GWP – Global Warming Potential

IAQ – Indoor Air Quality

IQR – Interquartile Range

ISO – International Organization for Standardization

LCA – Life Cycle Assessment

LCI – Life Cycle Inventory

LCIA – Life Cycle Impact Assessment

MBIE – Ministry of Business, Innovation and Employment (New Zealand)

MCDA – Multi-Criteria Decision Analysis

MCDM – Multi-Criteria Decision-Making

NZBC – New Zealand Building Code

NZGBC – New Zealand Green Building Council

PE – Preferential Independence

SEM – Structural Equation Modelling

UI – User Interface

UV – Ultraviolet

W – Kendall's Coefficient of Concordance

WSM – Weighted Sum Model

Chapter 1: Introduction

The construction sector across the world is experiencing a paradigm shift as the effects of climate change are rapidly increasing, and governments and other institutions are acting accordingly (Abbass et al., 2022). Buildings account for approximately 40% of global energy-related CO_2 emissions, making the sector a central focus for climate-change mitigation efforts (Li et al., 2019). Global climate agreements, including the Paris Agreement, have created obligations to curb carbon emissions, which encourages a national policy to achieve net-zero goals (Van Soest et al., 2021). In this regard, the use of low- and zero-carbon building materials has become one of the most successful options in terms of minimising the embodied emissions of buildings (Giesekam et al., 2016).

The Climate Change Response (Zero Carbon) Amendment Act 2019, which commits New Zealand to achieving net-zero carbon emissions in 2050, was officially passed in 2019 (Leining et al., 2020). Although operational building emissions was a growing policy consideration (including through the Building for Climate Change (BfCC) programme), embodied carbon through materials production, transportation, and construction remains an expanding and less-regulated source of national emissions (Skillington et al., 2022). The construction industry still has a serious problem: ensuring that the national climate aspirations are translated into practical and justifiable material selection choices at the design level (Hobbs & Meier, 2012).

As an increasing number of zero-carbon and low-carbon materials are offered to material professionals, the process of choosing a material to work with is still quite fragmented and depends mostly on their personal experience and data provided by suppliers (Braulio-Gonzalo et al., 2022). In addition, many certification-based rating tools assess sustainability performance only after design decisions have been finalised, offering limited support for early-stage material selection (Doan et al., 2016). This creates a clear need for structured, transparent, and evidence-based decision-support mechanisms that can operate at the early design stage and systematically integrate environmental, technical, economic, and contextual factors (Senerth et al., 2025).

The study addresses that requirement by developing a multi-criteria decision-support model of zero-carbon material choice in the New Zealand building sector. The research uses a combination of a systematic material review, empirical identification of factors, appraisal of criteria, and validation of the experts in order to create and utilize a digital decision-support tool (DST), which allows making an informed, transparent, and context-specific choice of materials.

1.1 Background

Often, zero-carbon buildings can be characterized as energy-efficient buildings which run on on-site and/or off-site renewable sources of energy and have a net-zero carbon impact over their lifetime (Lou & Hsieh, 2024). However, the actualization of zero-carbon building is way beyond the scope of operational energy and is immensely dependent upon the embodied carbon of building materials (Xing et al., 2011). Traditional building materials, namely concrete, steel, and aluminium continue to prevail in the construction industry but contribute to a major part of the global carbon emissions because of the energy-intensive production cycles of these materials (Sizirici et al., 2021).

The global surveys reveal that the construction industry contributes more than 40 percent of the total energy consumption in the world and about one-third of the total GHG emission (Nejat et al., 2015). The large portion of this footprint can be credited to embodied emissions due to material extraction, processing, transport, and installation (Hertwich, 2021). Although the building design has changed towards increasing energy efficiency, such embodied emissions keep growing as the construction activity increases (Eleftheriadis et al., 2017).

In New Zealand, the building and construction industry makes about 20 percent of the total greenhouse gas emissions in the country (Bui et al., 2022). Even though the proportion is lower compared to some bigger economies because of the population size and housing density, the sector emissions have been rising steadily over the past decades (O'neill et al., 2010). The issue of increasing residential energy prices, the escalating housing demand, and the increased building activity only exacerbate the environmental and economic consequences of the existing building practices (Güneralp et al., 2017).

Internationally, timber-based systems, straw bale, rammed earth, adobe, cork, and earth-based materials have a great potential in lowering embodied carbon because they are renewable, have the ability to sequester carbon, and they do not require the use of much energy in their production (Cabeza et al., 2022; Kuittinen et al., 2023). In New Zealand, especially, the country has excellent domestic forestry resources, as well as the increasing skill of alternative construction systems (The NZ Ministry for Primary Industries, 2025). Nevertheless, the use of these materials, except timber, is still restricted due to the uncertainty in the fields of durability, cost, constructability, compliance with regulations, and availability in the market (Araghi et al., 2025).

Moreover, the environmental product declarations and the datasets of life-cycle inventories that can be offered to New Zealand professionals are often incomplete, inconsistent, and based on the international averages (Strazza et al., 2016). This lack of standardised and locally representative data further complicates comparative material evaluation and weakens confidence in carbon-based decisions (Nguyen et al., 2024).

Against this backdrop, there is a pressing need for an integrated, practitioner-oriented decision-support framework that enables professionals to evaluate zero-carbon materials using transparent, multi-criteria logic grounded in New Zealand conditions (Bajwa et al., 2025). Such a framework must combine environmental performance with cost, durability, buildability, availability, and aesthetic considerations to reflect real-world decision requirements (Li, 2022).

1.2 Research Problem and Justification

Despite high international pressure for sustainable construction, the transformation of zero carbon aspirations into building-sector practice is uneven. While many countries (e.g., New Zealand), accepted the Paris Agreement and sustainable long-term carbon neutrality, the implementation mechanisms in construction supply chains are not integrated (The NZ Ministry for the Environment, 2022). The Zero Carbon Act 2019 established a key duty for Aotearoa New Zealand to pursue net-zero emissions of long-lived gases by 2050 but embodied emissions in buildings are on the rise (MBIE, 2020c). This disconnect between what policy represents and what really happens is the central motivation for this research.

To help minimise the impact of building emissions, the Ministry of Business, Innovation and Employment (MBIE) in 2019 launched a Building for Climate Change (BfCC) programme to reduce both operational and embodied emissions throughout a building's entire life cycle (MBIE, 2020b). However, the programme currently offers only high-level guidance, not practical decision-making protocols for professionals interested in reducing carbon emissions, leaving them at a loss to choose or swap materials to achieve carbon targets. Simultaneously, Vierra (2016) observes that numerous product environmental-declaration datasets are incomplete, variable, or derived from international averages. Lack of common and standardized data models makes comparing materials challenging, especially when architects or engineers have to weigh factors like cost, availability, materials, strength, and aesthetics against carbon performance (BRANZ, 2025).

Although international rating systems such as LEED (U.S.) (Newsham et al., 2009), BREEAM (U.K.) (Cole & Jose Valdebenito, 2013), and Green Star (Australia/NZ) (Xia et al., 2013)

provide structured sustainability indicators and benchmarks, they are primarily designed as certification frameworks aligned with predefined performance targets rather than as exploratory DTSs for early-stage design and material selection. As noted by Vierra (2016), these systems are most effective when applied to evaluate and verify design outcomes against established criteria, rather than to systematically compare alternative materials or design options during the formative stages of decision-making. Consequently, in early design phases design teams may still rely on professional judgement, prior experience, and supplier-provided information, highlighting the need for complementary evidence-based decision-support approaches.

1.3 The Research Aim and Objectives

The primary aim of the current research is to build on the outcome of DST to support the systematic choice of high-performance zero-carbon building materials for construction in New Zealand. The tool is intended to synthesise environmental, technical, economic, and social factors so that stakeholders can make evidence-based decisions that meet the national target of net-zero emissions by 2050. This aim addresses the acknowledged disconnect between government policy aspirations that are often undermined by the operational reality of material selection in New Zealand's construction industry. To operationalise this aim, the study articulates four related objectives linked by the exploratory and applied perspective for sustainability research:

1. To investigate the most common zero carbon materials in the construction industry. This objective focuses on identifying existing or developing materials that have low embodied-carbon performance. It consists of evaluating case studies from outside New Zealand in order to gain insight into materials' performances, life cycle behaviour and market entry possibilities, including wood as engineering wood, straw-bale, rammed earth and hempcrete.
2. To explore the main factors influencing the selection of zero-carbon building materials in New Zealand. Material choice is seldom based on a single criterion, but on the interaction between cost, durability, thermal efficiency, aesthetics, cultural preference and policy. This objective, based on literature review, stakeholder surveys, and expert consultation, isolates and prioritises these determinants and a ranked list is generated of decision variables that will contribute to New Zealand practice.
3. To examine the contextual constraints, risks and implementation issues associated with the identified material-selection criteria. This objective measures the environmental impacts of each factor and links embodied carbon metrics to key sustainability metrics,

such as recyclability and local production. Therefore, this assessment guides the weighting mechanism that determines the DST framework; thus, it guarantees the incorporation of quantitative and qualitative characteristics.

4. To develop, implement, and validate the DST for zero-carbon building-materials selection. This is achieved by turning the previous analytical results into a practical digital resource that architects, engineers, and policy makers can harness. The DST will enable the user to input design specifications and receive comparative assessments of candidate materials.

1.4 Significance of the Research

The significance of the research is that it is able to amend zero-carbon aspirations into practical and evidence-based mechanisms of decisions that can be actually implemented in the New Zealand construction sector. Instead of repeating the problems related to embodied carbon and the disjointed material selection practices, this section puts the emphasis on the practical value the positive results of this research will present to the industry participants, policymakers, and the academic population. Industrially, the study offers a systematic and clear-cut process to aid in the early material choice, which is an aspect of the developmental phase of this field wherein choices are skewed towards the final embodied carbon results but are often undertaken under uncertainty and time constraints.

The DTS resultant of this study allows practitioners to provide a structured comparison of zero-carbon and low-carbon materials by various criteria that serve as indicators of the realistic constraint such as cost-effectiveness, durability, buildability, availability, embodied carbon, and aesthetic. With these criteria combined in one evaluative system, the research will also minimize the use of ad-hoc judgement, supplier-motivated claims and incomplete environmental information. This enhances consistency and repeatability of material selection decisions between projects. To architects and engineers, the tool helps to make more informed trade-off analysis at the concept and schematic design phase where changes remain cost-effective and can be made. To contractors and developers, it gives a higher level of confidence that the materials that have been chosen are not only in tandem with the sustainability requirements but also the constructability and accessibility in the market.

More to the point, the study justifies the minimization of risk. Assumptions, criteria weightings and scoring logic are explicitly presented in the decision-support framework which increases levels of transparency and accountability and minimizes the uncertainty linked to the adoption

of other materials or less conventional materials. This can increase the rate of industry adoption of zero-carbon materials by reducing the risks of cognitive, informational and perceived performances. This study provides a practical process at the policy-practice interface of operationalisation of national decarbonisation goals into the daily construction decision-making process. Although, the current policies and programmes have expressed the targets of emissions and the high-level principles, they rarely have the tools to scaffold the practitioners on how to accomplish the targets in the material-selection level.

The results of this study bring a link between the strategic policy intent and the project-level implementation. The decision-support structure aligns material assessment with the New Zealand-specific requirements, such as the local supply chains, regulatory imperatives, and market facts. Such contextual basis increases the plausibility and applicability of the tool to the professional practice and provides possibilities of its inclusion in the industry guidelines, professional education, and further regulatory assistance systems.

In this way, the study will help in the reinforcement of the evidence base necessary to have more coherent and data-driven policy interventions to reduce embodied carbon. In the academic perspective, this study has a number of substantive contributions. To begin with, it contributes to theoretical knowledge by theorising the concept of zero-carbon material selection as a multi-dimensional socio-technical problem and not a mere environmental maximization activity.

The study is more realistic in its representation of the material decision-making process in practice through the empirical validation of the interaction between environmental, technical, economic, and contextual factors. Second, the study has a methodological contribution because it shows an effective use of mixed-methods and design science studies in the field of the built environment. The combination of systematic literature review, quantitative modelling, qualitative SWOT analysis and Delphi-based expert validation are a clear and repeatable model of decision-support artefact development and validation. The approach will be able to inform further studies that aim to fill the gap between sustainability theory and applied instruments.

Third, the study provides a tested digital artefact that goes beyond conceptual frames that are often provided in the literature. The study can add to the growing body of applied sustainability research that places more emphasis on the usability, transferability, and practical impact of empirical findings through the implementation of a practical DTS. All in all, the importance of the given research is that it will shift the discussion of the zero-carbon building not to the problem identification, but to the implementation of the solution. The rigorously developed

decision-support framework designed in a context-sensitive way empowers the New Zealand construction sector with the ability to make informed, transparent, and defensible material decisions that will make a positive contribution to national net-zero goals. At the same time, it also contributes to the academic knowledge of sustainable material choice and provides a methodological way that can be followed in the future in order to support decision-making in the built environment through research.

1.5 Thesis Structure

This thesis is structured into seven chapters, each representing a distinct phase of the research and, in most cases, a corresponding peer-reviewed publication (see Figure 1.1). The following summarises the thesis chapters:

Chapter 1 – Introduction: This chapter introduces the global and New Zealand context of climate change and zero-carbon construction, defines the research problem, outlines the study's aims and research questions, and presents the overall structure of the thesis.

Chapter 2 – Research Methodology: This chapter explains the research philosophy, approach, and methods used in the study, including ethical considerations and the justification for adopting a mixed-methods design.

Chapter 3 – Common Zero-Carbon Materials (Publication 1): The chapter is a review of the most common generally accepted and practical zero-carbon building materials in New Zealand, such as timber, straw bale, adobe, rammed earth, cork, stone and earth bags and analyses the advantages and disadvantages.

Chapter 4 – Systematic Literature Review (Publication 2): This chapter is a PRISMA based systematic literature review of zero carbon materials in the context of durability, energy efficiency, and environmental performance of the international studies that are of interest to New Zealand.

Chapter 5 – Factors Influencing Material Selection (Publication 3): This chapter quantifies using survey data, structural equation modelling and hypothesis test, the key factors that affect sustainable material selection in New Zealand.

Chapter 6 – SWOT Evaluation of Selection Criteria (Publication 4): This chapter uses a qualitative SWOT analysis of the strengths, weaknesses, opportunities, and threats of six zero-carbon material selection criteria.

Chapter 7 – Decision-Support Tool Development and Validation (Publication 5): Decision-Support Tool Development and validation (Publication 5): This chapter focuses on the development of a multi-criteria decision-support tool, its software implementation, and its validation by use of Delphi process with 14 experts and sensitivity analysis.

Chapter 8 – Discussion: This chapter interprets the findings of the preceding chapters in light of the research aims and objectives, assesses the significance of the decision-support tool developed for zero-carbon material selection, and explores its broader implications for theory, practice and policy.

Chapter 9 – Conclusion: This chapter will make a conclusion with which the main findings were summarised, the theoretical and practical contributions of the study are described, limitations are mentioned and the future research directions are indicated.

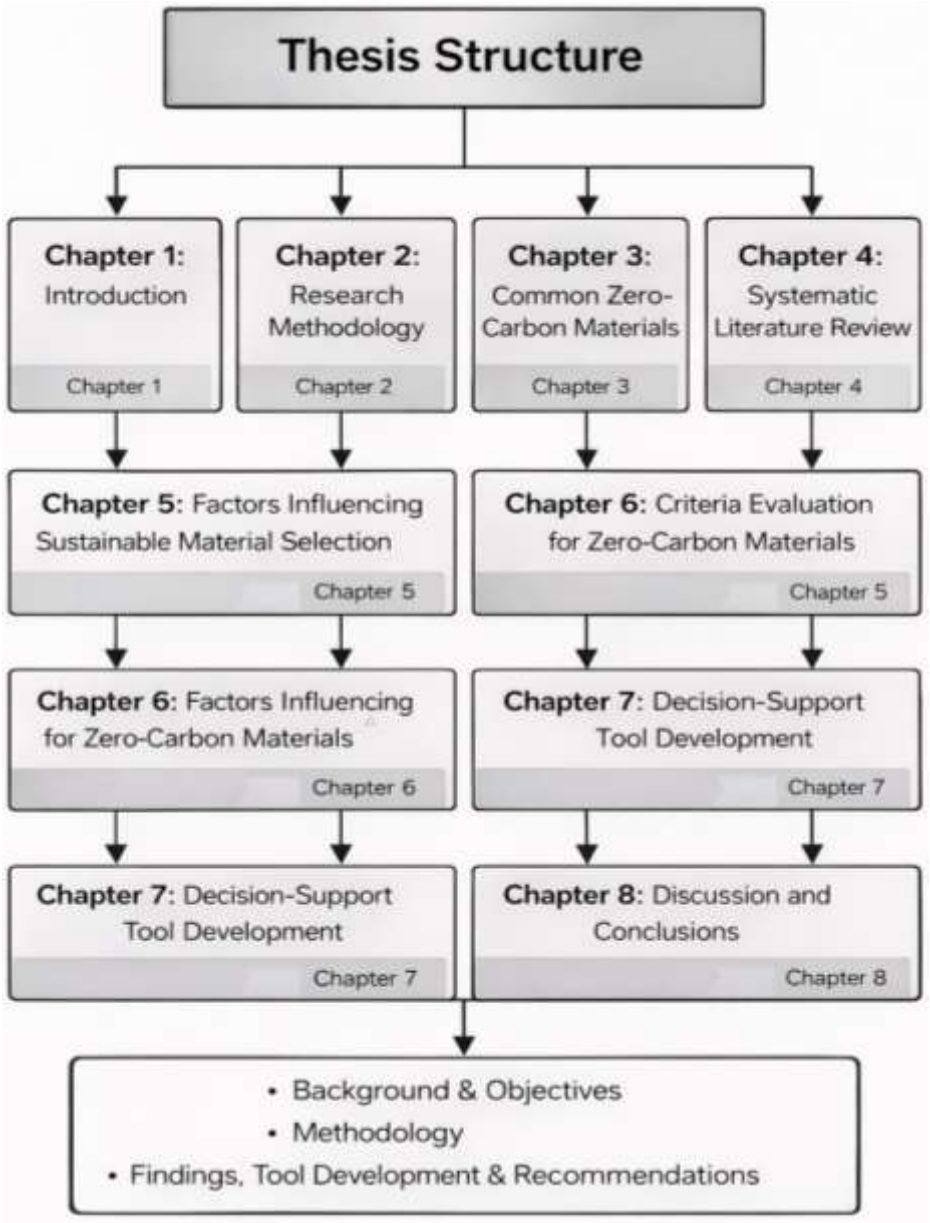


Figure 1.1: The thesis structure overview

Chapter 2: Research Methodology

2.1 Introduction

In this chapter, the research methodology to be used in order to attain the overall objective of this thesis, which is the creation and validation of a DST on zero-carbon material in the New Zealand construction industry is presented and justified. Since the research problem is applied and solution-oriented, the methodology will not just produce new knowledge but also convert the new knowledge into a practical and useful artefact to the stakeholders of the industry.

The methodological framework has been motivated by the fact that zero-carbon material selection is a complicated socio-technical choice issue. These decisions include interplay of

environmental performance indicators, costs and cost benefits, technical and regulatory constraints as well as professional judgement. Consequently, there is no single research method which can make this complex to be captured. Rather, the research project takes a pragmatic, mixed methodology that incorporates quantitative analysis, qualitative research, and research in design science so that it becomes possible to have explanatory richness and practical significance.

The chapter describes the philosophical positioning of the research, the development of theory, reasons behind methodology, and the strategy of the research at large. It also defines the time frame of the research and considers the ethical issues. Every decision of the methodology is clearly connected with the research goals and objectives illustrating consistency between the essence of research problem and the applied methods. By doing so, the chapter creates a clear and justifiable methodological background of the empirical investigations and artefact building that follows in the following chapters.

2.2 Positioning the Mixed-Methods Design within Established Methodological Literature

2.2 Locating the Mixed-Methods Design in the Existing Methodological Literature. Mixed-method research has gained popularity in construction management and sustainability research to resolve complex decision-related problems that entail unanimous quantifiable or measurement-based performance indicators as well as subjective professional judgement. Creswell and Clark (2017) and Tashakkori and Teddlie (1998) are seminal works on methodology that justify the reason as to why the mixed-method design is especially suitable when neither a quantitative nor qualitative paradigm can be sufficient to explain the nature of the research problem. Mixed methods have been widely used in previous research in the built-environment sector to determine the factors of sustainability, stakeholder attitudes, or test the conceptual models. Nevertheless, most of these works assume mainly explanatory approach on mixed methods and stop at statistical modelling or qualitative explanation. Conversely, the current study builds on this methodological tradition by incorporating mixed-methods inquiry in a design-driven workflow in which empirical evidence is synthesised and operationalised in a systematic fashion into an operational work artefact. This goes beyond explanation to solution development, which is consistent with methodological rigor with practical applicability in professional decision-making situations.

2.3 Methodological Contribution Relative to MCDA-Based Material Selection Studies

To overcome the trade-offs between environmental, economic, and technical criterion, multi-criteria decision-making (MCDM) and multi-criteria decision analysis (MCDA) methods have been widely used to conduct research on sustainable material selection (Govindan et al., 2015; Zavadskas et al., 2016). Among the techniques that are typical of the earlier research, one can single out Analytic Hierarchy Process (AHP), TOPSIS, or weighted sum models of the ranking of materials in accordance with a set of predetermined criteria (Behzadian et al., 2012). Although these methods offer systematic and open comparative tools, they often depend on weights set by the researcher or modest expert groups, which may restrict empirical foundation, strength, and cross-contextual transferability (Wang et al., 2009). In addition, a significant number of MCDA tools used in sustainable architecture are theoretical or hypothetical, and they do not take into account application to actual design processes or decision-making frameworks (Akadiri et al., 2013; Huang et al., 2018). The present research extends previous MCDA-based material-selection studies by grounding the criterion structure in literature, assessing the constructs and their relationships through survey analysis and SEM, and deriving the operational DST weights from practitioners' direct importance ratings. The resulting weights were incorporated into a digital WSM-based tool and subsequently examined through Delphi review and sensitivity analysis.

2.4 Alignment with Design Science Research and Advancement beyond Prior Applications

The general methodological framework of this study is consistent with design science research (DSR) which focuses on the systematic design, testing, and improvement of artefacts that are aimed at addressing the perceived practical challenges. Basic DSR models developed by A. R. Hevner et al. (2004) and Peffers et al. (2007) appear to emphasize the need to base artefact design on empirical evidence and subject its utility and relevancy to strict evaluation. Although the use of DSR has gradually found its way into built-environment literature, most of the research use DSR terminology without undertaking the entire design-evaluation process and therefore tend to propose conceptual models without application or verification. The study contributes to the utilization of DSR in the area of construction sustainability by fulfilling all the fundamental steps of the design science cycle: the problem identification, artefact creation, digital implementation, and multi-stage evaluation. Both the inclusion of Delphi-based expert validation and sensitivity analysis make sure that the resulting DTS is not only theoretically informed but also robust, transparent and consistent with the expectations of a profession, which enhances both methodological and practical relevance.

2.5 Consistency with and Extension of Prior Doctoral Methodological Practice

The sequential mixed-methods designs which generally apply to the doctoral research in sustainable construction and decision-support systems involve a combination of literature synthesis, empirical modelling, and expert consultation to solve complex challenges in the industry. A significant portion of the sustainability research in this area ends with conceptual frameworks, factor models, or policy recommendations, as much sustainability research is exploratory in nature. As much as they facilitate the theoretical insight, these contributions tend to arrive at a point to provide operational tools that can be immediately translated into practice. The current study expands on the existing doctoral methodology practice and adds to it by implementing empirical results into a validated digital artefact. This research presents an entire research-to-implementation journey through the systematic literature review framework that has been combined with quantitative modelling, qualitative SWOT analysis, and Delphi-based expert consensus under one consistent methodological framework. This method not only meets the doctorate standards in the built-environment field, but it also goes beyond the meeting by making usability, transparency, and real-world decision support the methods of the core methodology outcomes.

2.6 Methodological Foundations and Key Scholarly Influences

The methodological design of this research draws on established scholarship in mixed-methods research, MCDA, and design science research within the built-environment and information systems domains. Mixed-methods research is widely advocated for studies addressing complex real-world problems where both numerical patterns and contextual understanding are required (Creswell & Clark, 2017; Tashakkori & Teddlie, 1998). In construction and sustainability research, mixed-methods designs have been shown to enhance explanatory power and support the development of practice-oriented solutions by enabling triangulation across data sources and analytical perspectives.

The quantitative components of this study are grounded in the use of survey research and SEM, which have been extensively applied to investigate decision-making behaviour, latent constructs, and factor interrelationships in construction management and sustainability studies (Hair et al., 2022). SEM enables the simultaneous examination of multiple relationships among observed variables and underlying theoretical constructs, making it particularly suitable for modelling the interdependencies among material selection criteria such as cost, durability, embodied carbon, and availability.

The qualitative components of the research are informed by established approaches to contextual analysis and expert judgement elicitation. SWOT analysis has been widely used in sustainability and construction research to explore strategic strengths, weaknesses, opportunities, and threats that are not easily quantified but have significant implications for implementation. The Delphi technique is similarly well established as a structured method for achieving expert consensus in areas characterised by uncertainty, incomplete data, or emerging practices, particularly in environmental decision-making and technology assessment (C.-C. Hsu & B. Sandford, 2007; Okoli & Pawlowski, 2004).

Finally, the overall methodological structure aligns with design science research (DSR) principles, which emphasise the development, evaluation, and refinement of artefacts intended to solve identified problems in practice. DSR has been increasingly adopted in built-environment and decision-support research where the objective extends beyond explanation to include the creation of actionable tools (A. Hevner et al., 2004; Peffers et al., 2007). In this thesis, empirical findings from literature review, survey analysis, and qualitative evaluation are systematically synthesised and operationalised into a digital DTS, consistent with design science best practice.

By drawing on these established methodological traditions and integrating them within a coherent research design, this study positions itself within recognised scholarly approaches while extending them through the application of a context-specific, practitioner-oriented decision-support artefact for zero-carbon material selection in New Zealand.

2.7 Research Philosophy

This research adopts a pragmatism research philosophy. Under the research onion of Saunders et al. (2023), pragmatism is suitable when the researcher seeks to solve real-world problems rather than be concerned with a single ontological or epistemological viewpoint. Pragmatism holds that knowledge is evaluated based on practical applicability. Depending on the research question addressed, one may choose research methods and approaches to inquiry based on their usefulness to answer the question, rather than focus on consistency with a specific philosophy.

The overall aim of this PhD is not only to understand the zero-carbon material selection behaviour but also to generate and validate an applicable and usable DTS that could be used by practitioners. This would require combining quantitative evidence (for example, through the factor identification and weighting in the survey) and qualitative judgement (for example, expert consensus in Delphi rounds). Pragmatism allows subjectivity and objectivity to coexist

and can make explicit the technical, professional, policy and contextual considerations that inform construction decisions.

2.7.1 Research Approach to Theory Development

The research uses a mix of abductive and deductive methods to develop theory. A purely inductive approach would not be enough, as the study does not aim to create a theory from nothing. On the other hand, a purely deductive method would limit the research to testing set hypotheses without considering new insights.

First, existing theories and frameworks related to sustainable material selection, embodied carbon, and MCDM shaped the study's conceptual framework (deductive element). These theories helped identify selection criteria and develop survey tools.

Second, the results of stakeholder surveys, statistical modelling, and expert comments showed trends, stressors and context information that were not adequately reflected in the literature. By applying these insights, researchers could define the criteria and weighting approaches and make an argument about the rationale of the tools.

Such combination of methods is perfect in the design-oriented research. In this case, theory is directed and developed through the development of a practical artifact. The DTS that has been created is grounded on the actual conditions of the New Zealand industry and it is based on the principles.

2.7.2 Methodological Choice

The research questions were addressed using a mixed-methods research design, integrating quantitative and qualitative approaches to capture both the measurable relationships among decision factors and the contextual complexities influencing material selection. Mixed-methods research is particularly appropriate when neither quantitative nor qualitative data alone is sufficient to fully explain a complex research problem, and when integration of multiple forms of evidence enhances explanatory power and validity (Creswell & Clark, 2017; Tashakkori & Teddlie, 1998).

In this study, quantitative methods were employed to:

- identify and rank the most critical material selection factors using a large-scale industry survey, enabling statistical generalisation of practitioner priorities;

- test relationships among latent constructs using SEM, which is well suited for examining complex interdependencies between observed indicators and unobserved theoretical constructs (Hair et al., 2022);
- derive relative weights for decision criteria, which were subsequently embedded within the DTS to ensure that material rankings reflect empirically observed practitioner preferences rather than researcher assumptions.

Complementary qualitative methods were used to:

- interpret contextual and practice-based factors influencing material choice that are not readily captured through quantitative measures;
- conduct SWOT-based evaluations of decision criteria to identify strengths, weaknesses, opportunities, and threats associated with zero-carbon material adoption;
- validate and refine the DTS through a multi-round Delphi process, which is widely applied to achieve expert consensus in complex decision-making contexts where empirical benchmarks are incomplete or contested (C.-C. Hsu & B. Sandford, 2007; Okoli & Pawlowski, 2004).

The integration of quantitative and qualitative techniques enabled methodological triangulation, strengthening the credibility, validity, and practical relevance of the findings by cross-verifying results from independent data sources and analytical perspectives (Denzin, 2012). This mixed-methods design therefore provides a robust and transparent foundation for developing and validating a practitioner-oriented DTS for zero-carbon material selection.

2.7.3 Research Strategy

The methodology utilized in the research was multi-strategy design that entailed survey research, systematic literature review and design science research. To begin with, a systematic literature review was employed to identify zero-carbon materials. Second, they employed an online survey questionnaire to the construction professionals to study the significance of various factors and their association. The survey strategy was effective in capturing the perceptions and decision-making process among a wide range of professionals.

Third, this research adopted a Design Science Research (DSR) approach to develop the Decision-Support Tool (DTS). DSR is particularly appropriate for studies that aim to design, implement, and evaluate artefacts intended to address identified practical problems. The DTS was designed, implemented, tested, and iteratively refined through the integration of empirical

data and expert input. The tool was evaluated using a structured Delphi technique, which enabled the validation of its relevance and facilitated consensus among domain experts.

2.7.4 Time Horizon

The study employed a cross-sectional period whereby data were collected at certain time intervals as opposed to a duration. Each of the studies was surveyed once and evaluated by an expert, in accordance with the industry practice, knowledge, and limitations applied during the data collection period. A cross-sectional design suits the objective of developing a DTS, which is in line with the existing regulations, market environment, and professional background in New Zealand. Although longitudinal data results may have been able to show the dynamics over time, it was not within the scope of this PhD and was not essential to address the objectives of the research.

2.8 Research Method

The research design adopted in this study was a mixed-method research design to create knowledge and establish tools. To develop a DST selecting zero-carbon materials, the study involved five connected steps: (i) evidence collection of potential materials, (ii) reviewing the existing information to clarify the criteria and define gaps in knowledge, (iii) modelling factors of material-selection by survey of practitioners, (iv) qualitative analysis of the criteria in SWOT analysis, and (v) development of the digital DST and expert validation with the help of Delphi assessment in several rounds.

Scoping review of common zero-carbon materials (Chapter 3): literature review of peer-reviewed literature, industry literature and other publications related to the topic of the study, as well as the literature on New Zealand in general, was carried out. This phase of initial steps was used to define and describe zero-carbon or low-carbon material candidates that fit the local context. It pre-empted the first group of materials and identified the advantages and constraints that had to be considered during the decision-making process.

Phase 2: Systematic literature review to consolidate material evidence and criteria (Chapter 4): A PRISMA systematic review by the author helped summarize evidence on performance aspects that are important in zero-carbon material selection. These factors were durability, energy, thermal and environmental performance. This step enhanced the evidence base to evaluate criteria and informed the definition that will be used in subsequent surveys and tool scoring logic. Phase 2 synthesised evidence on the performance dimensions, decision considerations, and knowledge gaps associated with low- and zero-carbon materials. Chapter 4

identified recurring themes including durability, thermal and energy performance, aesthetics, carbon and broader environmental impacts, and the limited treatment of material cost. These findings were supplemented by the targeted material-selection literature reviewed in Chapter 5. Phase 3 translated this evidence into six a priori survey constructs: cost-effectiveness, durability, buildability, embodied carbon, availability, and aesthetics. The survey did not generate these factors as new constructs. Instead, it assessed their perceived importance and examined their relationships with material adoption among New Zealand construction professionals.

Phase 3: Survey-based factor identification and quantitative modelling (Chapter 5): A questionnaire was distributed to the New Zealand construction stakeholders to investigate factors that impact sustainable or zero-carbon material choice. To determine the significance of major factors, including cost-effectiveness, durability, buildability, embodied carbon, availability, and aesthetics, the quantitative analysis involved the descriptive statistics, the one-sample tests, and SEM. This analysis assisted in establishing reasonable weight of factors to be included in the tools.

Phase 4: Qualitative SWOT-based evaluation of decision criteria (Chapter 6): In order to offer interpretive information about the statistical modelling, we conducted a qualitative SWOT analysis. This discussion has discussed the strengths, weaknesses, opportunities, and threats in relation to the principal selection criteria. It unveiled pragmatic problems, execution challenges, and context risks, which surveys could fail to capture. This increased validity and real-world applicability of the ultimate decision framework.

Phase 5: DST development, implementation, and expert validation (Chapter 7): The last phase was the development, implementation and expert validation of the decision support tool (DST) (Chapter 7). This last step transformed the synthesized evidence into a working DST. The tool was constructed on the basis of a MCDM logic and offered as a digital application with further checks on the robustness of it, including sensitivity analysis. We confirmed it using a three-round Delphi process of an expert panel of 14 individuals to determine the importance, usefulness, and intelligibility of criteria descriptions, scales, and weights. The results of these Delphi rounds were used to refine the framework and the software implementation through the iterative process.

Figure 2.1 indicates the methods of the research employed in this thesis. It provides the relationship between literature synthesis, empirical analysis, qualitative evaluation, and DTS development in the various chapters.

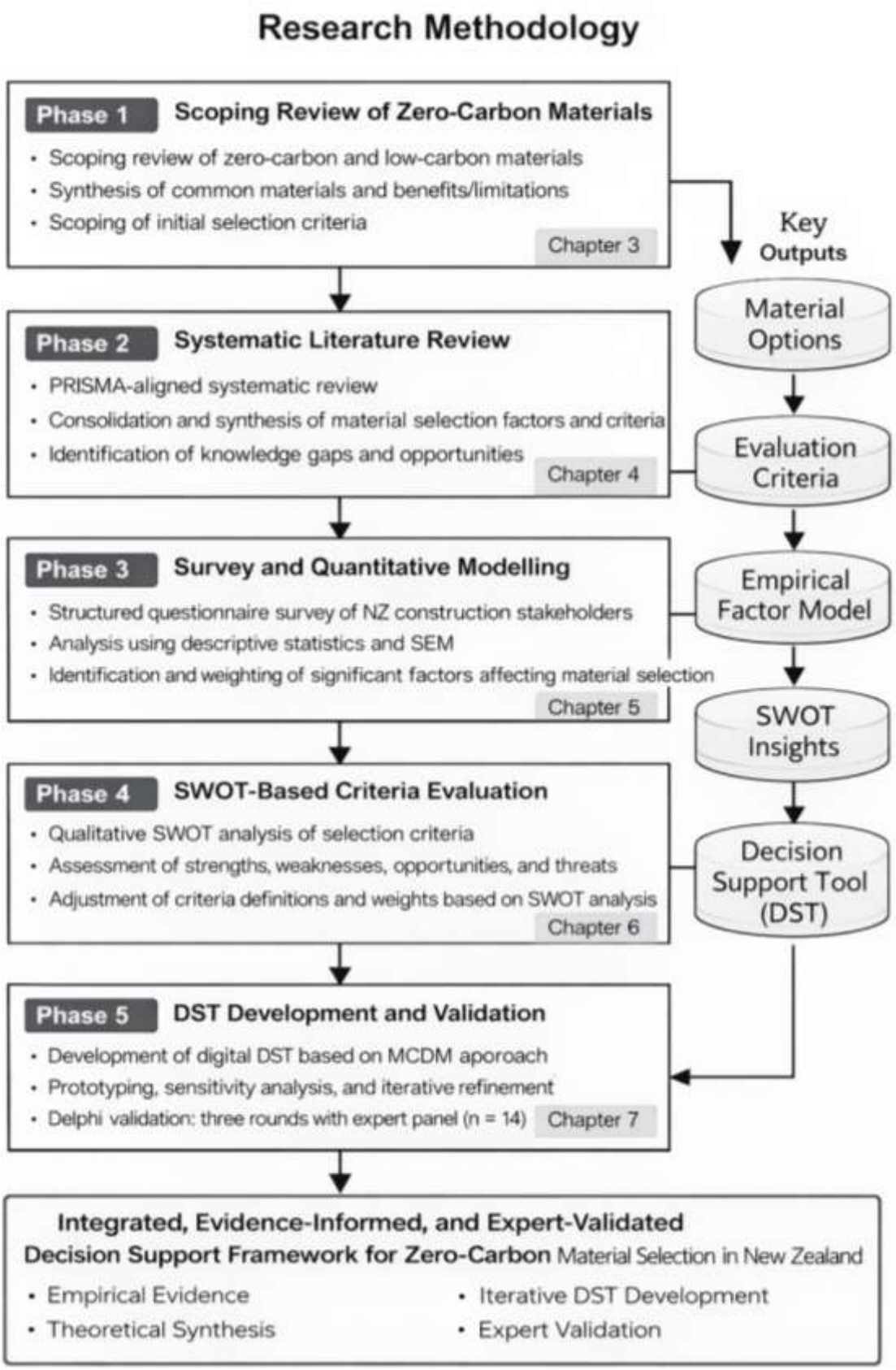


Figure 2.1: Research methodology framework for developing the zero-carbon material DTS

2.9 Ethics

This research was given ethical approval by the Low-Risk process of Human Ethics at the Massey University (see Appendix D). All the participants received informed consent to participate in the surveys and Delphi studies, which were voluntary. No personal identifiable data were gathered. The analysis and reporting of responses were anonymous. All the data were kept safely in accordance with the policies in the data management of the university and were applied in academic research only. Participants were notified of their free will to pull out at any given time without being charged. These steps were the means to make sure that the research was conducted in an ethical manner in regard to confidentiality, transparency, and participant welfare.

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STATEMENT OF CONTRIBUTION DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the student and the student's main supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the student's contribution as indicated below in the Statement of Originality.

Student name:	Ali Hashemi Araghi
Name and title of main supervisor:	Dr Eziaku Onyeizu Rasheed

In which chapter is the manuscript/published work? Chapter 3

Describe the contribution that the student and members of the supervisory team have made to the manuscript/published work:[1]

Ali Hashemi Araghi: Writing– review & editing, Writingoriginal draft, Visualization, Resources, Methodology, Investigation, Conceptualization. Eziaku Onyeizu Rasheed, Vishnupriya and Jeff Seadon: Writing– review & editing, Supervision, Conceptualization.

Please select one of the following three options:

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  Araghi, A.H., Rasheed, E., Vishnupriya, V., Seadon, J. (2024). Zero-Carbon Building Materials for the 2050 Net-Zero Emissions in New Zealand Construction Industry: Benefits and Limitations. Advances in Engineering Project, Production, and Technology. EPPM 2023. Lecture Notes in Mechanical Engineering. Springer, Cham. https://doi.org/10.1007/978-3-031-56878-7_13.

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Student's signature: Ali Hashemi Araghi Main supervisor's signature:

This form should be placed at the beginning of each relevant thesis chapter.

[1] Refer to the Massey University Publishing and Authorship guidelines (OneMassey for staff, Stream for students) and/ or Contributor Roles Taxonomy (CRediT) guidelines for guidance.

Chapter 3: Common Zero-Carbon Materials

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

Araghi, A.H., Rasheed, E., Vishnupriya, V., Seadon, J. (2024). Zero-Carbon Building Materials for the 2050 Net-Zero Emissions in New Zealand Construction Industry: Benefits and Limitations. In: Rotimi, J.O.B., Shahzad, W.M., Sutrisna, M., Kahandawa, R. (eds) Advances in Engineering Project, Production, and Technology. EPPM 2023. Lecture Notes in Mechanical Engineering. Springer, Cham. https://doi.org/10.1007/978-3-031-56878-7_13.

3.1 Chapter Summary

This chapter examined the most common zero-carbon and low-carbon building materials with potential application in the New Zealand construction industry. Using a structured review of peer-reviewed literature, industry reports, and New Zealand–specific data sources, the chapter identified and evaluated seven material groups: timber-based systems, straw bale, adobe (mud brick), rammed earth, cork, stone, and earth-based materials. The analysis focused on each material's embodied carbon characteristics, environmental benefits, technical performance, availability, and practical limitations within the local context.

The findings demonstrate that bio-based and earth-based materials generally offer substantial embodied-carbon advantages compared with conventional materials such as concrete and steel, particularly through carbon sequestration, low energy intensity during production, and local sourcing potential. Timber systems, especially plantation-grown Pinus radiata, emerged as the most mature and scalable option in New Zealand due to established supply chains, regulatory familiarity, and structural performance. Other materials, including straw bale, rammed earth, and adobe, showed strong environmental performance but were constrained by concerns related to durability, regulatory compliance, skills availability, and market acceptance.

This chapter established a foundational material evidence base for the thesis by clarifying both the opportunities and limitations associated with commonly cited zero-carbon materials. Rather than positioning any single material as universally optimal, the chapter highlighted the need for systematic, multi-criteria evaluation to support context-sensitive material selection. These insights directly informed the subsequent chapters by defining the material scope for analysis, motivating the identification of selection criteria, and reinforcing the necessity of a decision-support framework capable of balancing environmental performance with practical implementation considerations in New Zealand.

3.2 Introduction

Over the last few decades, the world's population has increased rapidly with our world in data organisation indicating that the world population could rise to more than nine billion by 2040. Consequently, the demand for housing is growing with the increasing population; based on recent projections, a record 48,522 new residential houses were consented to in the year ended November 2021 in New Zealan Construction was the fourth largest employer in New Zealand in the December 2021 quarter, an increase of 5.4% from the December 2020 quarter due to the boom in construction. However, the greenhouse gas emissions from New Zealand buildings are increasing. From 2007 to 2017, greenhouse gas emissions from the building industry were shown to have risen by 66 percent (New Zealand Green Building Council, 2022). This is despite the implemented sustainable building practices that prioritise using renewable resources and energy-efficient designs in new construction towards reducing the CO_2 emissions generated during the construction process. According to the research published by United Nations (2021), the construction industry consumes more than 40% of the global energy, and 33% of greenhouse gas emissions. Materials used in construction play a crucial role in the overall sustainability of a building (Kibert, C. J., 2022). Sandanayake et al. (2018) found that sustainable material selection is crucial in reducing the environmental impact of buildings, as selecting sustainable materials can significantly reduce greenhouse gas emissions and energy consumption in the construction industry. Similarly, Fei et al. (2021) found that focusing on sustainable materials in construction can help achieve sustainable development goals, including climate action and responsible consumption and production. Using unsustainable materials such as concrete and steel contributes significantly to the carbon footprint of a building. On the other hand, using sustainable materials such as wood and bamboo can help reduce a building's carbon footprint and promote sustainable development (Yang et al. 2019).

The importance of focusing on materials in sustainable construction is evident in the literature. Therefore, as using sustainable materials is critical to promoting sustainable development and mitigating the negative impacts of climate change, this paper presents a background study on zero-carbon materials suitable and available in the New Zealand construction industry. It also presents the benefits and limitations of these materials towards facilitating their use and adoption towards meeting the NZ 2050 net-zero carbon economy target.

3.3 Background

There are diverse definitions for zero-carbon building. According to the World Green Building Council, a zero-carbon structure is an energy-efficient building entirely powered by on-site and

off-site renewable energy sources. Net zero carbon construction is when the volume of carbon dioxide emissions released annually is negative or zero (World Green Building Council, 2021).

While optimal, achieving zero carbon or net-zero carbon construction is marred by complex challenges associated with construction projects, particularly in the context of sustainability and environmental impact. For instance, the construction phase produces less emissions, the traditional materials such as steel, aluminium, and concrete, mainly used in construction, are responsible for 23% of CO_2 global emissions (EIA, 2018). These materials are noted as one of the most crucial issues in structural engineering and architecture globally (EIA, 2018) as shown in Figure 3.1.

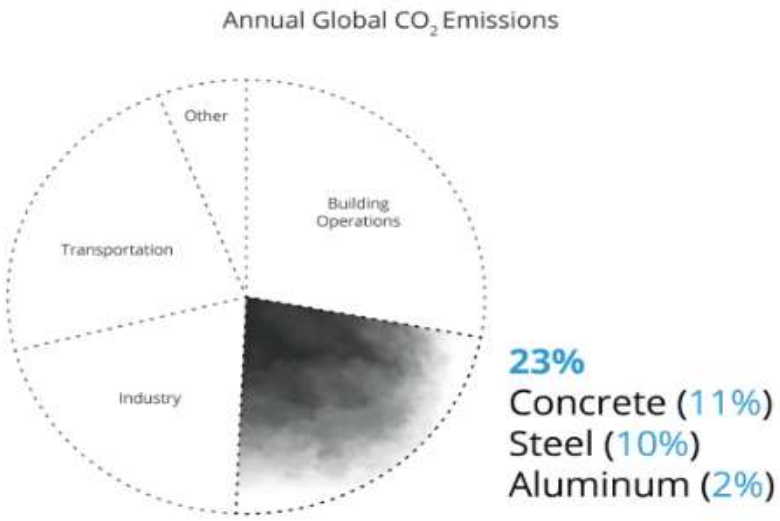


Figure 3.1: Annual Global CO2 Emissions (EIA, 2018)

Taking New Zealand as an example, approximately 20% of New Zealand's greenhouse gas emissions are from the building and construction sectors. Compared with the rest of the world, the statistics of CO_2 emissions are less. This may result from a relatively small population counting approximately 5 million people, compared to other developed countries. As a result, there may be fewer buildings constructed, leading to lower CO_2 emissions from the construction sector. According to the statistics for 2022, the national residential electricity costs are about 5.2% more than in 2021 (New Zealand Green Building Council, 2022). Decreasing the emissions related to the construction and building sector would benefit many New Zealanders in terms of better air quality, healthier, and saving money on household bills (New Zealand Green Building Council, 2022). Also, reducing carbon emissions in buildings will be crucial for achieving the aims of the Paris agreement on climate change, including keeping the world temperature rise to "well below 2 C (United Nations Climate Change, 2022) and Net-Zero

emissions by 2050 while simultaneously eliminating the negative impacts, such as sea-level rise, melting glaciers, food shortage, and risks of human lives.

So, New Zealand needs to minimise its carbon dioxide emissions to meet the 2050 government and UN goals. One practical solution is exploiting locally sourced and manufactured materials to construct zero-carbon buildings. In the long term, these locally sourced zero-carbon buildings will contribute to society and environment; and achieve economic, environmental, and social sustainability. The emphasis on locally sourced zero-carbon building materials aligns with global goals, such as those set forth in the Paris Agreement and United Nations climate initiatives. Furthermore, the research underscores the economic and environmental benefits of transitioning towards zero-carbon buildings, emphasizing the potential for long-term contributions to society and the environment.

In this paper, we investigate the most suitable zero-carbon building materials for New Zealand building industry. The findings will have significant implications for both the construction industry in New Zealand and the broader global context of sustainability and climate change mitigation. By highlighting the environmental impact of traditional construction materials and practices, as well as the increasing greenhouse gas emissions from the construction sector in New Zealand, it raises awareness of the urgent need for sustainable alternatives. As New Zealand aims to meet its 2050 government and UN targets, this research can serve as a valuable reference for policymakers, industry stakeholders, and researchers seeking to promote sustainable practices in the construction sector, both within New Zealand and as part of the global effort to combat climate change.

3.4 Methodology

To achieve the aim of this study – to identify suitable zero-carbon materials with the potential of contributing to a net-zero carbon future of the New Zealand construction industry, a review of secondary data was conducted. Google Scholar and Scopus databases were used to find academic literature by searching relevant keywords such as “zero-carbon materials”, “sustainable materials”, “green materials” in New Zealand. Moreover, the websites of key relevant construction materials and housing providers were explored to identify conventional materials with zero-carbon potentials. These resources provided insights into the current state of zero-carbon building materials, including their availability, affordability, and performance. The contribution of these zero-carbon materials to environmental sustainability was investigated. Their features, benefits and limitations are presented in the next section.

3.5 Findings: Zero-Carbon Building Materials for the New Zealand Construction Industry

From the literature review conducted, common zero carbon building materials in the building and construction industry were investigated and six building materials with zero-carbon features were identified namely:

1. Wood (Timber)
2. Strawbale
3. Adobe or mud/clay brick
4. Rammed earth
5. Cork
6. Stone

3.5.1 Wood (Timber)

Stocchero et. al (2017) point out that Auckland's goal of a 40% carbon mitigation by 2040 is supposed to be achieved 20% faster than planned by optimising the usage of timber in city construction. However, to achieve sustainability, timber can only partially substitute steel and concrete. It is encouraged to maximise the use of timber in a mixture with other building materials in construction (Stocchero, et al., 2017).

(Buchanan, et al. (2013) compared three building materials options, concrete, steel, and timber, used to construct a three-level structure. The results indicate that the carbon emissions of timber were between 90% and 96% lower than for concrete and 93% to 97% lower than steel because of carbon sequestration. A similar study was demonstrated by John et al. (2009). The team compared building materials, comprising timber, steel, concrete, and TimberPlus, chosen in a new laboratory building in the University of Canterbury's campus in Christchurch. The findings revealed that the Global Warming Potential (GWP) of one of the structure components made of timber was 38% lesser than for concrete and 40% less than for steel (John, et al., 2009).

Timber significantly contributes to carbon emissions cutback by sequestration and storage. Trees can sequester carbon during their growth period, and carbon can be stored in timber over the building's life cycle. When timber reaches the end of its life, it can be burnt or degraded (Stocchero, et al., 2017). Therefore, timber presents less embodied energy over its life cycle, unlike other structural components such as concrete (Stocchero, et al., 2017).

The surge in demand for structural timber in the construction industry is a consequence of the sustained expansion of the housing sector, which in turn stimulates an upsurge in the utilization of structural timber for construction purposes. (MPI, 2021). According to the statistics from the

Ministry for Primary Industries, the quantity of timber harvested in New Zealand is estimated at 34.38 million cubic meters in the year ended March 2021(MPI,2021). Data conducted by Buchanan and Levine (1999) showed that using 17% more timber in the New Zealand building industry could carry out a 20% reduction in GHG emission, which is generated from the construction of all housing materials, with an equivalent decline in total fossil fuel consumption in New Zealand (Buchanan & Levine, 1999) (Table 3.1).

Table 3.1: Density: 490 kg/m3 (5% humidity) plywood lifecycle assessment

Material (kg)	Energy renewable [MJ]	Energy non Renewable [MJ]	GWP [kg CO_2 Equiv.]	AP [kg SO_2 Equiv.]	EP [kg PO_4^{3-} Equiv.]	POCP [kg C_2H_2 Equiv.]
Plywood	8.054	6.905	0.210	0.00211	0.000295	0.000245
CO_2 uptake			-1.385			

Density: 490 kg/m^3 (5% humidity)

As shown in Table 3.1, producing plywood is not 100 percent environmentally friendly; sourcing wood for plywood products in New Zealand is sustainable. But turning wood into plywood could have a crucial carbon footprint because of the energy required to run machinery. Although wood waste could be used as pellets to offset some of the carbon emissions, transporting could be another carbon-intensive phase in the life cycle of plywood because of the emissions associated with operating the vehicles that carry timber to factories. However, the consumption and usage of plywood are completely clean and safe for the environment because it does not produce any toxic gases. Although entirely recyclable. the lifespan of plywood is not as long as natural wood since plywood is non-biodegradable.

Laminated veneer lumber: Laminated veneer lumber is one of the common engineered wood materials used in the building industry. It is a composite product made from some thin layers of veneer that are joined by the length of the finished lumber. The main difference between Laminated veneer lumber and Plywood is the grain orientation of each veneer. The complete carbon footprint of untreated LVL (Laminated Veneer Lumber) produced in New Zealand, from its creation to disposal within the country, along with transport to a typical landfill, has a total global warming potential of 645 kg CO2-equivalent emissions. However, it also absorbs 912

kg CO2-equivalent during its life cycle. This results in a net storage of 266 kg CO2-equivalent. Figure 2.1 shows a Structural Laminated Veneer Lumber framing in New Zealand.

Particle board: low-density chipboard and fibreboard. It is an engineered wood-based product produced from sawmill shavings, sawdust or wood chips, and a synthetic resin or another suitable binder extruded and pressed (Asfaw, et al., 2019). Table 3.2 indicates the lifecycle assessment of particle board in New Zealand. It also shows that particle board that does not contribute to more deforestation as it uses just wood waste material, so this engineered wood is one of the best ways to recycle wood shavings, sawdust, and chips collected from sawmills (MacRae & Harnett, 2019). The use of wood waste is sustainable for the carbon uptake by timber trees. However, usage of synthetic adhesives makes particle board not biodegradable and has no carbon-offset value; moreover, glues could emit toxic gases (Mai, et al., 2004) (Figure 3.2).

Table 3.2: Density: 697 kg/m3 (8.5% humidity) LCA particle board in New Zealand (Nebel, et al., 2011)

Material (kg)	Energy renewable [MJ]	Energy non Renewable [MJ]	GWP [kg CO_2 Equiv.]	AP [kg SO_2 Equiv.]	EP [kg PO_4^{3-} Equiv.]	POCP [kg C_2H_2 Equiv.]
Particle Board	4.069	5.003	0.279	0.00092	0.000184	0.000320
CO_2 uptake			- 1.417			



Figure 3.2: Structural Laminated Veneer Lumber (JNL 2022)

The most common timber produced in New Zealand is plantation-grown Pinus radiata or radiata pine, used in timber structures throughout New Zealand. New Zealand Pinus radiata is a softwood mostly used as a reinforced timber composite (Mlote & Budig, 2022).

There are several advantages to using pine as a building material in New Zealand as given below:

- Renewable Resource: The New Zealand pine is renewable and sustainable. It is a good alternative to the threatened tropical woods or timbers (Collins, et al., 2003). The expanding pine resource in New Zealand secures sustainable harvest levels for decades to come, resulting in a natural timber product from a renewable resource (Collins, et al., 2003).
- Compared with frameless beams, the carbon fibre-reinforced timber constructions add up to a 49% extra increase in load-bearing capacity, which makes it simultaneously structurally capable while contributing to the decrease in CO_2 emissions in timber composites (Mlote & Budig, 2022).
- Resistance against rot and decay: In many cases, wood exposed to water needs treatment and care to avoid fungal decay or insect attack (Ministry of Business, Innovation and Employment, 2022). Pine timber could be treated to resist rotting and decay and decrease the risk of rot and decay.

There is only one issue with pine timber. It dents and scratches easily due to being a softwood (Franich, 2019). Consequently, pine wood is not as durable as hardwoods, but with suitable maintenance, pine timber will not warp for a long period (Parker, 2022). Table 3.3 provides various the wood types in New Zealand and their embodied energy (Architecture School, Victoria University, 2022).

Table 3.3: Types of wood in New Zealand (Architecture School Victoria University, 2022)

Material	**MJ/kg**	**MJ/m^3**
air dried, rough sawn	0.3	165
kiln dried, rough sawn	1.6	880
air dried, dressed	1.16	638
kiln dried, dressed	2.5	1380
mouldings	3.1	1710
hardboard	24.2	13310
Medium Density Fibreboard (MDF)	11.9	8330
Glulam	4.6	2530
particle bd	8	
plywood	10.4	
shingles	9	

3.5.2 Straw Bale

Straw bale construction utilizes straw, typically from oats, rice, wheat, and rye, as the structural element, which is often covered by stucco, plaster, clay, or other treatments on the interior and exterior sides of the bale walls. This building method offers a sustainable, bio-based insulation material derived from a co-product of cereal food crop production (Walker et al., 2020). Straw, being an agricultural by-product, is a bio-based material used in construction to achieve environmental sustainability. It has extremely low embodied energy (Bendapudi et al., 2012). Throughout the life of a straw bale building, straw acts as a carbon sink (Dutil et al., 2011). Using straw bales as a structural material is exceptional in terms of energy efficiency and sustainability (Diker & Yazicioglu, 2020). Straw bales have low embodied carbon, consume less energy, and are cost-effective (Diker & Yazicioglu, 2020). Research by Dattijo (2017) indicates that straw bales provide a sustainable alternative to emitting carbon dioxide into the atmosphere through the burning of grain stalk waste. The study found that, compared to adobe blocks, straw bales have a cost efficiency of 48% and lightweight properties of 68% (Dattijo, 2017).

Straw bale construction offers remarkable properties as a building material, aiding in reducing a structure's energy demand (Bendapudi et al., 2012). Straw bale buildings have relatively lower insulation capacity compared to traditional brick houses, which have superior insulation values. This reduction in insulation demand cuts the amount of coal required for heating, subsequently diminishing CO_2 emissions (Bendapudi et al., 2012). A wood frame or equivalent fiberglass insulation is over thirty times more energy-intensive than straw bales (Bendapudi et al., 2012). Likewise, producing a ton of steel requires a tremendous 6.15 million KJ of energy, whereas a ton of straw consumes only 120 thousand KJ of energy (Bendapudi et al., 2012). Furthermore, using straw bales as a building material can increase the energy consumption of constructions by around 83.12%, but compared to traditional houses, straw bale structures can reduce embodied carbon by up to 76% (Mehravar et al., 2022).

Straw bales contribute to reduced emissions and heating demand due to their high R-values and ability to sequester CO2 (Alcorn & Donn, 2010). Overall, CO_2 reductions from straw bale insulation can be as high as 560 kg. Moreover, if straw bales remain dry, they can last for over 100 years (Alcorn & Donn, 2010). The Food and Agriculture Organization (FAO) of the United Nations reported in 2019 that approximately 800 to 1000 million tons of rice straw are produced (GIEWS, 2019), making straw a cheap and readily available material in most countries (Drozd

& Niak, 2018). Additionally, straw can be grown within a few months. Throughout the lifecycle, straw bales generate minimal pollutants and can be easily and economically disposed of in an environmentally friendly manner (Kubba, 2012).

There are several advantages to using straw bales as a construction material in New Zealand. Straw bales are locally sourced and readily available in arable cropping regions (Millner & Roskruge, 2013). They are non-toxic, biodegradable, and cost-effective (Athar et al., 2014). Straw construction is easy to adapt, particularly when used as infill to a wood or timber structural frame (Ghaffar, 2017). The durability of straw bales depends on the key element of keeping them dry throughout their lifespan, as well as proper structure design and correct installation and maintenance (BRANZ, 2015). With attention to these factors, straw houses can have a lifespan of over a century (BRANZ, 2015).

Straw bales provide excellent sound insulation and resistance to heat loss or gain due to the thickness of the walls. The embodied energy of straw bales is 0.24 MJ/kg, while the exact energy used in transportation depends on the distance between the construction site and the source of straw (Alcorn, 2010). On the other hand, there are a few disadvantages associated with straw bales. They cannot be readily recycled or reused (BRANZ, 2015). Straw bales are flammable (Brojan et al., 2014) and bulky to transport (BRANZ, 2015). The applied internal finish to straw bales may provide minimal thermal mass (Ghaffar, 2017). They require proper maintenance and weather-proof coatings to keep them dry, which can be labour-intensive (BRANZ, 2015).

3.5.3 Adobe or mudbrick

Adobe is an ancient construction method dating back to 8300 BC, and some of the oldest continuously inhabited structures in the world are made of adobe (Pohl & Nachtigall, 2015). Adobe is a common construction material that is often utilized through recycling processes (Aeslina & Mohajerani, 2011). It is a green and environmentally friendly material that does not require additional energy resources for its application and production. It can be fully recycled and generates minimal waste when disposed of (Illampas et al., 2009). In terms of sustainable design, it offers structural integrity, a finished appearance, and improved indoor air quality by eliminating the need for painting (Williams, 2020). Los Alamos National Laboratory (2002) states that painting is unnecessary for brickwork construction (Los Alamos National Laboratory, 2002). Additionally, clay bricks are flame-retardant and can impede the spread of fire (Vahidi et al., 2020).

Furthermore, bricks provide both acoustic comfort and thermal comfort. The density of bricks offers efficient acoustic insulation, reducing external noise levels within a building (Aditya et al., 2017). Bricks also have excellent sound absorption properties (Okongwu et al., 2020). Moreover, the thermal mass of bricks contributes to energy efficiency by slowing down heat transfer through the walls (Biddulph et al., 2014). According to experiments conducted by Djamil (2016), the indoor temperature fluctuation inside a clay brick building is only 2°C, with a range of 21 to 23°C. These results indicate that clay brick structures provide interior thermal stability (Djamil, 2016).

Bricks can be reclaimed and reused, extending their lifespan and giving them a second life (Nubholz et al., 2019). In New Zealand, bricks have a waste rate of 5 percent, with 90 percent of the waste expected to be reused, while the remaining portion is sent to landfills (Dowdell et al., 2016). Bricks can withstand extreme weather conditions (Huarachi et al., 2020). According to statistics from the Department of Planning, Transport, and Infrastructure under the Government of South Australia (2017), the embodied energy of brick is 2.50 MH/kg (DPTI, 2022). Brick is a long-lasting and durable building material that can withstand rot, wear, fire, warping, dents, and tearing (Los Alamos National Laboratory, 2002).

3.5.4 Rammed earth

Rammed earth is used for building floors, walls and foundations using compacted natural raw materials like chalk, earth, gravel, or lime. It is an ancient technique revived lately as a sustainable construction method (Maniatidis & Walker, 2003). Rammed earth has been used in many constructions in different parts of the world; the most famous case is the Great Wall of China (Su, et al., 2022). While most earth structures are single or two-storied, a five-story hotel was constructed using rammed earth in Corralben, Australia (Waitakere City Council, 2008). In New Zealand, rammed earth construction has been used by Early European immigrants with traditional English methods on the North Island buildings (Waitakere City Council, 2008).

A limitation of the rammed earth technique is the need for stringent limits on shrinkage to avoid cracking (Waitakere City Council, 2008). Several soil types require sand to be added to decrease shrinkage. Pre-construction checks for shrinkage and the suitable limits are explained in detail in NZS 4298, which outlines durability tests and compression and a simple on-site assessment for moisture content (Waitakere City Council, 2008). Rammed earth is a sustainable and eco-friendly building material that offers numerous benefits. These advantages include:

- Breathability: Rammed earth walls are non-toxic, non-polluting, and biodegradable. The clay content and material mass of rammed earth allow the structure to "breathe" more than concrete buildings, preventing condensation problems without significant heat loss. This can regulate internal humidity and improve indoor air quality, making them suitable for individuals with respiratory issues (Arrigoni et al., 2018).
- Durability: Rammed earth is highly durable in compression, with load-bearing capacities often exceeding those of most timber-framed structures. Research in New Zealand has shown that rammed-earth walls perform better than brick walls under earthquake conditions (Preciado & Santos, 2019).
- Moisture resistance: Rammed-earth walls have moderate to good moisture resistance and generally do not require waterproofing. However, the addition of water-repellent additives to exposed external walls may inhibit the breathability of the material (Downton, 2013).
- Sound insulation: Rammed-earth walls provide excellent sound insulation due to their mass and materials, creating a quieter environment by reducing outdoor noise (Avila et al., 2021).
- Low maintenance: Rammed-earth walls are easy to maintain. After being sealed, they typically do not require maintenance for at least 10 to 20 years. After that period, a second coat of sealer may be applied to exposed walls (Arya, 2022).
- Fire resistance: Rammed-earth walls are highly fire-resistant as they do not contain flammable materials. CSIRO tests have confirmed that a 15-centimeter rammed-earth wall can achieve a four-hour fire-resistance rating (Downton, 2013).
- Environmental impacts: Rammed earth generally has low manufacturing impacts and is dependent on cement content and material sourcing location (Downton, 2013). The embodied energy of rammed earth is minimal. However, transportation and cement manufacturing can significantly contribute to the total emissions associated with modern rammed earth construction (Downton, 2013). The primary energy used in the construction of rammed earth is in extracting the raw materials and transporting them to the construction site (Downton, 2013).

Rammed earth also has the advantage of being recognized as a material with the lowest carbon footprint, with an average of 48kg of embodied carbon per m^3. A case study conducted in Kashan city, Iran, showed that replacing fired bricks with rammed earth could reduce CO2 emissions by nearly 1,245 kg/ton and embodied energy by around 4,646 MJ/ton (over 95

percent reduction) (Nouri et al., 2021). Rammed earth structures have a long lifespan, with many houses still standing after centuries, demonstrating the reliability of unsterilised rammed earth if its production is well-controlled and executed (Bui et al., 2009).

3.5.5 Cork

The cork oak tree is a significant species within the ecosystem in which it grows and supports an abundance of biodiversity and ecological processes, as well as the societies and economies that have cultivated it for centuries (Aronson et al., 2009). Cork is considered one of the most sustainable and eco-friendly construction materials due to its natural properties, 100% recyclability, energy-saving characteristics, and excellent sound absorption capabilities (Mestre & Vogtlander, 2013). Cork is primarily used for walls and flooring, and it originates from sustainably managed forests. The bark of the cork oak tree is stripped at approximately nine-year intervals, causing no harm to the trees, and then ground into granules. These granules are subsequently compressed with specific glues at high temperatures and pressures to produce sheets, planks, tiles, and other cork products (BRANZ, 2022).

In New Zealand, cork products are primarily imported from Portugal and Spain (BRANZ, 2022). There are several advantages to using cork, including ease of installation, resistance to moulds and rot, fire resistance, and a lifespan of over 25 years (BRANZ, 2022). However, it is worth noting that upfront prices for cork products and associated finishes tend to be relatively high (BRANZ, 2022).

Although no carbon footprint assessment was found to be conducted specifically in New Zealand, research conducted by Tartaro et al. (2017) in Portugal indicates that cork board has the lowest carbon footprint among insulation building materials, with a value of -116.229 kg CO2/m3 (excluding transportation carbon emissions). Cork's embodied carbon is crucial because it absorbs carbon during its growth, and the greenhouse gas emissions and net energy consumption throughout the cork board's life cycle are very low compared to its embodied carbon (Tartaro et al., 2017).

3.5.6 Stone

Stone is a recyclable natural material that can last for years with appropriate maintenance and care (Vierra, 2016). As a structural material, stone offers several advantages in terms of structure, environment, and design compared to other construction materials (Morel et al., 2001). It provides excellent soundproofing qualities and offers excellent fire protection, both of which are requirements based on building regulations. Stone is also resistant to water damage

and provides energy efficiency through thermal mass (Yazdani Mehr & Wilkinson, 2018). Moreover, while normal buildings are typically designed and constructed to last only 60 to 70 years, stone structures can remain in use for an extended period, spanning hundreds of years. Stone exhibits significant strength has a long lifespan and incurs low maintenance costs. It has proven durability over thousands of years and plays a crucial role in human heritage, sustainable communities, and societies (Viles, 2013).

In New Zealand, stone was primarily used for public structures. Some structures had windows, door openings, and corners formed with cut stones, while walls were made from concrete. While both imported and local stones were used in the construction of structures in the 19th century; however, stone is not a common conventional structural material in New Zealand (Salmond, 2010).

3.5.7 Earthbags

Earthbag housing is a type of earth-based construction where large bags are filled with granules of material, laid horizontally, and compacted in a running bond to form the core of a wall structure. Earthbags are excellent materials for zero-carbon buildings due to their resistance to moisture damage. Installing and building houses with earthbags is easy and could decrease construction expenses. When filled with insulation such as scoria or perlite, earthbag walls and foundations enable people to grow plants year-round (Geiger, 2009). Earthbag construction is a natural technique developed from historic military bunker structure techniques and the temporary flood-control ditch structure method (Kumar Jain, 2013).

The walls made of earthbags can be straight or curved, domed with topped or earth with conventional roofs. Curved walls offer the advantage of forming round rooms, lateral stability, and domed ceilings similar to an igloo. Structures with straight walls longer than 5 meters in length require either bracing buttresses, intersecting walls, or added piers (Jain, 2013). Several international standards have been published for bracing wall spacing and size for earthen structures in diverse types of seismic risk areas, with notable examples such as the New Zealand performance-based standard 4299, which many organizations recommend in their standard guides, including ASTM (Jain, 2013). The construction and maintenance of earthbag walls are approximately 68.7 percent cheaper than mud brick walls, and earthbag walls exhibit better thermal and physical comfort compared to mud brick walls (Wesonga et al., 2021).

3.6 Discussion

The world of construction is evolving, driven by a growing awareness of the environmental impact of our buildings. As we seek to construct homes and structures that harmonise with nature and reduce our carbon footprint, it is important to explore the potentials of available and locally sourced sustainable building materials. In this review of six zero-carbon building materials identified in the New Zealand construction industry, we delved into the remarkable advantages and the limitations associated with their materials.

Wood, as a renewable resource, is widely available in New Zealand and has been used for centuries in construction. It possesses excellent thermal properties, providing natural insulation and energy efficiency. Wood is also lightweight, durable, and versatile, allowing for flexible designs and construction methods. Its low embodied energy and carbon sequestration capacity make it an ideal choice for zero-carbon buildings.

Straw bale construction presents several compelling advantages as a sustainable building material. It harnesses agricultural by-products, boasts low embodied energy, serves as a carbon sink, and delivers excellent insulation properties. Straw bales are readily available locally, cost-effective, environmentally friendly, and biodegradable. They excel in sound insulation, resist heat loss or gain effectively, and contribute to reduced CO2 emissions. Despite some drawbacks such as flammability and maintenance needs, their overall merits make them an appealing choice for eco-friendly construction practices. Straw bale construction utilises agricultural waste materials, such as rice, oats, wheat, or rye straw, to create highly insulated and energy-efficient walls. Straw bales act as carbon sinks, reducing CO2 emissions, and contribute to a reduced environmental footprint.

On the other hand, adobe and brick construction also offer numerous merits as sustainable building materials. With a rich history of use, they can be recycled, provide robust structural integrity, eliminate the need for painting, offer acoustic and thermal comfort, and generate minimal waste. Bricks, in particular, exhibit exceptional durability and resilience to various environmental conditions. These characteristics render adobe and brick highly attractive options for sustainable and eco-friendly construction practices.

Rammed earth construction, too, boasts numerous advantages as a sustainable building material. Its breathability, durability, moisture resistance, sound insulation properties, low maintenance requirements, and fire resistance make it a desirable choice. Additionally, its low carbon footprint and extended lifespan make it particularly appealing for eco-conscious building

projects. Rammed earth construction combines natural materials, such as chalk, earth, gravel, or lime, to create durable and energy-efficient structures. Rammed earth walls have excellent thermal mass properties, providing temperature regulation and energy savings. The use of locally sourced materials further reduces carbon emissions associated with transportation.

Cork stands out as an environmentally friendly construction material with numerous benefits, including sustainability, recyclability, energy-saving qualities, and exceptional sound absorption capabilities. It is commonly employed for walls and flooring and derives from sustainably managed forests. While initial costs may be higher, cork products offer advantages like resistance to moulds and rot, fire resistance, and impressive durability. Moreover, cork's ability to absorb carbon during growth results in a low carbon footprint, making it a highly attractive option for eco-conscious construction projects.

Stone, with its durability, environmental merits, and design versatility, also deserves consideration as a construction material. Its long lifespan, strength, and low maintenance requirements make it a compelling choice for sustainable building practices. Although not widely used as a structural material in New Zealand, its historical significance and inherent qualities make it a worthy candidate for future construction endeavours.

Furthermore, the utilisation of earthbags in construction provides various benefits for zero-carbon buildings, including cost-effectiveness, resistance to moisture damage, and the potential for year-round plant growth. The flexibility in wall design, whether straight or curved, allows for the creation of imaginative and stable structures.

3.7 Conclusion

In this paper, we aimed to pinpoint zero-carbon materials capable of aiding the New Zealand construction industry in achieving a net-zero carbon future. we conducted a comprehensive review of secondary data from academic research outputs, government publications, and industry reports related to sustainable building materials in New Zealand. As a key finding, each of these materials —wood, straw bales, stone, cork, adobe mudbrick and rammed earth— offers unique advantages that align with the goals of sustainability, energy efficiency, and reduced environmental impact.

The use of these building materials contributes to zero-carbon construction practises in New Zealand, and each has substantial sustainability benefits. They help lessen the built environment's carbon footprint by providing ecologically friendly substitutes for conventional

construction techniques. These resources also complement New Zealand's rich natural resources and the nation's commitment to sustainable development.

By embracing these materials as primary construction materials, New Zealand can foster a sustainable and resilient built environment. These materials not only offer ecologically responsible and energy-efficient solutions, but they also support regional economies and the preservation of natural resources. Incorporating these materials into building techniques can assist New Zealand in achieving its zero-carbon building objectives while fostering healthier, longer-lasting communities.

3.7.1 Scope and Limitations of Research

The paper focused on finding a common zero-carbon building materials in New Zealand. The study reported here is limited to the available published works on these materials. As such, it is possible that there are other innovative modern zero-carbon materials available in the construction industry that are not represented in this paper. This suggests the need for research into these materials and subsequent publications. This study is part of a doctoral project that aims to develop a decision support tool for selecting best-fit zero carbon building materials for stakeholders in the construction industry. Further work will be conducted that include field work for empirical data towards achieving the aim of this project.

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STATEMENT OF CONTRIBUTION DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the student and the student's main supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the student's contribution as indicated below in the Statement of Originality.

Student name:	Ali Hashemi Araghi
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In which chapter is the manuscript/published work?	Chapter 4

Describe the contribution that the student and members of the supervisory team have made to the manuscript/published work:[1]

Conceptualization, A.H.A.; methodology, A.H.A.; software, A.H.A.; validation, A.H.A.; formal analysis, A.H.A.; investigation, A.H.A.; resources, A.H.A.; data curation, A.H.A.; writing—original draft preparation, A.H.A.; writing—review and editing, A.H.A., E.O.R., V.V. and J.S.; visualization, A.H.A.; supervision, E.O.R., V.V. and J.S.; project administration, A.H.A.; funding acquisition, E.O.R., V.V. and J.S. All authors have read and agreed to the published version of the manuscript.

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Chapter 4: Literature Review

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

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4.1 Chapter Summary

This chapter systematically examines the suitability of zero-carbon building materials for application within the New Zealand construction sector, with a specific focus on wood, rammed earth, and straw bale systems. Using a PRISMA-guided systematic literature review, peer-reviewed studies published between 1999 and 2024 were identified and screened across Scopus, Google Scholar, and IEEE Xplore databases. Following rigorous inclusion and exclusion criteria, 24 eligible studies were analysed to evaluate material performance across six key dimensions: durability, energy efficiency, thermal and insulation performance, environmental impact, cost considerations, and aesthetic attributes.

The findings indicate that all three materials demonstrate strong potential to support zero-carbon construction objectives, particularly through low embodied energy, carbon sequestration capacity, and favourable thermal behaviour. Straw bale systems consistently exhibit high insulation performance and low operational energy demand, while rammed earth shows notable durability and thermal mass benefits, especially when stabilised. Wood-based systems demonstrate comparatively lower embodied carbon than conventional materials such as concrete and steel, though durability remains sensitive to moisture and treatment conditions.

Despite these strengths, the review reveals critical gaps in the existing literature. Notably, cost-effectiveness and aesthetic considerations remain underexplored, and comprehensive life-cycle assessments tailored to New Zealand's climatic and regulatory context are limited. These gaps constrain informed decision-making and hinder wider industry adoption of zero-carbon materials.

Chapter 4 established the evidence base for the subsequent empirical investigation. The review showed that existing studies largely assess individual material-performance dimensions, particularly durability, thermal and energy performance, insulation, carbon emissions, and environmental impact. It also identified comparatively limited evidence concerning cost-effectiveness and aesthetics and showed that practical selection conditions were seldom considered systematically.

The review did not produce a final set of empirically validated decision criteria or determine their relative importance in New Zealand practice. Instead, its themes and identified gaps provided the conceptual starting point for Chapter 5. These findings were combined with the targeted material-selection literature and New Zealand-specific evidence reviewed in Section 5.3 to define six survey constructs: cost-effectiveness, durability, buildability, embodied carbon, availability, and aesthetics. Chapter 5 then examined how construction professionals evaluated these pre-specified constructs and how the constructs related to material adoption.

4.2 Introduction

The impact of climate change on the building sector is substantial. In New Zealand, buildings contribute directly and indirectly to approximately 16–20% of the country's total Greenhouse Gas (GHG) emissions (BRANZ, 2024a). Fraser-Jones et al. (2023) indicate that the building and construction industry is responsible for 15.1% of New Zealand's overall emissions while (MBIE, 2020b) maintains that the construction sector produces 20% of NZ's GHG emissions. The sector's substantial diesel fleet, concrete production, and management of building waste represent significant sources of emissions that require considerable investment and transformation. As such, the NZ government has committed to minimise its carbon dioxide emissions by 2050 in line with UN goals (Gamage et al., 2019). To achieve this, NZGBC (2023b) recommended that new buildings should be constructed with zero carbon and with 20% less embodied carbon by 2025. The BRANZ Transition to a zero-carbon built environment initiative aims to ensure that by 2050, the building and construction industry achieves the goal of delivering affordable net-zero carbon buildings (BRANZ, 2024b).

The construction industry plays a critical role in climate change by adopting eco-friendly practices and materials (Bui et al., 2021; Cabeza et al., 2013). Many countries worldwide are increasingly prioritising the transition towards zero-carbon building materials to mitigate climate change impacts and promote sustainable building practices (Joensuu et al., 2020; Lai et al., 2011). Zero-carbon building materials are fundamental to reducing GHG emissions and offer several advantages, such as reduced environmental impact, carbon neutrality, energy efficiency, renewable and sustainable sourcing, and improved health and indoor air quality (Baghaei Daemei & Jamali, 2022; Khotbehsara et al., 2019; Tirelli & Besana, 2023). These materials are a fundamental component of sustainable construction, and the careful selection of available materials has prompted a growing interest in green alternatives (Daemei et al., 2021).

Materials such as wood, rammed earth, and strawbale offer sustainability alternatives due to their renewability and versatility as construction materials. Such green materials have garnered significant attention as a building resource that aligns with ecological principles (Daemei et al., 2019; Sun et al., 2023). These materials are sourced from renewable resources or recycled materials, reducing environmental degradation. They often have minimal or no net carbon emissions, contributing to climate change mitigation (Yang et al., 2023). Additionally, they provide excellent insulation (Islam & Bhat, 2019), lowering energy consumption (Reynoso et al., 2021) and operational costs (Brown & Buranakarn, 2003). Sourced sustainably, they promote long-term environmental responsibility (Kinoshita et al., 2020). Lastly, they emit fewer pollutants, enhancing indoor air quality and occupant health (Zhou et al., 2022).

Zero-carbon materials hold immense promise for revolutionising the construction sector while significantly mitigating environmental impact (Wang et al., 2023). By minimising or eliminating carbon emissions throughout their life cycle, these materials offer a sustainable alternative to traditional construction materials (Arenas & Shafique, 2024). Their use can substantially reduce the carbon footprint of buildings (Ramaswami et al., 2021), making a significant contribution to global efforts to combat climate change (Panos et al., 2023). With their potential for durability and longevity, zero-carbon materials offer a pathway towards constructing resilient and environmentally responsible buildings for a sustainable future (Guo et al., 2018).

While the benefits of zero-carbon materials are evident, there remains a significant gap in comparing these materials based on critical features such as climate responsiveness, local availability, economic feasibility, and cultural appropriateness, particularly in the context of New Zealand's unique construction environment (Bui et al., 2021). This lack of region-specific knowledge poses a challenge for stakeholders, as current guidance does not sufficiently support informed decision-making regarding which materials are most suitable for achieving zero-carbon goals in New Zealand's building sector (Nidhin et al., 2023). Given New Zealand's distinct climatic conditions and its ambitious goal of achieving carbon neutrality by 2050 (Gen Less, 2024), identifying optimal zero-carbon materials is crucial. Moreover, as a country with a strong focus on sustainability, the relevance of selecting regionally appropriate, low-emission materials is heightened compared to other regions, where such practices may not be as advanced or emphasised (Bui et al., 2023).

This review seeks to identify the most suitable zero-carbon building materials for New Zealand's construction industry, focusing on wood, rammed earth, and strawbales. We assess

these materials across six key criteria: sustainability, cost-effectiveness, durability, aesthetic appeal, energy efficiency, and environmental impact. By thoroughly evaluating and comparing these materials, our research contributes to filling a crucial knowledge gap in the region. The primary contribution of this study is to provide clear, evidence-based guidance for stakeholders, architects, and policymakers in the New Zealand construction sector, enabling them to make informed decisions that align with the country's zero-carbon goals and sustainable development targets.

4.3 Background

The concept of Zero Carbon Buildings (ZCB), often synonymous with Net-Zero Energy Buildings (NZEB), goes beyond mere energy efficiency (Bui et al., 2023; Xing et al., 2011). It represents a holistic and ambitious effort to minimise the carbon footprint associated with a building's entire life cycle, encompassing design, construction, operation, and eventual decommissioning (Ohene et al., 2022). Achieving such a commendable goal demands innovative design strategies, advanced technological integration, and a commitment to sustainable practices throughout the building's lifespan (Pan & Pan, 2019). As the urgency to address climate change intensifies, the importance of zero-carbon buildings becomes increasingly evident. These structures contribute significantly to global efforts to curb carbon emissions and serve as beacons of innovation, showcasing the potential for harmonious coexistence between the built environment and the natural world (Zhao & Gu, 2024).

4.3.1 Building materials: Wood, rammed earth, and strawbale

Wood, rammed earth, and strawbale offer numerous benefits as building materials, contributing to sustainable construction practices and environmental stewardship (Orhon & Altin, 2020). Firstly, wood is renewable, readily available, and boasts excellent thermal properties, providing effective insulation and reducing energy consumption for heating and cooling (Swan et al., 2011). Its versatility allows for various construction techniques, from traditional timber framing to modern engineered wood products, catering to diverse architectural styles and design preferences. Additionally, wood sequesters carbon dioxide (CO_2) throughout its life cycle, acting as a carbon sink and mitigating greenhouse gas emissions. Moreover, wood construction supports local economies and forestry industries, fostering economic growth and job creation in communities (Snell & Callahan, 2009).

Similarly, rammed earth construction utilises locally available soil, minimising transportation and resource depletion associated with traditional building materials (Rabbat et al., 2022).

Rammed earth buildings exhibit exceptional durability and thermal mass, regulating indoor temperatures and reducing the need for mechanical heating and cooling systems (Nasr et al., 2023). This results in energy savings and lower operational costs over the structure's lifespan. Additionally, rammed earth structures offer aesthetic appeal and architectural diversity, blending harmoniously with natural landscapes and cultural contexts. Furthermore, the use of rammed earth promotes sustainable land management practices and soil conservation, enhancing ecosystem resilience and biodiversity (Ben-Alon & Rempel, 2023).

Strawbale, often considered a byproduct of agricultural activities, offers a sustainable insulation and wall construction alternative. Strawbale buildings boast excellent thermal performance, providing superior insulation compared to conventional materials (Sun et al., 2023). This contributes to energy efficiency and occupant comfort, creating healthier indoor environments with stable temperatures year-round. Additionally, straw bales are renewable, biodegradable, and locally sourced, reducing reliance on fossil fuels and minimising environmental impact (Mehravar et al., 2021). Moreover, straw bale construction supports rural economies and agricultural communities, providing additional revenue streams for farmers and promoting sustainable agricultural practices. Overall, wood, rammed earth, and straw bales offer multifaceted benefits as building materials, aligning with principles of sustainability, resilience, and environmental responsibility (B et al., 2023).

These materials were chosen for this review due to their significant contributions toward achieving Zero Carbon Buildings (ZCBs) and their alignment with sustainable construction practices (Cornaro et al., 2020; Li et al., 2024; Samarasinghe & Falk, 2022). These materials provide substantial environmental benefits that help mitigate climate change by reducing greenhouse gas emissions and improving energy efficiency. Wood, for example, not only offers renewable and readily available resources but also sequesters carbon dioxide (CO_2) throughout its life cycle, making it a key material for lowering a building's overall carbon footprint (Hildebrandt et al., 2017). Its excellent thermal properties contribute to energy savings in heating and cooling, directly supporting ZCB goals by reducing operational energy use. Wood's versatility also promotes local economic growth, furthering the sustainable development agenda (Cabeza et al., 2013).

Similarly, rammed earth utilises locally available soil, reducing the embodied carbon typically associated with long-distance material transportation (Pakand & Toufigh, 2017). Its thermal mass properties reduce reliance on mechanical systems for heating and cooling, enhancing energy efficiency and lowering operational costs over the building's lifespan. Rammed earth

construction supports the ZCB framework by using natural, low-carbon materials that contribute to durable and energy-efficient structures (Khadka, 2020). Strawbales, on the other hand, often a byproduct of agriculture, offer an eco-friendly insulation alternative. With superior thermal performance, straw bale construction enhances energy efficiency, contributing to the overall reduction of operational emissions (Bo et al., 2023). Being renewable, biodegradable, and locally sourced, straw bales further align with the goals of ZCBs, minimising the environmental impact of construction while supporting rural economies and sustainable farming practices (Koh & Kraniotis, 2020).

4.4 Materials and Methods

4.4.1 Formulating the research questions

This review aims to compare the viability of suitable zero-carbon building materials for application in the New Zealand construction industry. Based on a previous study Hashemi Araghi et al. (2022), three zero-carbon materials, namely wood, rammed earth, and strawbale, were identified as the most suitable for New Zealand. We examined these materials across various factors such as sustainability, cost-effectiveness, durability, aesthetic appeal, energy efficiency, and environmental impact, specifically focusing on.

4.4.2 Identifying the relevant studies

This research used a systematic literature review methodology guided by the Preferred Reporting Items for Systematic Reviews (PRISMA) Statement (Page et al., 2021). The systematic approach ensures a rigorous and transparent process in identifying, selecting, and synthesising relevant literature published in New Zealand about zero-carbon buildings and the associated green materials, including wood, rammed earth, and straw bales. Adhering to the PRISMA guidelines enhances the quality and reliability of the review, providing a structured framework for the systematic analysis of research findings (Cacciamani et al., 2023). By incorporating the PRISMA Statement, this paper seeks to uphold methodological rigour, transparency, and reproducibility, thereby strengthening the credibility of the systematic literature review and the validity of the insights gleaned from the synthesis of existing knowledge.

In pursuing a comprehensive and well-rounded exploration of the existing literature, this research harnessed the search capabilities of three prominent databases: Scopus, Google Scholar, and IEEE Xplore. These databases were selected to ensure a thorough and exhaustive review, encompassing various scholarly articles, conference proceedings, and research papers

(Elsevier, 2023; Martín-Martín et al., 2021). By incorporating Scopus, Google Scholar, and IEEE Xplore into the search strategy, the study aimed to access a broad spectrum of academic sources, enhancing the depth and inclusivity of the systematic literature review. Utilising these reputable databases reflects a commitment to a robust and methodologically sound exploration of the current knowledge landscape in sustainable construction practices.

Scopus is a comprehensive abstract and citation database of peer-reviewed literature (Goodman, 2005). It covers various disciplines, including science, technology, medicine, social sciences, and arts and humanities. Scopus provides access to many scholarly journals, conference proceedings, and patents. Its advanced search features and citation analysis tools make it a valuable resource for researchers seeking multidisciplinary information (Elsevier, 2024).

Google Scholar is a freely accessible search engine that indexes scholarly articles, theses, books, conference papers, and patents. It covers a broad spectrum of academic disciplines and is widely used for its user-friendly interface and inclusivity. Google Scholar provides a convenient way to explore scholarly literature across various sources, making it a popular tool for researchers, students, and academics. IEEE Xplore is a digital library and database specifically focused on content related to electrical engineering, computer science, and electronics. It includes a vast collection of IEEE (Institute of Electrical and Electronics Engineers) journals, conferences, and standards (IEEE, 2023). IEEE Xplore is a key resource for researchers and professionals in the fields of technology and engineering, offering a specialised repository of cutting-edge research and technological advancements. Table 4.1 provides the eligibility criteria for selecting the studies.

Table 4.1: The screening stages and criteria to select eligible studies

Stage	Criteria	Decision
Before screening	Not written in English	Exclusion
	Not a journal article	Exclusion
	If the study is a conference paper, book chapter, or a review paper	Exclusion
	When the specified keywords are present either in the entirety or at least within the title, keywords, or abstract of the paper	Inclusion
Initial screening	Studies provide sufficient information on the subject matter	Inclusion
	Studies that assessed or evaluated the materials	Inclusion
	Studies used experiment or simulation analysis the materials	Inclusion
	Studies must be directly relevant to the topic of interest within the scope of the research	Inclusion

Full-text manual screening	There were no experiment or simulation results	Exclusion

The search keywords used in this study are formulated as follows: “Zero Carbon” AND construction OR building* AND “New Zealand”. The search strategy utilises the AND and OR field operators to comprehensively explore relevant literature. Besides, to ensure comprehensive coverage of relevant studies, this research employs the backward and forward snowballing technique (Wohlin, 2014). This involves tracing citations backwards to earlier works (backwards snowballing) and exploring subsequent references citing the primary studies (forward snowballing), enhancing the inclusiveness of the literature review (Wohlin et al., 2022). Consequently, 20 papers are identified. Figure 4.1 illustrates the PRISMA Framework in this study.

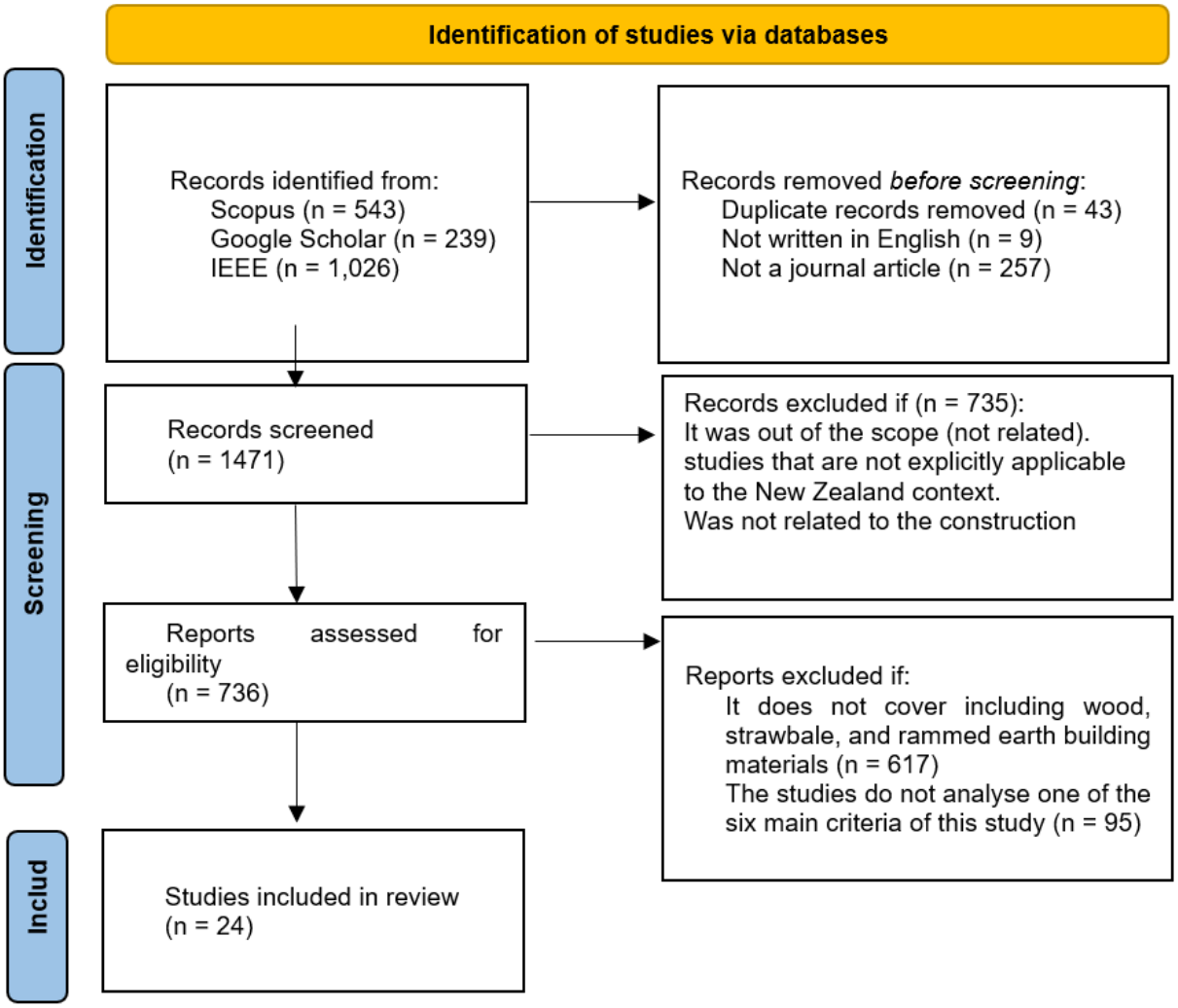


Figure 4.1: Identification of relevant studies via PRISMA Flow Diagram

According to the Figure 4.1, the studies undergone three different stages of selection such as identification, screening, and include. For each stage, there are some inclusion and exclusion criteria, which formulated based on the research aim and scope to refine our results. Consequently, the last stage showed that how many studies are relevant to full-text manual screening.

4.5 Results

4.5.1 General overview

In this systematic literature review, we identified 24 papers published between 1999 and 2024, including 21 journal articles and 3 conference papers. Figure 4.2 illustrates the number of publications and types of scholarly outputs per annum.

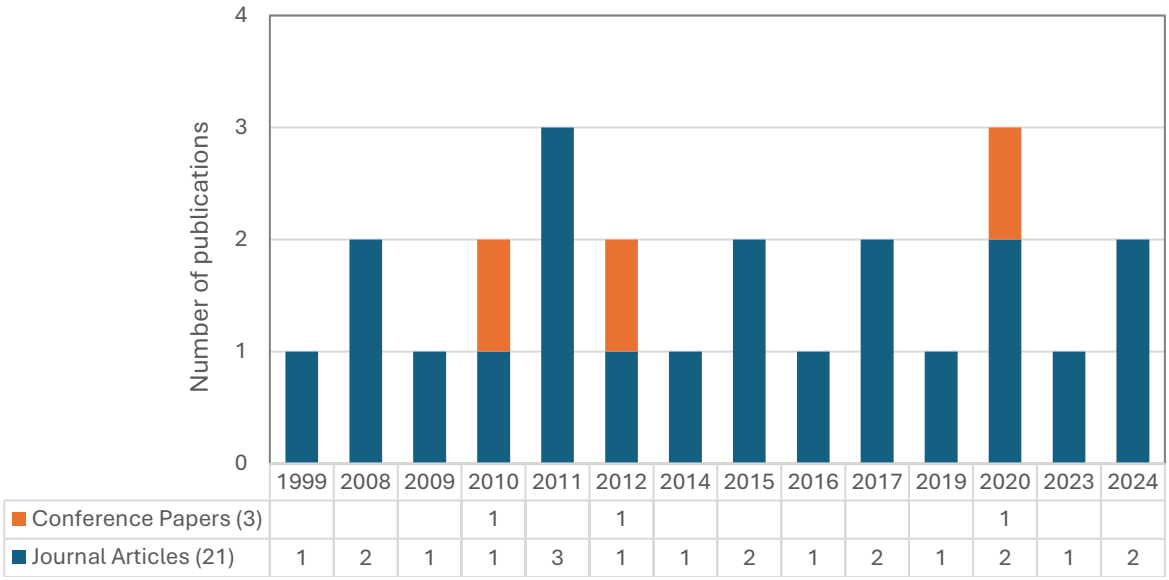
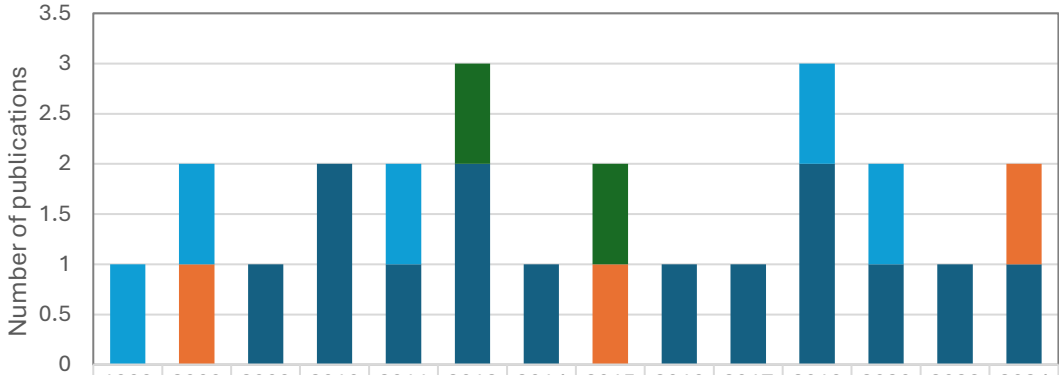


Figure 4.2: Overview of the scholarly outputs of the selected studies

The selected studies have employed various methodologies for data collection and analysis of these building materials. Among them, twelve studies utilised experimental measurements as a primary means of gathering data. Three studies employed simulation software, demonstrating a reliance on computational modelling for analysis. Additionally, two studies relied on survey methodologies, focusing on gathering qualitative or quantitative data directly from participants. For the survey, the studies used a survey to get participant feedback and a questionnaire to collect subjective information. Beyond these primary approaches, 5 studies employed other methods. Here, we categorised Laboratory measurements (Ashour et al., 2011; D'Alessandro et al., 2017), Field measurements (D'Alessandro et al., 2017), and Stereo-photogrammetry (Bui et al., 2009) as experimental methods. However, for the category "Others", papers used review

analysis (Swan et al., 2011), a comparative study (Buchanan & Levine, 1999), and CORRIM assessment: Life Cycle Inventories (Upton et al., 2008). Figure 4.3 provides further details on this.



	1999	2008	2009	2010	2011	2012	2014	2015	2016	2017	2019	2020	2023	2024
Others (5)	1	1			1						1	1		
Survey (2)						1		1						
Simulation (3)		1						1						1
Experiment (14)			1	2	1	2	1		1	1	2	1	1	1

Figure 4.3: Summary of the methodologies utilised in the selected studies

This research aims to identify the potential impact of the target materials on 6 themes which are: These themes include:

- Durability, which examines the longevity and resilience of building materials and structures.
- Thermal performance, which assesses the ability of buildings to maintain comfortable temperatures and minimise energy consumption.
- Insulation, which focuses on materials and techniques for reducing heat transfer and improving sound insulation.
- Aesthetics, which considers the visual appeal and design elements of buildings.
- Energy performance, which evaluates the overall energy efficiency and consumption of buildings.
- Co_2 emission, which addresses the environmental impact of building materials and processes in terms of carbon dioxide emissions.
- Cost, which analyses the economic implications of various building strategies and materials.
- Environmental impact encompasses broader considerations of the ecological consequences of building design and construction.

These themes collectively highlight the multidimensional nature of research in the field, emphasising the importance of addressing practical and environmental concerns in building practices. Table 4.2 summarises the main themes of this study, indicating which studies focused on each theme to highlight the areas that have been most extensively explored. We achieved this by highlighting the themes and providing a summary of the total occurrences at the end.

Table 4.2: The frequency of topic/theme occurrence among the eligible articles

Sources	The research theme				
	Cost-effectiveness	**Durability**	**Aesthetic appeal**	**Energy efficiency**	**Environmental impact**
(Mutani et al., 2020)				×	
(D'Alessandro et al., 2017)		×		×	
(Alcorn & Donn, 2010)				×	×
(Buchanan & Levine, 1999)					×
(Resendiz et al., 2020)		×			
(Umubyeyi et al., 2023)		×			
(Ciurileanu & Bucur Horvath, 2012)					
(Swan et al., 2011)		×			
(Mi et al., 2020)			×	×	
(Høibø et al., 2015)		×			×
(Bui et al., 2009)		×			
(Venkatarama Reddy & Prasanna Kumar, 2010)				×	
(Upton et al., 2008)				×	
(Yan et al., 2024)					×
(Thomson & Walker, 2014)		×			
(Ashour et al., 2011)		×		×	

(Jové-Sandoval et al., 2024)				×	
(Wall et al., 2012)				×	
(Kariyawasam & Jayasinghe, 2016)		×		×	
(Taylor et al., 2008)				×	
(Kallavus et al., 2017)		×			
(Singh et al., 2019)		×			
(Nofal & Kumaran, 2011)		×			
(Chaussinand et al., 2015)				×	
Total	0	12	1	12	5

4.5.2 Durability of materials

New Zealand's climatic conditions are dominated by persistent environmental factors, which are responsible for the lifespan of the materials. Rammed earth favours well in New Zealand weather conditions as unstabilised rammed earth walls can experience erosion rates of approximately 1 mm/year over 20 years of natural weathering (Umubyeyi et al. (2023), without significant deterioration. A study showed that the estimated lifespan of the freestanding unstabilised rammed earth wall with minimal protection from natural climatic conditions in a temperate climate is between 37 and 75 years. Swan et al. (2011), in their study, found that in areas that experience up to 635 mm (25 in.) of rain per year, unstabilised earthen walls left unprotected are likely to erode at a rate of 25.4 mm (1 in.) in 20 years on vertical surfaces and 50–75 mm (2–3 in.) per year on horizontal surfaces.

Bui et al. (2009) studied the durability of rammed earth walls exposed for 20 years to natural weathering. They found that none of the walls collapsed completely during the 20-year period despite being on-site exposed to the weather for over 100 years. In a specific study context with a precipitation annual of about 1000 mm, the erosion measurement of unsterilised rammed earth walls after 20 years of exposure was about 6.4 mm, corresponding to 1.6% of wall thickness. This erosion led to an extrapolated lifetime longer than 60 years, indicating potential durability.

Also, Kariyawasam and Jayasinghe (2016) focused on assessing the strength and durability of Cement Stabilized Rammed Earth (CSRE) as a sustainable construction material. Compressive

and flexural strength tests on CSRE wall panels with different cement contents demonstrated satisfactory results, meeting Earth Building standards. The material exhibited lower embodied energy than traditional burnt clay bricks, contributing to sustainable construction practices. CSRE has been successfully applied in various construction projects, showcasing its strength, durability, and cost-effectiveness, making it a promising alternative for environmentally friendly building practices.

Moisture is a significant environmental factor affecting the durability of construction materials and structures. Strawbales are highly susceptible to high-moisture environments. This is because, in high-moisture environments, the proliferation of fungi and bacteria responsible for straw deterioration occurs within an optimal temperature range of 20-70°C, with survival below 10°C being unlikely (D'Alessandro et al. (2017). Moisture content evaluation is crucial for assessing the durability of straw bale buildings, with values below 20% preventing decomposition and deterioration typically starting at moisture content levels of 25-30% (Ibach, 2012).

That said, Strawbale has its positive features when exposed to environmental factors. For instance, Thomson and Walker (2014) conducted a durability assessment on the resilience of straw bales exposed to high humidity levels. The findings indicated an initial rapid growth of CO_2, which ceased after 10 days. Observations revealed no significant decay in three-year-old straw bales exposed to 87% relative humidity. These insights suggest that straw bale construction can be durable under certain conditions. In the study by Ashour et al. (2011), the researchers observed that temperature decreases over time in a manner that can be mathematically described by an exponential equation. The strength of this relationship is quantified by a correlation coefficient of approximately 80.05%, indicating a strong correlation between time and the decrease in temperature.

Additionally, the relative humidity in the straw bales increased exponentially with time, showing a correlation of 94.04% (relationship between time and the increase in relative humidity in the straw bales). Notably, the results highlighted the exceptional insulation properties of straw materials against external relative humidity, attributed to their low moisture content. Mechanical tests indicated higher strength in vertical orientation, and deformation modulus was evaluated for horizontal and vertical bales. Furthermore, the study demonstrated stable temperature and relative humidity distribution within the straw walls, with slow moisture migration observed. Overall, the findings underscored straw's durability and decay resistance

as a building material, with a measured pH value inside the bales of 7.29. Table 4.3 shows the final summary of the durability of the durability performance of the target materials.

Table 4.3: Finalizing the summary of the selected studies on durability

Study	Focus	Properties
(D'Alessandro et al., 2017)	Durability of straw in high moisture environments	Fungi and bacteria thrive at 20-70°C; survival below 10°C is unlikely. Moisture below 20% prevents decomposition; deterioration starts at 25-30% moisture content.
(Umubyeyi et al., 2023)	Erosion of unstabilised rammed earth walls	Erosion rate is about 1 mm/year over 20 years. Lifespan is estimated between 37-75 years in a temperate climate.
(Swan et al., 2011)	Rain effects on erosion of unstabilised earthen walls	The erosion rate is 25.4 mm in 20 years for vertical surfaces and 50-75 mm per year for horizontal surfaces in areas with up to 635 mm of rain annually.
(Høibø et al., 2015)	Consumer preferences for building materials	The complex interplay of durability perceptions, environmental attitudes, knowledge, and past experiences influence preferences, with a trend towards stone or bricks over wood.
(Bui et al., 2009)	The durability of rammed earth walls exposed to natural weathering	No complete collapse after 20 years; erosion of 6.4 mm after 20 years with a lifespan of over 60 years.
(Thomson & Walker, 2014)	Durability of straw bales in high humidity	Initial CO2 growth ceased after 10 days; no significant decay in the three-year-old straw at 87% RH.
(Ashour et al., 2011)	Insulation properties and durability of straw bales	Exponential decrease in temperature, exponential increase in relative humidity, high insulation properties, slow moisture migration, and pH value of 7.29.
(Kariyawasam & Jayasinghe, 2016)	Strength and durability of Cement Stabilized Rammed Earth (CSRE)	CSRE met Earth Building standards, showed lower embodied energy, and demonstrated strength and durability suitable for sustainable construction.

However, three studies explored the durability of wood or wood-based construction materials mostly on moisture and mould growth. The findings of Nofal and Kumaran (2011) regarding

wood decay and durability include the development of a wood-rotting model specific to wood-based materials, calculating the impact of operating conditions on building envelope service life and identifying loss in strength and microstructural changes due to wood-rotting fungi. The study also discusses the damage variation caused by fungi under different air leakage conditions and the progress of fungal decay in wood samples exposed to outdoor weather conditions. Additionally, the research highlights the importance of understanding deterioration mechanisms under fungal attacks and the need for further studies to identify potentially harmful wood-decay fungi in different environments. The study proposes a relationship to estimate the percentage of viable spores in terms of multiples of the dry period time, with the equation VS = 2.258e^(-0.7548N). This relationship helps understand the impact of viable spores on damage rate under wet conditions after a drying period. Also, the study reveals that mould growth increases with higher air leakage rates, but damage decreases as the wall dries due to mould being a surface phenomenon. Figure 4.4 illustrates the optimal conditions for mould growth and the impact of air leakage on wood-rot damage provided by (Nofal & Kumaran, 2011).

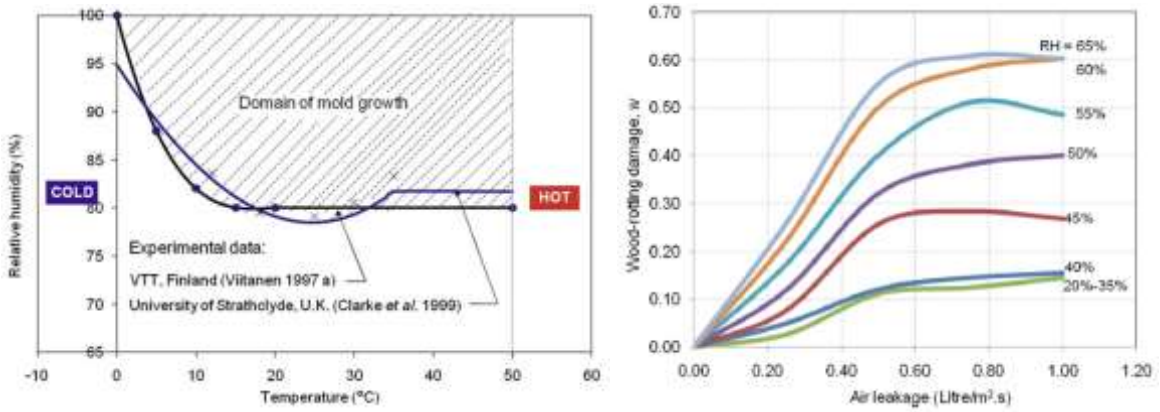


Figure 4.4: Conditions promoting mould fungi growth due to optimal moisture and temperature levels (left) and the impact of air leakage rates on the extent of wood-rot damage (right) (Nofal & Kumaran, 2011)

The results of the study by Singh et al. (2019) indicated that laminated veneer lumber samples exhibited minimal mycelium growth and localised decay near feeder blocks after 6 months, contrasting with untreated solid wood samples that showed extensive mycelium growth and severe decay. Leaching increased moisture content in oriented strand board samples, leading to mould growth. Boron treatment effectively prevented decay in cross-laminated timber samples, irrespective of leaching, highlighting the susceptibility of untreated oriented strand board and cross-laminated timber to biodegradation. These findings underscore the need for further

research to enhance the durability of wooden panels in construction applications. After 6 months of exposure, it was observed that differences in decay development were evident among the various wood products tested. Untreated solid wood exhibited severe decay, while laminated veneer lumber samples showed minimal mycelium growth and localised decay. This suggests that the duration of exposure to environmental conditions may influence the extent of decay in different wood materials.

Kallavus et al. (2017) explored the vulnerability of environmentally friendly wood-based panels to surface mould growth in conducive moisture conditions. Testing was conducted in a laboratory using a modified method that omitted sterilisation and oven-drying of samples. The findings underscored the risks associated with surface mould growth on construction materials, emphasising the significance of appropriate handling to avert spoilage and potential health hazards. The key findings regarding moisture and durability in relation to mould growth on wood-based construction materials indicate that these materials are highly susceptible to surface mould development in environments with elevated moisture levels. Improper handling, such as delays in construction processes and inadequate storage, can lead to significant mould proliferation. The presence of moisture and organic material, along with exposure to mould spores from the air, are critical factors contributing to mould growth on these materials. The relationship between durability and time in the context of mould growth on wood-based construction materials suggests that prolonged exposure to moisture over time can compromise the durability of these materials. As time progresses, the likelihood of mould development increases, especially if the materials are not stored or handled properly. The longer the materials are exposed to moisture, the greater the risk of surface mould growth, potentially leading to deterioration and reduced longevity of the wood-based panels.

4.5.3 Energy efficiency

Notably, due to the common terms they have used in their work, the research team combined the theme ‘sustainability’ in this category. Thus, eleven studies focused on the target materials' energy efficiency and thermal behaviour. Figure 4.5 shows the themes derived from studies on energy efficiency, which are classified according to the prevailing terminology found in relevant literature.

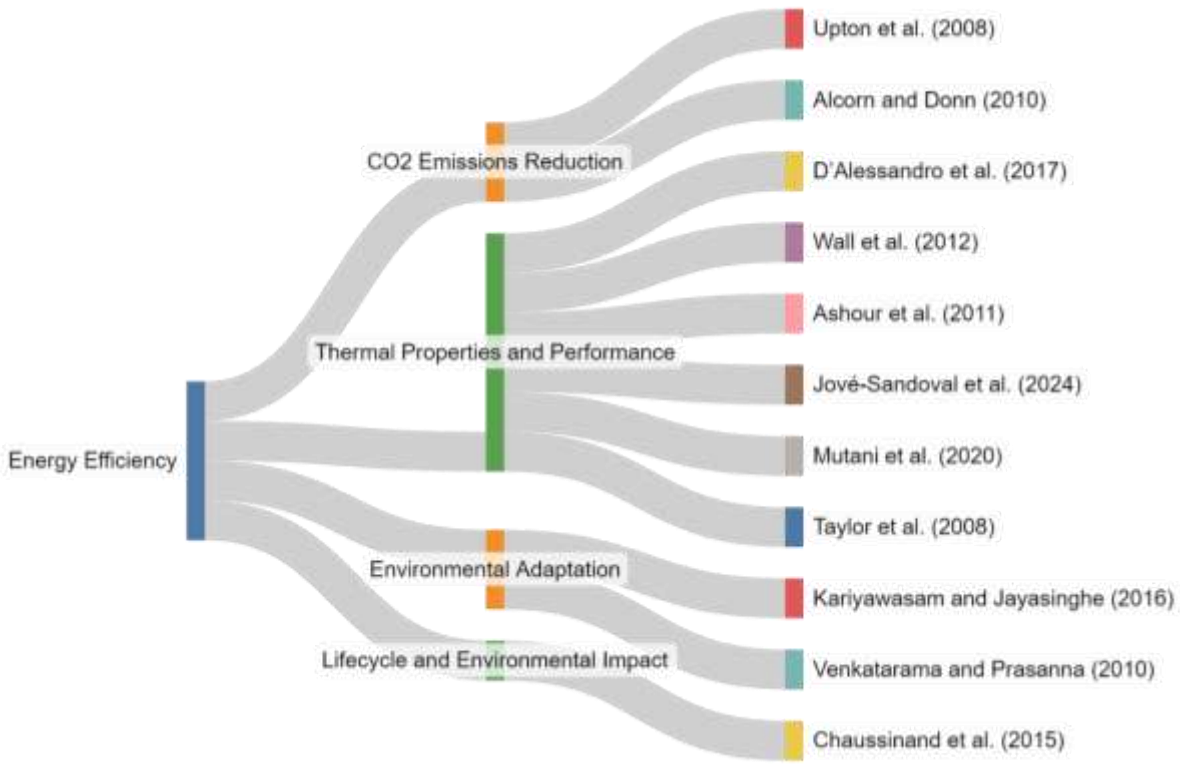


Figure 4.5: The themes derived from studies related to energy efficiency are categorised based on commonly used terms within the relevant literature (Source: the author)

Energy efficiency is one of the key factors influencing the selection of zero carbon materials and makes strawbale, wood and rammed earth favourable amongst other construction materials. For instance, Alcorn and Donn (2010) show that using materials like strawbale and timber in construction can significantly reduce energy consumption and CO_2 emissions. The thermal properties of straw bales, with comparable thermal conductivity to high-insulation materials, make them a viable and sustainable option for construction projects.

The study of D'Alessandro et al. (2017) investigated the thermal conductivity of straw bales using a guarded hot plate apparatus and compared the results with in-situ measurements. The thermal transmittance values obtained align well with commercial earthen plaster and straw bale thermal conductivity data. The research emphasises the importance of accurate thermal performance assessments for sustainable building materials like straw bales. They found that the embodied energy of straw bale walls accounts for 6% of the total, with the wooden frame being the most impactful component at 54%. The use phase of the building, particularly electricity consumption, contributes to about 92% of the whole life cycle impact in terms of global warming potential. Straw bale production is the major contributor to CO_2 equivalent emissions at 47%, highlighting the significance of material selection in sustainable construction practices.

Wall et al. (2012) discussed constructing and testing a prototype house made of prefabricated straw bale panels with softwood timber frames and lime renderings. The air permeability of the house met UK Building Regulations standards. Thermal surveys were conducted to assess energy efficiency, with findings showing minimal heat loss and uniform temperatures across the panels. Fire resistance and sound insulation tests were also performed, exceeding regulatory requirements. Another study done by Taylor et al. (2008) assessed the evaluation of a rammed-earth building in terms of thermal comfort and energy use. Findings revealed that the building faced challenges with excessive heat in summer and cold in winter, leading to discomfort among occupants. High energy consumption for heating was identified, prompting simulations to propose design and control modifications for improved efficiency. The study highlights the struggle to maintain thermal comfort while reducing energy consumption, emphasising the need for enhancements in building design and operational strategies.

Jové-Sandoval et al. (2024) investigated the energy and thermal behaviour of boards and adobe walls with natural fibres. The insulation properties were enhanced by incorporating agro wastes like wheat straw fibres, reducing thermal conductivity. Boards exhibited lower thermal transmittance than adobes, suggesting the potential for energy-efficient building materials. The study found that incorporating natural fibres like wheat straw significantly reduced thermal conductivity, with up to 60% observed improvements. Additionally, boards showed a considerable decrease in thermal transmittance compared to adobe walls, with reductions of around 50% achieved. The energy performance of the straw bales was demonstrated by a study performed by Ashour et al. (2011), wherein they evidenced the ability to maintain stable temperature levels within the walls, indicating efficient insulation properties that can help reduce heat loss in buildings. The study also emphasised the impact of external conditions on the thermal stability of the bales, highlighting their potential to contribute to energy efficiency in construction. The results underscored the importance of straw bales as a renewable and sustainable building material that can effectively regulate temperature and enhance energy conservation in structures.

Rammed earth's energy efficiency is well noted, especially when combined with other materials. For example, Kariyawasam and Jayasinghe (2016) assessed the energy efficiency of cement-stabilised rammed earth (CSRE) and showed that CSRE has lower embodied energy than traditional materials like burnt clay brick masonry. The embodied energy of CSRE walls was found to be 15–25% of burnt clay brick masonry, making it a more sustainable option. Additionally, CSRE has demonstrated better thermal comfort performance, with approximately

a 3°C reduction in indoor temperature compared to cement block walls, leading to lower energy demand for maintaining comfortable buildings (Kariyawasam & Jayasinghe, 2016). Venkatarama Reddy and Prasanna Kumar (2010) also studied cement-stabilised rammed earth walls and revealed that the compaction energy input varies with the clay fraction in the soil mix and is sensitive to the density of the walls. The compaction energy ranged from 0.033 MJ/m3 to 0.36 MJ/m3 for different densities and cement contents. It was found that the energy expended during compaction is minimal compared to the energy content of cement. Additionally, the total embodied energy in the walls increased linearly with higher cement content, ranging from 0.4–0.5 GJ/m3 for cement content between 6–8%.

For wood, the study results of Upton et al. (2008) indicated that wood-based construction materials have lower embodied energy and CO_2 emissions compared to concrete, steel, or brick systems in residential buildings with comparable thermal performance. The embodied energy in residential construction materials ranges between 0.5 and 1 EJ year^-1 (exajoules per year), with embodied CO_2 emissions between 30 and 60 million tonnes (Mt) year^-1. Wood-based wall systems consistently show lower energy and emissions impacts, significantly reducing non-renewable energy use in the residential sector.

Chaussinand et al. (2015) focused on analysing the thermal behaviour and energy performance of a straw bale building in Switzerland. The research aimed to understand the building's energy consumption and environmental impact by creating a thermal-dynamic model and conducting a life cycle assessment. The findings revealed that the straw bale construction exhibited low heat capacity, leading to overheating challenges in summer, which could be mitigated by managing solar gains and using external blinds. Despite these challenges, the ECO46 building showcased efficient energy consumption, surpassing standard buildings, and demonstrated sustainability using solar panels, ventilation systems, and insulation. Overall, the study concluded that straw bale buildings could offer a sustainable alternative in construction due to their low embodied energy and favourable thermal performance. The study showed that the ECO46 building consumes less than 10% of the energy consumed by a standard office building, highlighting its excellent energy performance for heating compared to most Swiss administrative buildings. Additionally, the discomfort rate due to overheating in occupied rooms ranged from 3.7% to 12.1%, considered good compared to the ASHRAE 14-2002 Guide's criteria of below 10%.

Mutani et al. (2020) focused on evaluating the energy and thermal behaviour of two different buildings, Casa Cembo and a pre-assembled prototype constructed with straw walls. Thermal

conductance measurements were conducted in homogeneous areas exposed to the north to avoid incident solar radiation issues. Results showed that Casa Cembo met the Ulim limits set by Italian regulations, while the pre-assembled prototype exhibited higher heat dispersion and did not meet the Ulim limits due to potential transport issues with the straw. The dynamic characteristics of the straw walls were analysed, showing differences in thermal performance between the two case studies. A good result in the study was defined as thermal conductance not deviating by more than ±5% from the value obtained 24 hours before over a period of more than 72 hours. The analysis revealed that Casa Cembo demonstrated very good results, meeting the Ulim limits set by Italian regulations. In contrast, the pre-assembled prototype showed higher heat dispersion and did not meet the Ulim limits due to potential transport issues with the straw.

4.5.4 Environmental impact

Only two studies focused on the environmental impact of the materials. The results of Høibø et al. (2015) discusses various aspects of building material preferences in urban housing, focusing specifically on wood and its environmental impacts compared to other materials. They highlighted that the timber-framed buildings generally have a lower global warming potential than concrete and steel structures. This makes wood a more positive option from a carbon perspective. the findings emphasize that wood is perceived as an environmentally friendly alternative to conventional building materials, particularly in the context of sustainability and carbon footprint reduction. Alcorn and Donn (2010) concluded that using materials like strawbale insulation and timber framing can significantly reduce CO_2 emissions due to their carbon sequestration properties. Both strawbale and timber are highly effective at sequestering carbon, thus reducing CO2-equivalent (CO2-e) emissions in house construction. For example, using strawbale insulation in walls, floors, and ceilings can reduce CO2-e emissions by up to 29%. The study found that strawbale and timber significantly reduce CO2 emissions by absorbing carbon throughout their life cycle, whereas materials like concrete and polystyrene contribute to higher emissions.

4.6 Discussion

We found 24 studies published between 1999 and 2024, among them 3 conference papers and 21 journal articles. Notably, no studies have investigated the cost-effectiveness of the target materials in their respective research endeavours. We also consolidated studies that focused on both 'sustainability' and 'energy efficiency' due to their overlapping topics and the use of shared terminology. According to the studies, we identified two additional themes, namely 'thermal

comfort' and 'insulation', frequently addressed due to their significant focus in the literature. Figure 4.6 illustrates the repetition rate of each topic/theme in the studies.

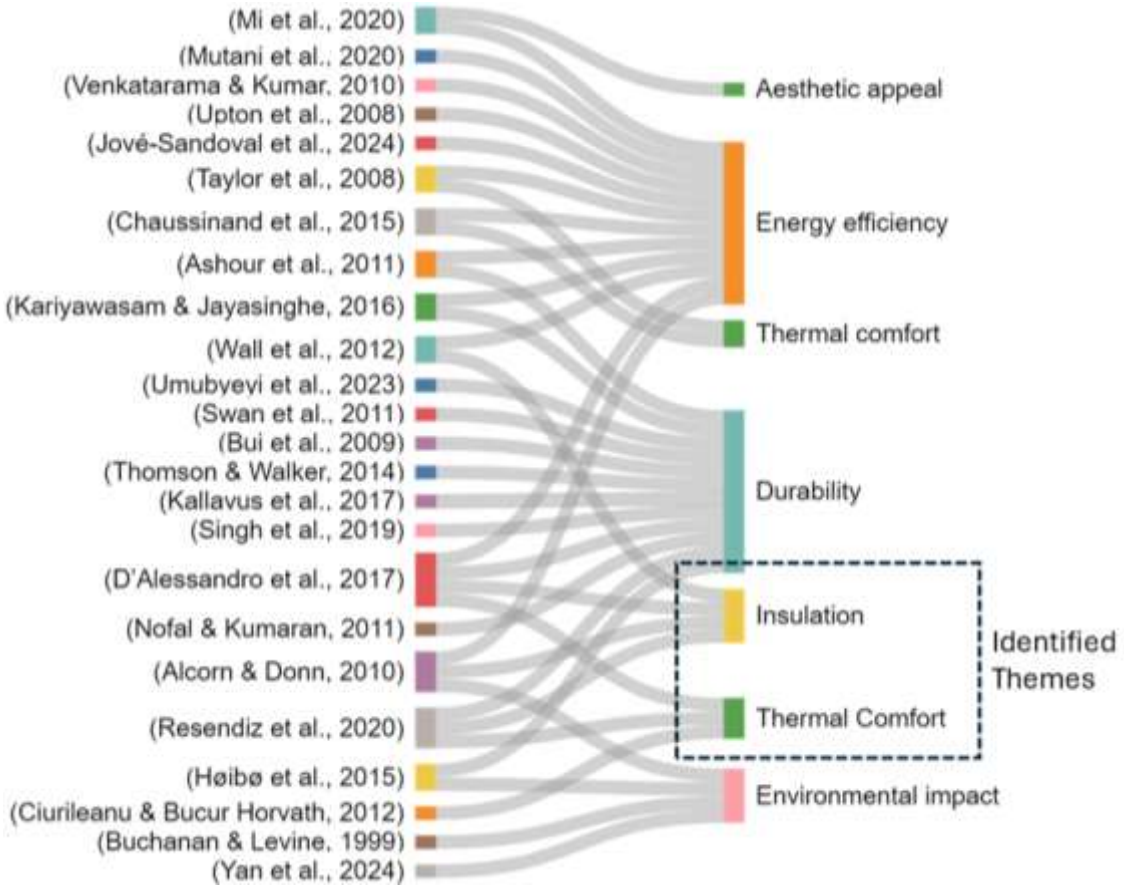


Figure 4.6: The frequency of topic/theme occurrence among the eligible articles (Source: the author)

While the study by Yan et al. (2024) provides valuable insights into the economic implications of material choices, it stands alone among the selected studies in addressing this aspect comprehensively. The dominance of wood and wood products in construction expenses highlights the need for further exploration into cost-effective alternatives, especially considering the increasing demand for sustainable building materials. Future research should aim to conduct more comprehensive cost-benefit analyses, considering not only material costs but also long-term maintenance and operational expenses to provide a holistic understanding of cost-effectiveness in sustainable construction.

Regarding durability, the selected studies offer valuable insights into the factors influencing the lifespan and resilience of construction materials. From the impact of environmental conditions on unsterilised rammed earth walls to the decay resistance of straw bales and the strength of cement, there remains a need for further research to standardise durability assessment

methodologies and expand the scope of the investigation to include emerging sustainable materials. Future studies could explore the synergistic effects of combining different materials for enhanced durability and resilience and investigate novel materials and construction techniques to address durability challenges in sustainable construction. The study Bui et al. (2009) examined rammed earth walls over a 20-year period in a wet continental climate, utilizing stereo-photogrammetry to measure erosion. It reported an average erosion depth of 2 mm (0.5% of wall thickness) for walls stabilised with 5% hydraulic lime and 6.4 mm (1.6% of wall thickness) for unsterilised walls. The international literature often notes wood's susceptibility to decay and termite damage, especially in warm, humid climates. However, advancements in treatment methods such as thermal modification and the use of preservatives have significantly improved wood's durability, making it a viable material for long-lasting construction. Studies from Finland (Samuel V. Glass & Zelinka, 2010) further support this, showing that properly treated wood can maintain durability comparable to more traditional materials like concrete or steel, especially in residential construction.

Regarding aesthetic appeal, the limited focus on this aspect in the selected studies underscores a gap in understanding the visual and sensory aspects of sustainable building materials. While Mi et al. (2020) offer insights into the fabrication and characterisation of transparent wood for smart building applications, more research is needed to explore the aesthetic potential of other sustainable materials. Future studies could investigate sustainable materials' design possibilities and aesthetic qualities and their integration into architectural and interior design practices to enhance visual appeal while maintaining environmental integrity.

Energy efficiency emerges as a key theme in the discussion of sustainable construction materials, with several studies highlighting the potential of materials like straw bales and Cement Stabilized Rammed Earth (CSRE) to contribute to energy conservation in buildings. Despite the comprehensive exploration of energy performance in the selected studies, future research could delve deeper into optimising energy efficiency through material selection, design strategies, and technological innovations. Additionally, there is a need for more rigorous assessments of energy performance under real-world conditions and long-term monitoring to validate the effectiveness of sustainable materials in reducing energy consumption and carbon emissions.

Environmental impact considerations are central to discussions on sustainable construction materials, yet only a few studies directly address this aspect in the selected literature. However, these findings of Høibø et al. (2015) underscore the complex interplay between durability

perceptions, environmental attitudes, knowledge levels, and past experiences in shaping consumer preferences for building materials in urban housing contexts. While insights from Høibø et al. (2015) and Alcorn and Donn (2010) shed light on material preferences and CO_2 emissions reduction strategies, there is a notable gap in understanding the holistic environmental impact of sustainable materials throughout their lifecycle. Future research should adopt a lifecycle assessment approach to quantify environmental impacts, including resource extraction, manufacturing, transportation, use, and end-of-life disposal, to inform more sustainable material choices and construction practices.

Energy efficiency is a critical factor driving the adoption of construction materials such as strawbale, wood, and rammed earth due to their sustainability benefits. Strawbales offer excellent thermal properties comparable to high-insulation materials, making them suitable for reducing energy consumption and CO2 emissions in building projects. Rammed earth, particularly when stabilised with cement, exhibits lower embodied energy than traditional materials like burnt clay bricks, contributing to improved thermal comfort and reduced energy demands. Wood-based construction materials also demonstrate promise with lower embodied energy and CO_2 emissions than concrete or steel systems, enhancing their appeal in residential buildings.

Recent studies underscore the thermal and energy performance advantages of strawbale, wood, and rammed earth in sustainable construction practices. Studies highlight the ability of straw bales to maintain thermal stability and reduce heat loss, meet regulatory standards for air permeability, and demonstrate insulation and fire resistance. Rammed earth, known for reducing indoor temperature fluctuations and energy consumption, shows significant potential when stabilised with cement. Wood-based materials exhibit lower environmental impacts and superior thermal performance than conventional building materials, supporting their use in energy-efficient residential construction. The challenges and benefits of using straw bale construction are highlighted, noting issues with summer overheating but showcasing efficient energy consumption and sustainability through innovative building techniques. Research explores the dynamic thermal behaviour of straw walls in different building prototypes, revealing thermal conductance variations and construction methods' impact on energy performance.

These findings collectively underline the potential of strawbale, wood, and rammed earth as environmentally friendly building materials that can significantly contribute to energy-efficient and sustainable building designs. Future research could focus on refining construction

techniques, optimising material properties, and addressing thermal performance challenges to further enhance these materials' viability and widespread adoption in global construction practices.

Energy efficiency drives the selection of sustainable construction materials like strawbale, wood, and rammed earth. These materials offer significant environmental benefits, such as reduced energy consumption and CO_2 emissions. Strawbales provide excellent thermal properties comparable to high-insulation materials, while rammed earth, particularly when stabilised with cement, exhibits lower embodied energy than traditional materials like burnt clay bricks. Wood-based construction materials show promise with lower environmental impacts and superior thermal performance compared to concrete or steel systems, supporting their use in energy-efficient residential buildings.

Two notable studies focus on the environmental impact of construction materials. One study highlights urban dwellers' preferences for non-wood materials in structural applications in Oslo, particularly among younger individuals favouring wood for cladding. The importance of assessing wood facades for environmental impact in urban housing development is emphasised, reflecting the growing interest in environmentally friendly building materials. Another study underscores the environmental benefits of using strawbale insulation and timber framing. It concludes that these materials can significantly reduce CO_2 emissions through carbon sequestration properties, contributing to sustainable construction practices. These findings underscore the growing recognition of environmental considerations in material selection, urging the building industry to prioritise sustainable alternatives for future urban housing development.

4.7 Conclusion

The primary aim of this study was to identify the best zero-carbon building materials in the construction industry. We focus on wood, rammed earth, and strawbales, evaluating them based on six key criteria: sustainability, cost-effectiveness, durability, aesthetic appeal, energy efficiency, and environmental impact. By examining these materials through these diverse lenses, our research aims to offer valuable insights for choosing the most suitable eco-friendly building components. Mostly, the term ‘sustainability’ is defined by thermal behaviour, energy performance, and life cycle assessment by the eligible articles we found. Therefore, we consider this in the field of energy efficiency. Key findings include:

- Durability Insights: The selected studies provide valuable insights into the durability of these materials, emphasizing the influence of environmental conditions on unsterilised rammed earth walls and the decay resistance of straw bales. While rammed earth walls can last over 20 years, future research is needed to standardise durability assessment methodologies and explore synergistic effects between different materials.
- Energy Efficiency: Energy efficiency is a prominent theme, with straw bales and CSRE demonstrating significant potential for reducing energy consumption and CO_2 emissions. Straw bales offer excellent thermal properties, while CSRE contributes to improved thermal comfort. The findings underscore the importance of rigorous assessments under real-world conditions to validate energy performance.
- Economic Considerations: Notably, there is a gap in research addressing the cost-effectiveness of these materials. While existing studies provide insights into the economic implications of material choices, further exploration is necessary to conduct comprehensive cost-benefit analyses that encompass both material costs and long-term maintenance expenses.
- Environmental Impact: Although the literature acknowledges the environmental benefits of using sustainable materials, there is a need for more in-depth lifecycle assessments to fully understand their impacts throughout production, use, and disposal. Future studies should adopt a lifecycle perspective to inform better material choices in sustainable construction.
- Aesthetic Appeal: The limited focus on the aesthetic aspects of sustainable materials presents a gap in understanding their visual and sensory qualities. Future research should investigate the integration of aesthetics in sustainable building practices to enhance their acceptance and appeal in architectural design.

Collectively, these findings affirm the potential of wood, rammed earth, and straw bales as environmentally friendly building materials that significantly contribute to energy-efficient and sustainable construction practices. Continued research is essential to refine construction techniques, optimise material properties, and address challenges related to durability and cost-effectiveness, ultimately supporting the wider adoption of these sustainable materials in the construction industry.

4.7.1 Future Gaps and Directions

Moving forward, several avenues for future research and development in sustainable construction materials emerge from the gaps identified in the existing literature. The studies

reviewed highlight significant advances in understanding the durability and performance of various sustainable construction materials under different environmental conditions. However, several critical gaps remain that warrant further investigation:

- Long-Term In-Situ Performance Evaluations: Future studies should focus on long-term assessments of these materials' performance across diverse climatic zones, especially under extreme weather events. This aligns with our findings that the durability of materials like unsterilised rammed earth is influenced by environmental factors, necessitating real-world data to validate their performance.
- Cost-Effectiveness Analysis: The reviewed studies indicate a lack of research on the cost-effectiveness of using sustainable materials in the construction sector. Our findings stress the need to investigate not only the initial material costs but also the long-term operational and maintenance costs associated with materials such as wood, rammed earth, and straw bales. We recommend developing a comprehensive framework to assess cost-effectiveness by considering multiple factors, including:
- Initial Material Costs: Including production, transportation, and installation costs.
- Operational and Maintenance Costs: Analysing long-term energy savings, maintenance needs, and repair/replacement costs throughout the building's life cycle.
- Cost-Benefit Analysis: Conducting in-depth comparisons between traditional and sustainable materials to account for energy savings, environmental benefits (e.g., CO2 reduction), and any government incentives for green building.
- Aesthetic Appeal: The aesthetic appeal of sustainable materials should also be investigated, as our review indicated limited focus on this aspect. Understanding how these materials can be effectively integrated into design practices is essential for broader acceptance in the market.
- Case Studies and Field Experiments: Future research should include conducting case studies and field experiments to gather real-world data on the economic performance of these materials under various climatic and market conditions. This will provide a more holistic understanding of how materials perform not only environmentally but also economically over the long term.

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STATEMENT OF CONTRIBUTION DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the student and the student's main supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the student's contribution as indicated below in the Statement of Originality.

Student name:	Ali Hashemi Araghi
Name and title of main supervisor:	Dr Eziaku Onyeizu Rasheed
In which chapter is the manuscript/published work?	Chapter 5

Describe the contribution that the student and members of the supervisory team have made to the manuscript/published work:[1]

Conceptualization, A.H.A.; methodology, A.H.A.; software, A.H.A.; validation, A.H.A.; formal analysis, A.H.A.; investigation, A.H.A.; resources, A.H.A.; data curation, A.H.A.; writing—original draft preparation, A.H.A.; writing—review and editing, A.H.A., E.O.R., V.V. and J.S.; visualization, A.H.A.; supervision, E.O.R., V.V. and J.S.; project administration, A.H.A.; funding acquisition, E.O.R., V.V. and J.S. All authors have read and agreed to the published version of the manuscript.

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Chapter 5: Factors Selection

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

Araghi, A. H., Rasheed, E. O., Vishnupriya, V., & Seadon, J. (2025). Identifying Key Factors Influencing the Selection of Sustainable Building Materials in New Zealand. *Sustainability*, *17*(20), 9071. https://doi.org/10.3390/su17209071

5.1 Chapter Summary

This chapter investigated the key factors influencing the selection of zero-carbon building materials in the New Zealand construction industry and assessed the perceived suitability of four alternative materials: wood, hemp, rammed earth, and straw bale. Recognising the growing importance of embodied carbon reduction in achieving national and international climate targets, the research focused on understanding how industry professionals balance environmental, technical, and practical considerations when selecting sustainable materials.

A quantitative survey was conducted with 203 construction professionals, including engineers, architects, contractors, and building consultants. Six decision-making factors were examined: cost-effectiveness, durability, buildability, embodied carbon, material availability, and aesthetics. The data were analysed using descriptive statistics, one-sample t-tests, and Partial Least Squares SEM to identify both the relative importance of these factors and their influence on material adoption.

The results showed that cost-effectiveness and durability were rated as the most important selection criteria, followed by buildability. Embodied carbon and material availability received moderate importance, while aesthetics was consistently ranked as the least influential factor. In terms of material suitability, wood was perceived as the most appropriate zero-carbon material for the New Zealand context, followed by hemp, with rammed earth and straw bale viewed as less suitable due to concerns regarding practicality and mainstream adoption.

SEM revealed that embodied carbon and material availability were the strongest predictors of zero-carbon material adoption, indicating that environmental performance and supply accessibility play a more decisive role in adoption decisions than cost or aesthetics once multiple factors are considered. These findings highlight a shift toward more sustainability-driven decision-making within the New Zealand construction sector.

Chapter 5 builds directly on the evidence and research gaps identified in Chapter 4. Chapter 4 examined the performance of low- and zero-carbon materials and identified recurring themes

concerning durability, energy efficiency and environmental impact, together with gaps relating to cost-effectiveness and aesthetics. These findings demonstrated that environmental performance alone could not explain material-selection decisions and that practical considerations also required empirical examination. Accordingly, Chapter 5 translates and extends the literature findings into six decision-oriented constructs: cost-effectiveness, durability, buildability, embodied carbon, availability and aesthetics. The survey did not generate these factors independently; rather, it evaluated and prioritised the literature-informed criteria and examined their relationships with the perceived suitability of zero-carbon materials among New Zealand construction professionals.

5.2 Introduction

The construction sector plays a central role in global climate change, accounting for nearly 37% of energy-related carbon dioxide emissions (Hashemi Araghi & Sakhaee, 2014; Huang et al., 2018). A substantial portion of this footprint is attributed to embodied carbon, which encompasses the greenhouse gas emissions generated during the production, transportation, and installation of construction materials (Myint et al., 2025). Addressing embodied carbon is therefore a critical step toward achieving net-zero targets and reducing the overall environmental burden of buildings (Lützkendorf & Balouktsi, 2022; Röck et al., 2023). One of the most direct strategies for achieving this is the selection of zero-carbon building materials, which not only reduces emissions but also supports energy efficiency, enhances indoor environmental quality, and promotes long-term resilience (Araghi et al., 2024; Tazmeen & Mir, 2024).

The Building Research Association of New Zealand (BRANZ) estimates that buildings account for approximately 20% of the country's total greenhouse gas emissions, including both operational and embodied carbon (United Nation, 2022). Despite government initiatives such as the 2050 Net-Zero Carbon Strategy and commitments under the Paris Agreement, the construction sector continues to face significant challenges(Climate Change Comission, 2023). New Zealand's geographical isolation, heavy reliance on imported materials, and fragmented supply chains limit the availability of zero-carbon alternatives, while fluctuating costs and regulatory complexities add further constraints (Qian et al., 2024). These challenges highlight the need for context-specific insights into how material selection decisions are made and how sustainable practices can be better integrated into the local construction ecosystem (Dhawan et al., 2022).

While several studies have investigated frameworks for selecting zero-carbon building materials, very limited research has focused specifically on New Zealand's construction industry and its unique sustainability challenges. Bui et al. (2021) conducted exploratory semi-structured interviews with government representatives and construction industry experts in Aotearoa, New Zealand, and highlighted that there has been no detailed investigation of zero-carbon building practices in the country, underscoring the early stage of transition and the scarcity of in-depth, localised studies. Most existing models adopt globalised perspectives that do not adequately account for local constraints, such as supply chain dependencies, indigenous cultural considerations, or regulatory frameworks. Qian et al. (2024) addressed this gap by identifying and prioritising 30 critical criteria—including environmental, technical, economic, and social factors, specifically tailored to New Zealand's construction industry, demonstrating the inadequacy of generic global frameworks and the importance of locally contextualised models.

Little empirical evidence exists on how industry professionals in New Zealand perceive the trade-offs among cost-effectiveness, durability, buildability, aesthetics, availability, and embodied carbon when selecting materials. A recent empirical study by Bui et al. (2025) surveyed 115 New Zealand industry professionals using SEM to examine interrelations among social, economic, environmental, and technical decision-making factors. While their findings emphasise the importance of technical factors, they also point to gaps in understanding specific trade-offs such as durability, aesthetics, and embodied carbon. Finnie et al. (2024) investigated current practices for calculating and reducing embodied carbon in New Zealand commercial construction. They found that most industry professionals lacked experience, that embodied carbon assessments were rare, and were hindered by insufficient tools, client support, and lack of early cost data, factors that limit strategic decision-making and policy development.

Considering these critical observations, this research seeks to address the following pivotal questions: i) What are the primary factors influencing the selection of building materials in New Zealand? ii) How do these identified factors correlate with the carbon footprint associated with the materials? And iii) Which materials are most suitable for effectively reducing carbon emissions within New Zealand?

This study addresses these gaps by focusing on six decision-making factors, including cost-effectiveness, durability, buildability, embodied carbon, availability, and aesthetics, and by evaluating the perceived suitability of four zero-carbon materials: wood, hemp, rammed earth, and straw bale. Using a survey of 203 construction professionals, analysed through descriptive

statistics, one-sample t-tests, and SEM, the study identifies the relative importance of these factors and their influence on material adoption. The research makes two primary contributions. First, it provides the first empirical evidence from New Zealand on zero-carbon material selection, thereby contextualising international sustainability debates within a localised construction environment. Second, it advances the literature by integrating multiple evaluation criteria with robust quantitative methods, generating insights for policymakers, designers, and suppliers on how to overcome barriers and accelerate the adoption of zero-carbon materials. Importantly, the outcomes of this study align closely with multiple United Nations Sustainable Development Goals (SDGs), including SDG 9 (Industry, Innovation, and Infrastructure), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

5.3 Literature Review

Globally, the construction sector is a major contributor to climate change, accounting for roughly 37% of energy-related carbon emissions (Aeinehvand et al., 2021; UNEP, 2022). In response, there is a growing emphasis on sustainable building material selection as a key strategy to reduce the environmental footprint of buildings (Baghaei Daemei & Jamali, 2022; Chen et al., 2024). A wide range of research highlights that choosing eco-friendly materials, those with lower embodied carbon, higher energy efficiency, and minimal lifecycle impacts, is pivotal in making construction more sustainable (Abera, 2024). However, identifying and selecting suitable sustainable materials is a complex decision-making process involving many factors (Akadiri, 2015).

Recent studies underscore that designers and engineers face challenges balancing environmental performance with practical criteria such as cost, durability, and availability (Bui et al., 2025; Rasheed et al., 2024). Given these challenges, it is important to establish a clear understanding of zero-carbon construction goals and standards. The World Green Building Council defines a zero-carbon building as an exceptionally efficient structure powered by renewable energy sources, both on-site and off-site (Lou & Hsieh, 2024). While these aspirations are undeniably appealing, the journey toward zero-carbon or net-zero carbon construction is frequently complicated by intricate challenges, particularly within sustainability and environmental considerations. For instance, even as the construction process strives for reduced emissions, conventional materials like steel, aluminium, and concrete, ubiquitously employed in construction are collectively responsible for a substantial 23% of global carbon dioxide emissions (Arenas & Shafique, 2024). New Zealand is firmly committed to curtailing

its carbon dioxide emissions to align with the 2050 targets established by the United Nations and its government. A pragmatic approach to realising this objective involves the expanded utilisation of locally sourced and manufactured materials in constructing zero-carbon buildings.

By embracing locally procured, zero-carbon building practices over the long term, New Zealand can progressively fulfil its national ambitions for economic, environmental, and social sustainability. Building on these sustainable construction strategies, it is essential to examine the role of specific zero-carbon materials that can support these objectives in practice. Hempcrete has emerged as a highly promising zero-carbon building material due to its low embodied carbon, strong thermal and hygrothermal performance, and carbon sequestration ability. A 2025 review by Tong and Memari (2025) offers a comprehensive evaluation of hempcrete's formulation, construction applications, mechanical properties, thermal behaviour, cost, environmental impact, and overall sustainability potential.

Complementing this, Ansari et al. (2025) reviews hemp concrete specifically as a zero-carbon material, emphasizing its low carbon footprint and lifecycle advantages. Experimental studies further highlight hempcrete's hygrothermal benefits: Hrčka et al. (2025) investigates its moisture diffusion and thermal insulation properties in building envelopes. Together, these works make hempcrete a compelling choice when evaluating thermal performance, embodied carbon, moisture regulation, and sustainability as selection criteria.

Straw bale construction is notable for its exceptional insulation, low embodied energy, and significant carbon reduction potential. Yin et al. (2023) review multiple benefits of straw-bale houses including lower embodied energy and CO_2 emissions than conventional construction, high thermal performance, and strong fire resistance. Life-cycle impact assessments of load-bearing straw bale buildings further validate its environmental advantages, capturing both ecological and operational benefits across the building's service life (Vanova et al., 2021). Mehravar et al. (2022) quantifies this performance more directly, reporting that using straw bale in buildings can cut embodied carbon by up to 76% compared to conventional methods. Earlier work by (Sodagar et al., 2011) also underscores straw bale's capacity to lower whole-life CO_2 emissions in housing.

Rammed earth offers a sustainable alternative characterised by low embodied energy, thermal mass for passive heating and cooling, and high local material availability. Scoping studies highlight that structures using rammed earth achieve lower life-cycle energy consumption and environmental impact through sustainable sourcing and construction techniques (MBIE, 2022).

Halit Alkadri and ÇEtİN (2021) further explores its carbon reduction potential by analysing the embodied energy during material production, transportation, and construction stages. Nouri et al. (2021) Life cycle comparisons between rammed earth and traditional materials such as fired clay bricks reveal that rammed earth outperforms in terms of lower embodied CO_2 emissions. Practical guidance on material preparation is offered by Burroughs (2010), who provides recommendations on soil selection, stabilizer treatment, and compaction to optimize environmental and structural performance.

Wood, particularly in the form of engineered wood products and timber-framed systems, stands out as a low-carbon construction material owing to its carbon sequestration, lower embodied emissions, and high strength-to-weight ratio. Governmental analysis of New Zealand residential buildings finds that timber framing offers inherently low embodied carbon even excluding biogenic stored carbon, indicating a limited yet significant decarbonization potential (MBIE, 2022). Research has increasingly focused on materials such as bamboo, engineered timber, recycled composites, and low-carbon concrete mixtures, to highlight their reduced carbon and energy footprints (Abera, 2024). Yet, economic limitations such as cost competitiveness remain a significant barrier for these zero-carbon materials.

In New Zealand the drive toward zero-carbon building materials is influenced by several distinctive factors that set it apart from global trends. The country's geographical isolation and limited domestic manufacturing base mean it relies heavily on imported construction materials (Reuters, 2024). This reliance creates vulnerabilities in supply chains and can hinder the ready availability of novel sustainable materials. Recent supply disruptions revealed how dependence on imports can lead to cost spikes and delays in the construction sector (Building Institute Aotearoa, 2021).

Beyond cost and environmental performance, zero-carbon materials must also meet essential structural and safety requirements. Global studies stress evaluating compressive/tensile strength, fire resistance, and longevity of alternatives like straw bale, hempcrete, or rammed earth to ensure they perform comparably to conventional materials (Janowska-Renkas et al., 2025). These supply chain challenges highlight the importance of exploring zero-carbon materials that not only reduce emissions but also enhance sustainability and resilience.

Zero-carbon materials are generally characterised by less energy consumption and fewer emissions than their conventional counterparts (Figueiredo et al., 2021a). This reduced carbon footprint at the manufacturing and transportation stages of products and goods is directly

connected to decreased total carbon emissions. Eco-friendly materials usually imply a reduction in the energy used by buildings and later reduce the emissions related to heating and cooling (World Green Building Council, 2021). Moreover, most zero-carbon materials are manufactured to be efficient in energy consumption. An active policy should promote the desirability of utilising locally available zero-carbon construction material supplies for construction projects. This supports international goals, specifically those expressed within the UN climate action program and the Paris Agreement.

As such although numerous studies have examined the properties of zero-carbon materials such as hempcrete, straw bale, rammed earth, and timber, most focus on isolated performance aspects like thermal efficiency or embodied carbon while overlooking the interplay of multiple selection criteria such as cost, availability, buildability, and regulatory constraints. Furthermore, there is limited research that integrates these factors into a holistic framework tailored to New Zealand's unique context, where geographical isolation and supply chain challenges complicate material choices. This gap highlights the need for the present study, which empirically evaluates the key factors influencing the selection of four zero-carbon materials to support sustainable construction strategies in New Zealand.

5.4 Methodology

This study used a quantitative survey-based methodology to identify and assess the key factors influencing the selection of sustainable building materials in New Zealand. Aligned with the study's objectives, this study focused on: (1) identifying the most influential material selection factors, (2) examining how these factors relate to the carbon footprint of materials, and (3) determining which materials are best suited to support zero-carbon construction. The methodology included the development of a structured questionnaire, purposive sampling of construction professionals, and the use of statistical analysis techniques, including t-tests and SEM, to analyse responses and validate the proposed model. The following subsections outline the survey design, participant selection, data collection, and data analysis procedures.

The selection of evaluation criteria for sustainable building materials was built on a systematic literature review titled *"Zero-carbon building materials in New Zealand context"* This review synthesised existing research and policy reports to identify key factors influencing sustainable material selection within New Zealand's construction sector. Based on the preceding literature review and the targeted material-selection literature, six a priori constructs were established for empirical evaluation: cost-effectiveness, durability, buildability, embodied carbon, availability,

and aesthetics. These constructs were specified before data collection; the survey was subsequently used to evaluate and prioritise them rather than to generate new factors.

5.4.1 Identifying the Population and Designing the Sample Size

Participants were eligible for inclusion if they: (1) were aged 18 years or older; (2) had current or previous professional experience in the New Zealand building and construction sector; (3) worked in a role involving, or providing relevant familiarity with, building-material evaluation, specification, procurement, approval or application; (4) had sufficient knowledge of material-selection practices to complete the questionnaire meaningfully; and (5) provided informed consent.

Individuals were excluded if they had no professional experience in the New Zealand construction sector, lacked relevant familiarity with building-material selection, did not provide informed consent, submitted a duplicate response or returned a substantially incomplete questionnaire.

The achieved sample was geographically concentrated. Of the 203 respondents, 190 were based in Auckland (93.6%), nine in Wellington (4.4%), two in Christchurch (1.0%), and two in Tauranga (1.0%). The sample was also professionally imbalanced, with engineers representing 73% of respondents. Consequently, although participants had relevant construction-sector experience, the sample should not be interpreted as geographically or professionally representative of the New Zealand construction industry. The findings primarily reflect the perceptions of the participating professionals, particularly Auckland-based engineers.

A purposive sampling strategy was used because the study required responses from professionals familiar with construction materials and material-selection decisions. Potential respondents were recruited through professional associations, construction-industry events, direct contact with firms and consultants, and targeted online distribution. Before participation, potential respondents confirmed their professional role and involvement in the construction sector. Individuals without relevant construction-sector experience or familiarity with material-selection practices were not included.

The questionnaire contained 16 observed items. Based on the commonly applied guideline of 5–10 respondents per observed item (Hair, 2009; Kline, 2023), the recommended sample size ranged from 80 to 160 participants. The final analytical sample comprised 203 valid responses, equivalent to approximately 12.7 respondents per observed item, and therefore exceeded this recommendation. An a priori power analysis was also conducted using a significance level of α

= 0.05, statistical power of 0.80 and a medium effect size. The analysis indicated that the achieved sample was adequate for the statistical analyses undertaken in this study.

Recruitment occurred through professional associations, industry events, and targeted outreach to construction firms and consultants. In total, 266 surveys were distributed: 60 online (15% response rate) and 206 in person (94% response rate). The overall response rate was 76% (203 valid responses). While the high in-person response reduced concerns of low engagement, potential non-response bias was mitigated by comparing demographic characteristics of respondents and non-respondents, which revealed no significant discrepancies in professional role or years of experience.

In addition to sample-to-item ratio guidance, statistical power analysis was considered. A power level of 0.80 and a significance level of $\alpha = 0.05$ are commonly recommended for social science research (Cohen, 2013). Assuming a moderate effect size ($f^2 = 0.15$) and 5–6 latent constructs, the minimum required sample size using G*Power software for multiple regression (a proxy for SEM models) falls between 100 and 120 participants. With that said, the study meets the minimum power requirements for detecting medium-sized effects in SEM, supporting the validity of subsequent model estimation and hypothesis testing.

The participants were those who belonged to the construction and building sector, and their professional interests enabled them to provide input on the selection of materials, offering informed viewpoints on the various issues to be considered, including aesthetics, structural integrity, sustainability, and cost-effectiveness (Joshi et al., 2015). The inclusion criteria required at least five years of experience working in the construction sector, particularly in sustainable design and materials. We also placed no restrictions on geographical area or the nature of projects, so the variety of experiences was high.

The respondents were requested to verify their relevant construction sector experience before administering the survey. Only eligible individuals received invitations after confirming their qualifications. Consequently, we collected information from professionals such as architects, engineers, and contractors, preserving the data quality. This initial screening process added credibility and focus to the information about sustainable building materials.

Surveys were distributed across different regions in New Zealand to determine whether there were any regional variations in the choice of construction materials. This data collection activity lasted eight weeks, during which respondents could complete the survey at their convenience.

Allowing construction professionals to complete the questionnaire at their convenience helped reduce time pressure during participation.

In the first section of our five-part questionnaire, we sought to collect relevant demographic and background data from participants in the New Zealand construction industry. This section was aimed at helping us contextualize survey responses by capturing the respondents' professional roles and experience levels. The survey began by asking respondents to state their roles in the construction industry: engineer (N=148), architect (N=35), contractor (N=11), client (N=6), building manager (N=2), and others (N=1). These background data formed a source of analysis based on how professional background may influence attitudes towards green building practices (see Table 5.1).

Table 5.1: The summary of the participants' role in the construction industry

Participants' role	Percentage
Architect	17%
Engineer	73%
Contractor	6%
Building Manager	1%
client	3%

While engineers represented 73% of the sample, this reflects their strong presence in the zero-carbon building materials sector in New Zealand and their central role in material selection decisions. Other professional categories, including architects, contractors, clients, and building managers, were also represented to ensure a range of perspectives. The small proportion of participants with over 20 years of experience aligns with current workforce demographics, where mid-career professionals dominate. Furthermore, the statistical techniques applied (including SEM and one-sample t-tests) are robust to subgroup imbalances, focusing on sector-wide trends rather than subgroup-specific effects. The distribution of respondents based on their years of experience in the NZ construction industry was as follows: 21% of participants had less than 1 year of experience, 48% had between 1 and 5 years, 19% had 5 to 10 years, 11% had 10 to 20 years, and only 1% had over 20 years of experience, as seen in Table 5.2.

Table 5.2: Years of experience among participants

Years of experience	Number of participants
Less than 1 year	43
1-5 years	95
5-10 years	39
10-20 years	22
Over 20 years	4

Additionally, respondents were asked to specify their location from a list of central New Zealand cities, including Auckland (N=190), Wellington (N=9), Christchurch (N=2), and Tauranga (N=2).

5.4.2 Designing and Piloting the Questionnaire

The questionnaire was developed based on prior literature on sustainable material selection and refined through expert review by three academics in construction management and two industry professionals. A pilot test with 12 practitioners ensured clarity and usability. Construct validity was established through Confirmatory Factor Analysis (CFA), with all factor loadings exceeding 0.70. Reliability was confirmed using Cronbach's α and Composite Reliability (CR), which ranged between 0.79 and 0.89 across constructs, surpassing the recommended 0.70 threshold. Convergent validity was supported by Average Variance Extracted (AVE) values above 0.50, while discriminant validity was established through the Fornell-Larcker criterion and HTMT ratio.

The questionnaire was designed to evaluate six factors (i.e. cost effectiveness, cost effective, durability, buildability, embodied carbon, availability, and aesthetics) identified in the literature review, using multiple items for each domain. To ensure content validity and contextual appropriateness, the draft questionnaire was reviewed by six construction professionals in New Zealand during a pilot phase. Feedback focused on clarity, terminology, and coverage of the constructs. The final version was then distributed for formal data collection.

This questionnaire was designed with closed-ended questions. Using a5-point Likert-type response scale (1 = strongly disagree, 5 = strongly agree). The 5-point Likert scale provides a good balance between simplicity and granularity. It also reduces the likelihood of participant fatigue and helps maintain the reliability and ease of interpreting the collected data (Kusmaryono et al., 2022).

The primary justification for this methodological choice was our interest in collecting quantifiable data that could be statistically analysed to identify and understand the factors influencing the choice of building materials. The closed-ended question technique was utilised because it aids in standardizing responses, making them more uniform and comparable across all respondents (Louis M. Rea & Richard A. Parker, 2014).. The questions focus on identified key material selection criteria in the literature review namely cost-effectiveness, durability, buildability, embodied carbon, availability, and aesthetic value. Furthermore, participants were asked to rate selected building materials, wood, hemp, rammed earth, and straw bale.

5.4.3 Ethical Considerations

This research was conducted strictly according to the ethical guidelines and established standards of Massey University. The study underwent a thorough review and received approval from the Massey University Human Ethics Committee, under approval number 4000027896. Prior to data collection, all participants were comprehensively informed about the study's purpose, the nature of their involvement, and their rights. Informed consent was meticulously obtained from every participant. All collected data were securely stored and used exclusively for this study. The research consistently adhered to all ethical principles, ensuring the study's integrity and demonstrating profound respect for all individuals involved.

Data collection followed ethical approval from Massey University. Surveys were administered either online or face-to-face at professional events, with informed consent obtained from all participants. Of the 203 valid responses, less than 2% of item-level data were missing. Missing responses were handled using mean imputation, given the low rate of missingness and the assumption of randomness, which is consistent with best practice in survey research.

The survey was administered using a dual-mode approach to maximise participant reach and enhance response quality. An online questionnaire was distributed via SurveyMonkey to a curated list of 60 professionals, while printed surveys were distributed in person during industry forums, workshops, and other sector-specific events across New Zealand. This mixed-method strategy ensured broad coverage of the construction industry and allowed respondents flexibility in completing the survey. Participation rates varied significantly across the two modes. The online survey achieved a response rate of 15% (9 out of 60), which aligns with typical response rates reported for voluntary web-based surveys targeting professionals (Norman, 2010a; Rea & Parker, 2014). In contrast, the in-person approach produced a 94% completion rate (194 out of 206), owing to direct engagement opportunities and the ability to clarify queries during distribution. The combined overall response rate was 76%, which far exceeds the 50% threshold commonly recommended for social science survey research to ensure representativeness and minimise non-response bias (Cohen, 2013; Hair, 2009).

This high overall response rate also compares favourably with prior studies in the construction and sustainability domains, where rates above 60% are considered sufficient for robust inference (Bui et al., 2025; Figueiredo et al., 2021b). Given that 203 valid responses were collected from qualified professionals directly involved in design, procurement, and sustainable material selection, the dataset provides a statistically adequate foundation for SEM and hypothesis testing. Furthermore, the diverse professional backgrounds of respondents,

including engineers, architects, contractors, and sustainability consultants, enhance the generalisability of the findings across the New Zealand construction sector. The aggregated response rate, combining both distribution methods, is presented in Table 5.3.

Table 5.3: The survey's response rate

Survey Administration Method	Surveys Invited	Completed Surveys	Response Rate (%)
Online (SurveyMonkey)	60	9	15%
In-person	206	194	94%
Total	266	203	76%

5.4.4 Methods of Data Analysis

Data were analysed using a combination of descriptive statistics, inferential tests, and Partial Least Squares SEM (PLS-SEM). All statistical procedures were performed using SPSS (for descriptive and t-tests) and SmartPLS software (for SEM analysis). Descriptive statistics were first used to summarise demographic information and the distribution of responses across all questionnaire items. To assess differences in perceptions between respondent subgroups (e.g., based on role or experience), independent samples t-tests were employed. Although Likert scale data are ordinal, existing research (e.g., Norman, 2010) supports the application of parametric tests such as the t-test in larger sample contexts, given their robustness and interpretability. The core analytical technique employed was PLS-SEM, selected for its suitability in exploratory models, complex path structures, and small-to-moderate sample sizes. PLS-SEM was used to validate the measurement model and test the structural relationships among the latent variables.

The measurement model was assessed using standard PLS-SEM evaluation criteria to ensure the constructs were both reliable and valid. Indicator reliability was examined through outer loadings, which represent the correlation between each item and its respective construct. Loadings above 0.70 indicate that an item contributes substantially to measuring the construct, as values above this threshold suggest that more than 50% of the variance is explained by the construct (Hair Jr et al., 2021). In this study, all indicators exceeded this threshold, confirming satisfactory indicator reliability.

Internal consistency reliability was assessed using both Cronbach's Alpha and Composite Reliability (CR). Cronbach's Alpha measures the internal consistency of items, while CR provides a more precise estimate as it considers indicator loadings in the calculation. Threshold values of ≥ 0.70 are generally considered acceptable for both measures (Raykov & Marcoulides, 2011). In this study, Cronbach's Alpha and CR values ranged between 0.79 and 0.89, confirming

strong internal consistency across all constructs. Convergent validity was evaluated using the Average Variance Extracted (AVE), which measures the extent to which a construct explains variance in its indicators. An AVE value ≥ 0.50 indicates that the construct explains more than 50% of the variance in its associated items (Fornell & Larcker, 1981). All constructs in this study exceeded this benchmark, confirming satisfactory convergent validity. Finally, discriminant validity was assessed using two established methods: the Fornell-Larcker criterion and the Heterotrait-Monotrait ratio (HTMT). The Fornell-Larcker criterion requires that the square root of each construct's AVE be greater than its correlations with other constructs, ensuring clear conceptual separation (Ullman & Bentler, 2012). In addition, the HTMT ratio provides a more stringent assessment, with values below 0.85 (or 0.90 in some contexts) considered acceptable (Henseler et al., 2015). Both criteria were satisfied in this study, confirming that the constructs are empirically distinct and measure unique concepts.

All item loadings exceeded the recommended threshold of 0.70, demonstrating satisfactory indicator reliability. Items with loadings above 0.70 are considered to contribute to the respective construct. Internal Consistency Reliability: Cronbach's Alpha and Composite Reliability (CR) values for all constructs ranged between 0.79 and 0.89, indicating strong internal consistency (threshold > 0.70). Convergent Validity: The Average Variance Extracted (AVE) for all constructs exceeded the 0.50 benchmark, confirming that each construct captures more than 50% of the variance in its indicators. These results confirm that the measurement model is reliable and valid, and therefore appropriate for testing the structural relationships among the latent variables.

Discriminant validity was assessed to ensure that each construct was empirically distinct from the others. Two commonly used criteria were applied: the Fornell–Larcker criterion and the HTMT. Using the Fornell–Larcker criterion (Fornell & Larcker, 1981), the square root of the AVE for each construct was compared against its correlations with all other constructs. In all cases, the square root of AVE for a given construct was greater than its highest correlation with any other construct. This confirms that each construct shares more variance with its own indicators than with other constructs in the model, indicating satisfactory discriminant validity. Additionally, the HTMT ratio of correlations was calculated to further validate discriminant validity. All HTMT values were below the conservative threshold of 0.85, as recommended by Henseler et al. (2015). This further supports the conclusion that the constructs are distinct and non-redundant. Together, these results provide strong evidence of discriminant validity across all constructs, supporting the robustness of the measurement model.

To summarise participants' responses and provide an overview of central tendencies and variability, descriptive statistics were calculated. Specifically, mean scores, standard deviations (SD), and standard errors of the mean were used to evaluate the relative importance of each selection criterion and to compare perceptions across the identified zero-carbon materials. These measures offered a preliminary understanding of the data distribution before conducting inferential tests and structural modelling.

5.4.5 Data Analysis Approach

The six constructs included in the SEM, cost-effectiveness, durability, buildability, embodied carbon, availability, and aesthetics, were derived from the literature review and operationalised through the questionnaire. They were included in the model to assess their measurement properties and estimate their conditional relationships with perceived material adoption. The SEM path coefficients were not interpreted as decision weights because they are regression-type estimates influenced by model specification, covariance among predictors, and the selected dependent variable. Consequently, they indicate the strength of statistical associations but do not directly represent the relative importance assigned to the criteria by practitioners.

In this study, a power analysis was performed before data collection to determine an adequate sample size for detecting the anticipated effect. G*Power software was utilised to determine the required sample size (Mishra et al., 2019). Following Cohen's guidelines, the effect size for the correlation tests was set at $r = 0.30$, indicating a medium effect size (Mertler et al., 2021; Norman, 2010a). With an alpha level of 0.05, the desired statistical power was set at $(1 - \beta) = 0.80$, indicating an 80% probability of detecting the specified effect if it truly existed (Fan et al., 2016). The power analysis indicated that, to reliably detect a medium-sized effect, at least 85 participants were required. Meeting this power criterion reduces the likelihood of Type II error and provides an adequate basis for detecting the specified effect.

PLS-SEM was used to assess the measurement properties of the six literature-derived constructs and estimate their conditional relationships with the material-adoption outcome. The standardised path coefficients therefore indicate the strength of association between each predictor and the outcome while controlling for the other predictors in the structural model. These coefficients were not treated as criterion-importance weights in the DST.

The "path-weighting scheme" in SmartPLS refers to the internal algorithm used to estimate latent-variable scores. It should not be confused with the criterion weights subsequently used

in the weighted-sum decision model. Criterion weights for the DST were derived separately from respondents' direct importance ratings, as explained in Section 7.3.2.d Type II errors, thereby enhancing the quality and rigor of the study's findings.

An additional PLS-SEM analysis was conducted to examine the relationship between the two principal variable domains. The first composite, Selection Criteria Importance (SCI), comprised cost-effectiveness, durability, buildability, embodied carbon, availability, and aesthetics. The second composite, Perceived Material Suitability (PMS), comprised the ratings of wood, hemp, rammed earth, and straw bale. Both were specified as formative composites because their indicators represent distinct components rather than interchangeable manifestations of reflective constructs. A direct path was estimated from SCI to PMS. The following hypothesis was tested:

> **H1:** Selection Criteria Importance is significantly associated with Perceived Material Suitability.

The model was estimated in SmartPLS 4 using the path-weighting scheme. Statistical significance was assessed using two-tailed bootstrapping with 5,000 resamples. The formative measurement models were evaluated using outer VIF values, outer weights, outer loadings, and bootstrapped confidence intervals. The structural model was evaluated using the standardised path coefficient, 95% confidence interval, p-value, R^2, adjusted R^2, and f^2. The relationship was interpreted as associative rather than causal because the data were cross-sectional.

Table 5.4: SEM Results for the Indicators of Selection Criteria Importance and Perceived Material Suitability

Major variable	**Indicator**	**Standardised coefficient (β)**	***t*-statistic**	**Significance**
Selection Criteria Importance	Cost-effectiveness	0.132	8.803	$p < 0.001$
Selection Criteria Importance	Durability	0.156	10.792	$p < 0.001$
Selection Criteria Importance	Buildability	0.260	17.226	$p < 0.001$
Selection Criteria Importance	Embodied carbon	0.397	18.651	$p < 0.001$

Selection Criteria Importance	Availability	0.368	18.695	$p < 0.001$
Selection Criteria Importance	Aesthetics	0.342	14.581	$p < 0.001$
Perceived Material Suitability	Wood	0.093	5.507	$p < 0.001$
Perceived Material Suitability	Hemp	0.373	20.600	$p < 0.001$
Perceived Material Suitability	Rammed earth	0.365	18.270	$p < 0.001$
Perceived Material Suitability	Straw bale	0.361	18.126	$p < 0.001$
Structural relationship	Selection Criteria Importance → Perceived Material Suitability	Not available	Not available	Not tested

5.4.5.1 Descriptive Statistics

Besides the t-test, descriptive statistics were also calculated, including the averages, standard deviation, and standard error of the mean, to represent both the central measures and the range in the respondents' ratings of each element (Desai & Reimers, 2019).

5.4.5.2 Structural Equation Modelling (SEM)

Data analysis was conducted using Partial Least Squares PLS-SEM with SmartPLS 4. The path-weighting scheme was applied, and model identification was achieved with sufficient indicators per construct. To assess model fit, the following indices were reported: CFI = 0.982, TLI = 0.974, RMSEA = 0.046, and SRMR = 0.052, all indicating an acceptable fit. Multicollinearity was checked via VIF values, all of which were below 5, confirming no serious collinearity issues. Sensitivity analyses were conducted by testing alternative model specifications, which produced consistent results, strengthening the robustness of the findings.

In a bid to clarify the key factors and their impact on the acceptance of zero-carbon building material components, SEM methods were employed. As a two-step process, SEM enables the measurement of relationships between a set of independent variables – key factors influencing materials selection choice and a dependent variable—the perception of zero-carbon building materials (Yang et al., 2014):

1 First, the model fit was carefully assessed to ensure that the assumed relationships aligned with the observed values. This evaluation was based on fit indices such as the Comparative Fit Index (CFI) and the Root Mean Square Error of Approximation (RMSEA).
2 Second, standardised path coefficients were applied to accurately measure the strength and direction of associations among the variables.

5.4.5.3 One-Sample test

Given that all participants in this survey were actively engaged in residential building projects, and to address the study's specific research questions, six key factors were identified through a comprehensive literature review. The methodology for this review and the rationale behind selecting these factors have been detailed in a previous study (Ali Hashemi Araghi et al., 2025). These factors including cost-effectiveness, durability, buildability, embodied carbon, availability, and aesthetics.

A one-sample *t*-test was subsequently performed to ascertain whether the mean scores for each factor, such as cost-effectiveness and durability, exhibited a statistically significant deviation from the neutral midpoint of 3 on the 5-point Likert scale. The primary objective of this *t*-test was to determine whether there were general positive or negative perceptions concerning the factors by the respondents.

As noted by Dawes (2008), a few important steps must be taken before proceeding with the analysis.. First, data distribution was assessed for normality using the Shapiro-Wilk test, supported by skewness and kurtosis values analysis. The statistics were found to be approximately normally distributed, providing a strong basis for justifying the application of the *t*-test. Secondly, independence of observations was maintained, as responses were collected from isolated and separate individuals. Thirdly, the mean values obtained from the Likert-scale responses were treated as continuous variables, a conventional practice when applying parametric tests to Likert-scale data.

A one-sample t-test was employed to assess whether the mean score for each factor (e.g., cost-effectiveness, durability, embodied carbon) differed from the neutral midpoint of 3 on the 5-point Likert scale. The choice of a parametric t-test, rather than a non-parametric alternative, was justified based on prior evidence that Likert-type composite scores can be treated as approximately continuous when aggregated across multiple items, provided that the distribution meets the assumptions of normality (Norman, 2010b). Before running the t-test, we assessed

the normality of the data for each factor using the Shapiro–Wilk test, supported by skewness and kurtosis statistics, all of which indicated that deviations from normality were minimal. The assumption of independence of observations was met, as each participant completed the survey individually and only once.

5.4.6 Validity and Reliability

Construct validity was examined through Confirmatory Factor Analysis (CFA). All item loadings exceeded the recommended threshold of 0.70, confirming that each indicator contributed substantially to its respective construct. Average Variance Extracted (AVE) values were above 0.50 for all constructs, demonstrating adequate convergent validity. Discriminant validity was established using both the Fornell–Larcker criterion and the Heterotrait–Monotrait (HTMT) ratio, with results falling within acceptable thresholds.

Reliability was assessed using Cronbach's α and Composite Reliability (CR), which ranged between 0.79 and 0.89, exceeding the recommended 0.70 cut-off. To provide a more robust measure of internal consistency, McDonald's ω was also calculated, with all constructs showing values above 0.80, indicating strong reliability and consistency across items. These results confirm that the measurement model is both reliable and valid, supporting its use for subsequent SEM analysis.

According to a study done by Faul et al. (2007), reliability is important in measuring instruments. The reliability of six key factors including cost-effectiveness, durability, buildability, embodied carbon, availability, and aesthetics, and four zero-carbon building materials: wood, hemp, rammed earth, and straw bale, using the Cronbach's Alpha test. These four materials have been identified as suitable zero-carbon building materials in New Zealand by a previous study (A. Hashemi Araghi et al., 2025). The 203 valid responses without exclusions to ensure the sample's representativeness. The calculated Cronbach's Alpha value was 0.834, indicating strong internal consistency and demonstrating that these items measured the intended construct with high precision (Kang, 2021). Within this area of research, such a degree of reliability is acceptable reflecting that the instrument is well-suited to capture all pertinent attributes concerning material selection

Respondents rated factors like cost-effectiveness, durability, buildability, embodied carbon, availability, aesthetics, and specific materials such as wood, hemp, rammed earth, and straw bale. The analysis used descriptive statistics and a one-sample t-test to compare the results with a neutral baseline (test value = 3), as shown in Table 5.4.

Table 5.5: The status of the components affecting structural materials with zero carbon

Factors	N	Mean	Std. Deviation	Std. Error Mean
Cost-Effectiveness	203	4.9	0.28	0.02
Durability	203	4.8	0.33	0.02
Buildability	203	4.5	0.55	0.04
Embodied Carbon	203	4.0	0.77	0.05
Availability	203	3.6	0.79	0.05
Aesthetics	203	3.4	0.73	0.05

According to Table 5, the cost-effectiveness of the zero carbon building materials was examined, and a high mean score of 4.91 was obtained, indicating that respondents generally view the materials as very cost-effective. The low standard deviation (0.28) suggests a consensus among respondents regarding this factor. The standard error of the mean of 0.020 further supports the precision of this mean estimate. Durability was rated similarly high, with a mean score of 4.87 and a standard deviation of 0.33. This reflects strong agreement among participants on the perceived durability of the zero-carbon materials evaluated.

Buildability scored a mean of 4.53, suggesting that most respondents found the materials easy to work with. However, the standard deviation of 0.56 reveals a broader range of opinions, possibly due to differing experiences or familiarity with the materials. The average score for embodied carbon was 4.00, indicating that respondents perceive the materials to have moderate embodied carbon. The higher standard deviation of 0.77 points to a greater diversity of opinion on this factor, which differing levels of awareness regarding the environmental impacts of building materials may influence.

Availability received a mean score of 3.67, slightly below the other categories, indicating challenges in accessing these materials. The response variability (standard deviation of 0.79) may reflect regional differences in material availability or supply chain issues. With a mean score of 3.48, aesthetics was rated the lowest among all categories, suggesting a wide range of subjective opinions about the appearance of zero carbon materials. The standard deviation of 0.73 further highlights the variability in responses, which is expected given the personal nature of aesthetic preferences.

In addition to evaluating material selection factors, participants were also asked to rate the suitability of specific zero-carbon materials (wood, hemp, rammed earth, straw bale). The results are summarised in Table 5.5.

Table 5.6: The status of the materials

	N	Mean	Std. Deviation	Std. Error Mean
Wood	203	4.9	0.19	0.01
Hemp	203	4.2	0.80	0.05
Rammed Earth	203	3.9	0.78	0.05
Straw Bale	203	3.9	0.85	0.06

The results indicate that Wood received the highest overall rating, with a mean of 4.96 and low variability (standard deviation = 0.199). Cost-effectiveness and durability were also rated highly, with means of 4.91 and 4.87, respectively, indicating strong positive perceptions among respondents. Conversely, aesthetics had the lowest mean score of 3.48, suggesting that respondents found this factor less favourable than others. Additionally, availability and embodied carbon were rated moderately, with means of 3.67 and 4.00, respectively, reflecting a mixture of opinions regarding these materials' environmental and practical aspects. The standard deviations across components varied, with buildability (standard deviation = 0.559) and hemp (standard deviation = 0.801) displaying higher response variability, indicating that respondents had diverse opinions on these factors. The Standard Error Mean values provide confidence in the precision of the mean estimates, further supporting the reliability of these findings.

5.5 Results

This section presents the findings of the study in line with its objectives. Descriptive statistics (mean, SD, SEM) are reported first to highlight the relative importance of the material selection criteria and the perceived suitability of the four zero-carbon materials (wood, hemp, rammed earth, and straw bale). These are followed by one-sample t-tests, which examine whether the mean scores significantly differ from the neutral value, thereby assessing the strength of participants' preferences. Finally, the SEM results are presented, showing the relationships between the identified factors and the overall selection of zero-carbon materials. The results are presented according to the three research objectives:

- To identify the most influential selection criteria,
- To examine their relationship with carbon-related performance,
- To assess the suitability of zero-carbon materials.

5.5.1 Descriptive Statistics of Selection Factors

The following results represent the empirical evaluation of six literature-derived factors. They should not be interpreted as six factors newly discovered through the survey. Cost-effectiveness was identified in the literature as a relevant decision criterion and then emerged from the survey

as the highest-rated criterion, with a mean of 4.91. Respondents evaluated six key factors influencing the selection of zero-carbon building materials: cost-effectiveness, durability, buildability, embodied carbon, availability, and aesthetics. Descriptive statistics (mean, SD, SEM) were used to rank the relative importance of these factors (Table 5.6).

The six factors evaluated in the survey, cost-effectiveness, durability, buildability, embodied carbon, availability and aesthetics, were identified through the preceding literature review and subsequently operationalised as survey constructs. Therefore, these factors should not be interpreted as having been newly generated by the survey. The survey provided an empirical assessment of their perceived importance among New Zealand construction professionals. Cost-effectiveness emerged from the analysed survey responses as the highest-rated literature-derived factor, with a mean score of 4.91, followed by durability with a mean score of 4.87. By contrast, the SEM analysis indicated that embodied carbon and availability had the strongest unique associations with perceived material adoption when the six factors were considered simultaneously.

Table 5.7: The status of the components affecting structural materials with zero carbon

Factors	N	Mean	Std. Deviation	Std. Error Mean
Cost- Effectiveness	203	4.9	0.28	0.02
Durability	203	4.8	0.33	0.02
Buildability	203	4.5	0.55	0.04
Embodied Carbon	203	4.0	0.77	0.05
Availability	203	3.6	0.79	0.05
Aesthetics	203	3.4	0.73	0.05

The results address Objective 1, which aimed to identify the most influential factors in selecting zero-carbon building materials. The findings indicate that cost-effectiveness (M = 4.91) and durability (M = 4.87) were rated the highest among the evaluated factors, demonstrating strong agreement among respondents that these criteria are critical considerations when selecting sustainable materials. Buildability received a moderately high mean score (M = 4.53), suggesting that participants generally viewed these materials as practical to work with. However, the relatively larger standard deviation (SD = 0.55) indicates that opinions about buildability varied, possibly due to differences in prior experience or familiarity with these materials.

Embodied carbon (M = 4.00) and availability (M = 3.67) received more moderate ratings, highlighting mixed awareness and perceptions regarding the environmental impacts and supply accessibility of these materials. In contrast, aesthetics had the lowest mean score (M = 3.48),

indicating that visual appeal plays a relatively minor role in influencing material selection decisions. Overall, these findings confirm that functional, economic, and environmental considerations are prioritised over appearance when selecting zero-carbon materials.

Cost-effectiveness was significantly higher than the neutral baseline ($M = 4.91$, $SD = 0.28$, $t(202) = 35.2$, $p < 0.001$, 95% CI [4.86, 4.96], $d = 2.47$), indicating strong consensus on its importance. Durability ($M = 4.87$, $SD = 0.33$) showed a similar effect ($t(202) = 31.8$, $p < 0.001$, 95% CI [4.81, 4.93], $d = 2.23$). In contrast, aesthetics received the lowest rating ($M = 3.48$, $SD = 0.73$, $t(202) = 8.1$, $p < 0.001$, 95% CI [3.33, 3.63], $d = 0.57$), suggesting that appearance plays a limited role compared to functional and environmental considerations.

5.5.2 Perceived Suitability of Zero-Carbon Materials

Participants also rated the suitability of four specific zero-carbon materials, including wood, hemp, rammed earth, and straw bale, based on their perceptions of practicality, performance, and potential adoption (Table 5.7).

Table 5.8: Participants' ratings of material suitability

	N	Mean	Std. Deviation	Std. Error Mean
Wood	203	4.9	0.19	0.01
Hemp	203	4.2	0.80	0.05
Rammed Earth	203	3.9	0.78	0.05
Straw Bale	203	3.9	0.85	0.06

These findings address Objective 3, which focused on evaluating the perceived suitability of specific zero-carbon materials. Among the four materials assessed, wood emerged as the most highly rated option ($M = 4.96$, $SD = 0.19$), reflecting a strong consensus regarding its practicality, reliability, and widespread acceptance in construction. Hemp was also rated positively ($M = 4.21$), but its higher standard deviation ($SD = 0.80$) suggests that participants held more diverse opinions, likely due to limited familiarity or concerns about its broader application.

In comparison, rammed earth ($M = 3.98$) and straw bale ($M = 3.96$) received moderate ratings, with greater variability in responses. This suggests that while these materials are recognised for their environmental benefits, perceptions of their practicality and mainstream feasibility remain mixed. Taken together, the results demonstrate that while several zero-carbon materials hold potential, wood and hemp are perceived as the most suitable options for adoption in New Zealand's construction context.

5.5.3 One-Sample T-Test Results

To further assess the significance of these findings, a one-sample t-test was conducted using a test value of 3 (the neutral midpoint). The results show that all factors were rated significantly higher than 3, with p-values less than 0.001, confirming the significance of these differences (Table 5.8 and Table 5.9).

Table 5.9: One-sample t-test results for the most important factors influencing the choice of building materials

	Test Value = 3					
	t	**df**	**Sig. (2-tailed)**	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
Cost-Effectiveness	**93.960**	**203**	**.000**	1.91237	1.8722	1.9525
Durability	77.584	203	.000	1.87113	1.8236	1.9187
Buildability	38.144	203	.000	1.53093	1.4518	1.6101
Embodied Carbon	17.966	203	.000	1.00000	.8902	1.1098
Availability	11.793	203	.000	.67010	.5580	.7822
Aesthetics	9.078	203	.000	.47938	.3752	.5835

Table 5.10: Best fit zero carbon materials for NZ's building industry

	Test Value = 3					
	t	**df**	**Sig. (2-tailed)**	Mean Difference	95% Confidence Interval of the Difference	
					Lower	Upper
Wood	**136.855**	**203**	**.000**	1.95876	1.9305	1.9870
Hemp	20.981	203	.000	1.20619	1.0928	1.3196
Rammed Earth	17.467	203	.000	.98454	.8734	1.0957
Straw Bale	15.722	203	.000	.96392	.8430	1.0848

- Cost-Effectiveness: The t-value of 93.96 and a mean difference of 1.91 indicate that respondents view cost-effectiveness as a highly favourable factor.
- Durability: With a t-value of 77.58 and a mean difference of 1.87, durability also significantly exceeds the neutral rating.
- Buildability: A t-value of 38.14 and a mean difference of 1.53 show that buildability is rated positively.

- Embodied Carbon: The t-value of 17.97 and a mean difference of 1.00 suggest that respondents view embodied carbon more positively, though with less magnitude than other factors.
- Availability: The t-value of 11.79 and a mean difference of 0.67 show moderate favourability regarding availability.
- Aesthetics: A t-value of 9.08 and a mean difference of 0.48 confirm that aesthetics is rated slightly above neutral, though this factor is less influential than others.

5.5.4 Structural Equation Modelling Results

The descriptive rankings and structural-model results address different questions. Cost-effectiveness and durability received the highest mean importance ratings, indicating that respondents consciously rated them as important considerations. In contrast, embodied carbon and availability produced the largest standardised coefficients in the structural model, indicating the strongest modelled associations with material adoption when the six constructs were considered simultaneously. Cost-effectiveness therefore emerged as the highest-rated literature-derived criterion, whereas embodied carbon and availability were the strongest predictors within the specified structural model.

To assess the relationship between these factors and the overall perception of zero carbon building materials, SEM was employed. The results, based on standardised coefficients, reveal that the most significant factors influencing the adoption of zero carbon materials are embodied carbon (standardised coefficient = 0.397), availability (0.368), and hemp (0.373). These findings indicate that materials with low embodied carbon and high availability are more likely to be adopted in sustainable building projects. In contrast, factors such as wood (0.093) and cost-effectiveness (0.132) are more moderate in influencing material selection, reflecting their relatively lower impact on decision-making than environmental and accessibility considerations. The results based on standardised coefficients reveal that the most significant factors influencing the adoption of zero carbon materials are availability (18.699), embodied carbon (18.126), and buildability (17.229) (Figure 5.1). These figures represent how various factors and materials relate to the central constructs. The standardised coefficients offer a quantitative measure of the relationships within the model.

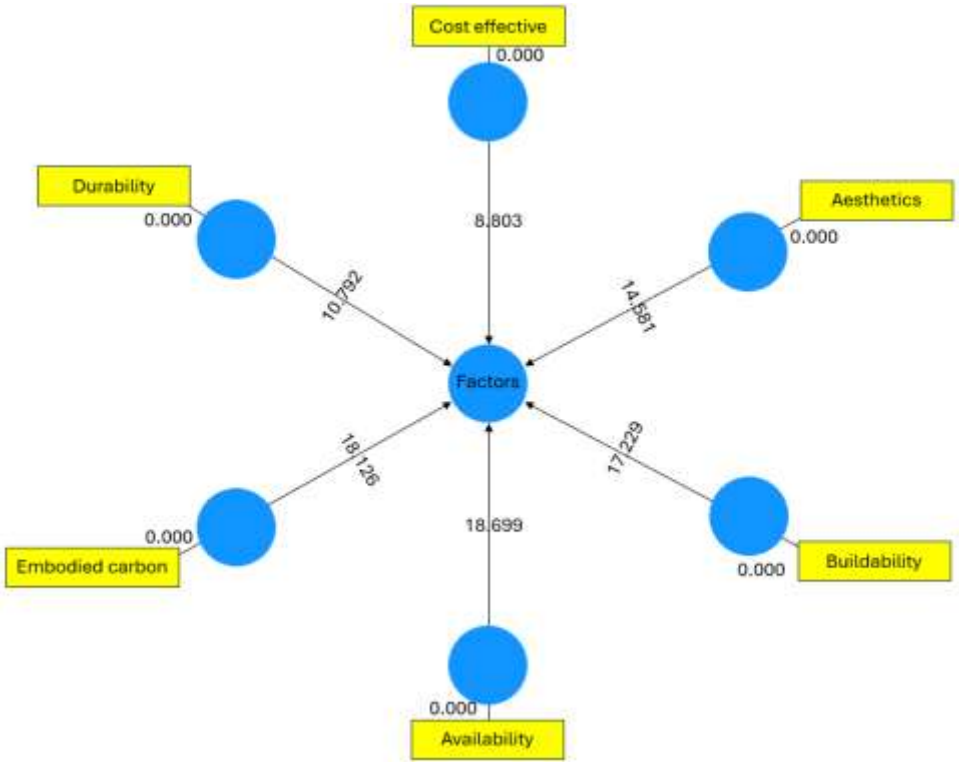


Figure 5.1: The SEM results for material selection factors. The diagram shows the standardised path coefficients and significance values for the six factors—cost-effectiveness, durability, aesthetics, buildability, embodied carbon, and availability

The structural model demonstrated a good overall fit: CFI = 0.982, TLI = 0.974, RMSEA = 0.046, and SRMR = 0.052, all within recommended thresholds (Hu & Bentler, 1999). Standardised path coefficients are reported with 95% confidence intervals. Embodied carbon (β = 0.397, 95% CI [0.32, 0.47]) and availability (β = 0.368, 95% CI [0.28, 0.45]) emerged as the strongest predictors of adoption, while aesthetics (β = 0.058, ns) was not significant (Figure 5.2).

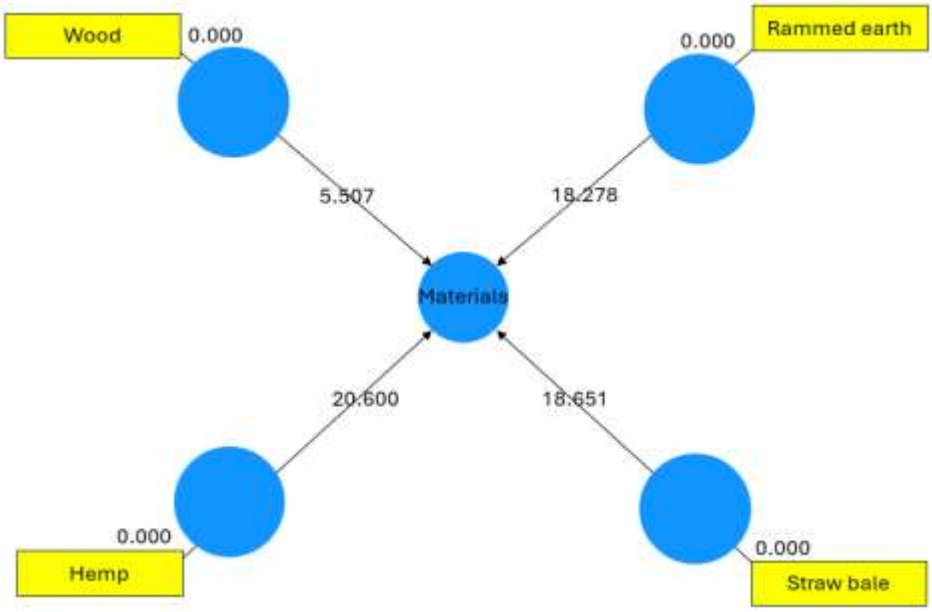


Figure 5.2: Structural equation model results for the materials based on standardised coefficients

These SEM results directly address Objective 2, confirming that embodied carbon (β ≈ 0.40) and availability (β ≈ 0.37) are the strongest predictors of zero-carbon material adoption, while aesthetics has negligible influence. This demonstrates that environmental and practical factors are the main drivers of decision-making.

According to Figure 5.2, factors such as wood (0.093) and cost-effectiveness (0.132) are more moderate in influencing material selection, reflecting their relatively lower impact on decision-making than environmental and accessibility considerations. The SEM results describe conditional associations and should not be interpreted as the criterion weights used in the DST. Embodied carbon had the largest standardised association with adoption (β = 0.397), followed by availability (β = 0.368). Cost-effectiveness (β = 0.132), durability (β = 0.094), buildability (β = 0.074), and aesthetics (β = 0.058) had smaller coefficients when the predictors were considered simultaneously. The corresponding bootstrapped t-statistics and confidence intervals are reported separately and are not criterion weights.

This differs from the descriptive importance ratings, for which cost-effectiveness and durability had the highest means. The difference is expected because mean ratings measure respondents' stated importance, whereas SEM coefficients estimate the unique association of each construct with adoption after accounting for the other constructs. Table 5.10 and Table 5.11 summarize the key factors achieved in this study.

Table 5.11: Summary of key factors influencing zero carbon building materials selection in NZ

Factor	Mean Score	Standard Deviation	Significance (T-Test)	Impact on Adoption (SEM Standardised Coefficient)	Importance Level
Cost-Effectiveness	4.91	0.28	$p < 0.001$	0.132	High
Durability	4.87	0.33	$p < 0.001$	0.094	High
Buildability	4.53	0.56	$p < 0.001$	0.074	Moderate
Embodied Carbon	4.00	0.77	$p < 0.001$	0.397	Moderate
Availability	3.67	0.79	$p < 0.001$	0.368	Low
Aesthetics	3.48	0.73	$p < 0.001$	0.058	Low

Table 5.12: Summary of best-fit zero-carbon building materials in NZ

Materials	Mean Score	Standard Deviation	Significance (T-Test)	Impact on Adoption (SEM Standardised Coefficient)	Importance Level
Wood	4.96	0.19	$p < 0.001$	0.093	High
Hemp	4.21	0.80	$p < 0.001$	0.373	Moderate
Rammed Earth	3.98	0.79	$p < 0.001$	0.084	Moderate
Straw Bale	3.96	0.85	$p < 0.001$	0.062	Low

5.6 Discussion

This study used a quantitative survey-based methodology to evaluate and prioritise the literature-derived factors influencing the selection of sustainable building materials (wood, hemp, rammed earth, and straw bale) in the New Zealand construction sector. The discussion addresses the study objectives by interpreting the findings considering existing literature and highlighting their implications for sustainable construction.

The results revealed that cost-effectiveness and durability were rated as the most important factors influencing material selection, followed closely by buildability. This finding is consistent with previous studies demonstrating that economic considerations and material longevity are often prioritised by industry professionals when selecting sustainable materials (Erdogan et al., 2019; Figueiredo et al., 2021b). The high ratings for cost-effectiveness reflect persistent pressures to balance environmental objectives with project budgets, especially in the New Zealand construction sector, where cost escalations are common.

Interestingly, embodied carbon and availability received only moderate importance scores. While this partially aligns with international studies (Giesekam et al., 2016; Pomponi & Moncaster, 2016), which identify embodied carbon as a critical sustainability driver, the relatively lower ranking observed here suggests that awareness and integration of life-cycle environmental impacts are still developing within the New Zealand context. Furthermore, aesthetics was rated the least influential factor, indicating that visual preferences are secondary to functional and environmental priorities when selecting zero-carbon materials.

Respondents perceived wood as the most suitable zero-carbon material, followed by hemp, while rammed earth and straw bale received lower ratings. The preference for wood is consistent with existing literature highlighting its familiarity, versatility, and extensive use in New Zealand's construction industry (Churkina et al., 2020). The strong consensus around wood's practicality suggests it could serve as a primary driver of low-carbon adoption strategies in residential construction.

Our findings regarding the prominent roles of embodied carbon and material availability in material selection echo national-level observations. Finnie et al. (2024) report systemic barriers in EC calculation and low material supply, particularly for timber alternatives like CLT and LVL. This aligns with our structural model, where embodied carbon and availability emerged as critical predictors. The use of SEM to quantify multi-factor influences in the New Zealand context is further validated by Bui et al. (2025), who identify similar interdependencies across technical, social, and environmental dimensions. A recent systematic review of zero-carbon building materials in NZ highlights cost, durability, and aesthetic considerations as under-explored yet critical factors, supporting the inclusion of these in our framework (A. Hashemi Araghi et al., 2025).

These findings are consistent with the literature reviewed earlier, particularly regarding the increasing emphasis on embodied carbon and the practical challenges of accessing low-emission materials (Figueiredo et al., 2021a; World Green Building Council, 2021). While theoretical models propose broad environmental and lifecycle advantages for sustainable materials, this study provides empirical evidence from New Zealand professionals, who prioritise environmental performance and practicality. In contrast to some global design narratives, the relatively low influence of aesthetics suggests a functional, pragmatic approach within New Zealand's construction industry, likely shaped by cost constraints, supply limitations, and regulatory requirements.

The SEM results provide deeper insights into the relationships between selection factors and overall material adoption. Embodied carbon (β = 0.397) and availability (β = 0.368) emerged as the most significant predictors of zero-carbon material selection, followed by hemp (β = 0.373). These findings echo studies highlighting embodied carbon reduction as a primary driver for sustainable material adoption globally [61] and reflect ongoing supply chain challenges unique to the New Zealand context [11].

In contrast, cost-effectiveness (β = 0.132) and aesthetics (β = 0.058) showed limited influence on adoption decisions once environmental and practical considerations were accounted for. This divergence from traditional construction priorities suggests an important shift in industry attitudes: professionals increasingly value environmental performance and material accessibility over superficial or short-term cost factors. These insights address Objective 2 by clarifying how decision-making is shaped by a combination of environmental awareness and practical feasibility.

These results have practical implications for both policy and industry. Policymakers should prioritise initiatives that strengthen local supply chains, incentivise low-carbon alternatives, and increase awareness of embodied carbon in material selection. For practitioners, the findings highlight the importance of considering both environmental and practical performance when evaluating materials. While causal claims cannot be made, the associations identified in this study provide evidence-based guidance for accelerating the transition to zero-carbon construction in New Zealand.

The study contributes to the international literature by providing an empirical, context-specific analysis of material perceptions and selection drivers within an island economy. These insights may be relevant to other regions facing similar geographic and market constraints.

5.6.1 Limitations and Future Research

Several sampling limitations affect interpretation of the findings. First, purposive rather than probability sampling was used; therefore, selection probabilities were unknown and statistical representativeness cannot be claimed. Second, the sample was strongly concentrated in Auckland, which accounted for 93.6% of respondents. Material availability, transport costs, construction practices, market maturity, and professional familiarity with alternative materials may differ considerably across New Zealand regions. Third, engineers represented 73% of the sample, while architects, contractors, clients, building managers, quantity surveyors, policymakers, and other relevant groups were less well represented or absent. Fourth, most

completed questionnaires were collected in person, which may have introduced recruitment-location and mode effects. The results should therefore be interpreted as evidence from the achieved sample rather than national estimates of professional opinion.

5.7 Conclusion

This study investigated the factors influencing the selection of zero-carbon building materials and assessed the perceived suitability of four alternatives — wood, hemp, rammed earth, and straw bale — within the New Zealand construction sector. The six material-selection factors examined in this study—cost-effectiveness, durability, buildability, embodied carbon, availability, and aesthetics—were derived from the preceding literature and operationalised as survey constructs. The survey did not generate these factors as new constructs; rather, it empirically evaluated and prioritised the pre-specified literature-informed factors. The analysed survey responses identified cost-effectiveness as the highest-rated factor, followed by durability and buildability, while embodied carbon and availability received moderate importance and aesthetics was rated lowest, addressing Objective 1. Through SEM, the study confirmed that embodied carbon and availability exert the strongest influence on the adoption of zero-carbon materials, whereas cost-effectiveness and aesthetics play relatively minor roles, thereby fulfilling Objective 2. Regarding Objective 3, respondents perceived wood as the most suitable zero-carbon material, followed by hemp, while rammed earth and straw bale were viewed less favourably due to perceived limitations in practicality and mainstream feasibility. These findings contribute to the literature on sustainable construction by providing empirical, context-specific insights into material perceptions and selection drivers in New Zealand. For policymakers and practitioners, the results highlight the need to improve awareness and accessibility of alternative materials, strengthen local supply chains, and introduce targeted incentives to make zero-carbon options financially competitive. Future studies should expand the material scope, incorporate perspectives from a broader range of stakeholders, and integrate cultural, regulatory, and policy-related dimensions to develop a more comprehensive framework for sustainable material adoption.

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STATEMENT OF CONTRIBUTION
DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the student and the student's main supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the student's contribution as indicated below in the Statement of Originality.

Student name:	Ali Hashemi Araghi
Name and title of main supervisor:	Dr Eziaku Onyeizu Rasheed
In which chapter is the manuscript/published work?	Chapter 6

Describe the contribution that the student and members of the supervisory team have made to the manuscript/published work:[1]

Conceptualization, A.H.A.; methodology, A.H.A.; software, A.H.A.; validation, A.H.A.; formal analysis, A.H.A.; investigation, A.H.A.; resources, A.H.A.; data curation, A.H.A.; writing—original draft preparation, A.H.A.; writing—review and editing, A.H.A., E.O.R., V.V. and J.S.; visualization, A.H.A.; supervision, E.O.R., V.V. and J.S.; project administration, A.H.A.; funding acquisition, E.O.R., V.V. and J.S. All authors have read and agreed to the published version of the manuscript.

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○ **It is intended that the manuscript will be published, but it has not yet been submitted to a journal**

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Chapter 6: SWOT analysis of zero-carbon building materials

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

> Araghi, A. H., Rasheed, E. O., Vishnupriya, V., & Seadon, J. (2026). Strengths, Weaknesses, Opportunities, and Threats of Zero-Carbon Materials in New Zealand: A Literature Review, International Conference on Digital Frontiers in Buildings and Infrastructure (DFBI2026) (Under Review)

6.1 Chapter Summary

This chapter presented a systematic narrative literature review examining the SWOT associated with low- and zero-carbon building materials in the New Zealand construction context. Drawing on both peer-reviewed academic literature and industry reports, the review evaluated these materials against six critical criteria: cost-effectiveness, durability, buildability, embodied carbon, availability, and aesthetics. The adopted evidence-mapping approach enabled a structured synthesis of fragmented knowledge across environmental, technical, and market-driven dimensions. The findings indicate that zero-carbon and low-carbon materials offer substantial lifecycle and environmental advantages, particularly in reducing embodied carbon and supporting national decarbonisation targets aligned with New Zealand's net-zero-by-2050 commitment. Several materials also demonstrate promising performance in durability, design flexibility, and long-term sustainability outcomes. However, despite these strengths, widespread adoption remains constrained by persistent barriers. These include high upfront costs, limited local availability, fragmented and immature supply chains, technical uncertainties, and inconsistent regulatory guidance and standards.

At the same time, the review identified emerging opportunities that could significantly accelerate uptake. Advances in material fabrication technologies, growing environmental awareness among stakeholders, and evolving policy and regulatory frameworks create favourable conditions for innovation and market transformation. These opportunities suggest that zero-carbon materials are not merely aspirational but increasingly viable, provided that systemic barriers are addressed through coordinated industry and policy interventions. Overall, this chapter contributes a holistic and thematically structured evidence base that clarifies the current state of zero-carbon materials in New Zealand. It highlights the need for integrated, multi-criteria decision-support tools to assist designers, policymakers, and industry practitioners in material selection. By framing material adoption as a balance between environmental performance, practical feasibility, and market readiness, the chapter establishes

a foundation for future empirical studies and decision-making frameworks aimed at enabling a scalable transition to low- and zero-carbon construction practices.

6.2 Introduction

The construction and building industry is a significant source of greenhouse gas emissions in the world, as it contributes to about 39 percent of all energy-linked greenhouse gases in the globe (Myint & Shafique, 2024). The construction sector in New Zealand is also central to supporting the net-zero emission target in the nation in 2050 (Bahrami et al., 2022; Dixit et al., 2012). Whereas much progress has been made in minimizing operational emissions by ensuring efficiency and harnessing renewable energy, the discussion is now moving to the concept of embodied carbon, the emissions produced during the extraction of materials, their manufacture, transportation, and disposal (Cheshmehzangi et al., 2023; Giesekam et al., 2016).

Although there is a growing awareness of the use of sustainable alternatives, the use of zero-carbon materials is still limited due to economic, technical, and attitudes (Baghaei Daemei & Jamali, 2022). Despite the great advantages of these materials in terms of lifecycle performance and environmental impact and resilience, their usage is limited by high initial price, absence of standardized data, and incompatibility with traditional building systems (Al Shdifat et al., 2023). The challenges highlight the existence of a need to have a holistic framework that addresses the benefits as well as the shortcomings of sustainable material options (Araghi et al., 2025).

The SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis system is a popular strategic planning methodology that is applied to integrate multifaceted and many-dimensional information. SWOT has shown itself to be useful in construction sustainability studies, such as determining barriers to adoption, market preparedness, and stakeholder issues, with the support of expert opinion or literature-derived data (Çağan & Ünel, 2024). Compared to strictly quantitative approaches, the SWOT analysis can help to realize the qualitative knowledge of trade-offs that drive the real-world decision-making process in materials selection (Aeinehvand et al., 2021; Zhou et al., 2019).

The paper is based on a narrative literature review that is structured in a systematic way to come up with a SWOT analysis of zero-carbon building materials in the New Zealand context. The analysis centres on six major measures of evaluation such as aesthetics, availability, buildability, cost-effectiveness, durability, and embodied carbon that were discovered in our previous research (A. Hashemi Araghi et al., 2025). This gives a thematically systematized evidence base to future decision-support systems like multi-criteria analysis and sustainability rating systems.

This is aimed at enlightening industry practitioners, policymakers, and researchers on the issues of a multifactorial basis behind the choice of low-carbon materials in fulfilling the New Zealand decarbonization objectives. New Zealand has a vision to have net-zero carbon emission and thus strives to ensure that the environmental effect of a building industry is minimized by using sustainable processes and low carbon materials.

6.3 Methodology

This study employed a structured literature review to develop a comprehensive SWOT analysis of zero-carbon building materials (i.e., wood, hemp, rammed earth, and straw bale (A. Hashemi Araghi et al., 2025), specifically within the New Zealand context. The goal was to synthesize scholarly and grey literature to support the development of a strategic evaluation framework across six critical performance dimensions: Cost-Effectiveness, Durability, Buildability, Embodied Carbon, Availability, and Aesthetics.

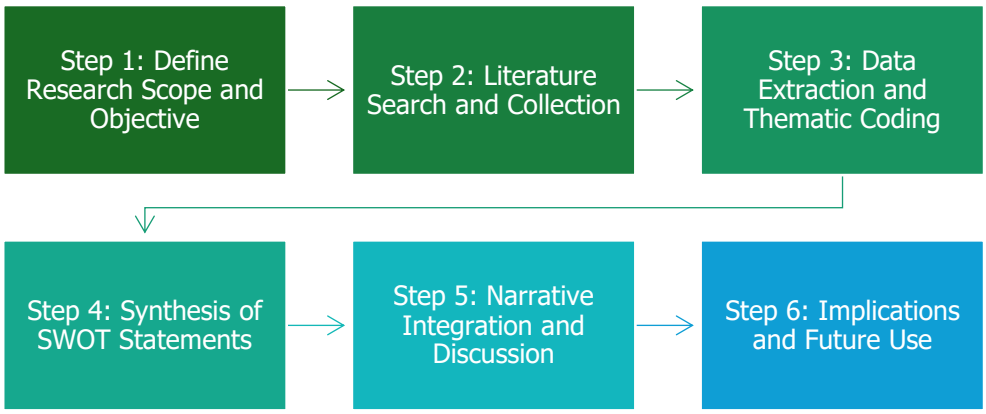


Figure 6.1: Research workflow

The research followed a six-step workflow (Figure 6.1), starting with the identification of the scope and purpose, then literature gathering, thematic coding, and SWOT statement synthesis. The steps made informed the conversation of the narrative and ended with the determination of the practical implications and future applications.

6.3.1 Review Approach

A systematic literature review was done in a form of a narrative to establish common themes around the advantages and difficulties of the adoption of low- and zero-carbon building materials. The research was conducted using a narrow evidence- mapping methodology, which gave it the flexibility to include both scholarly and grey literature that was industry relevant. It was not aimed at the comprehension of all existing literature but at the creation of the practically

based basis of a future DTS (Arksey & O'Malley, 2005; Gough et al., 2017; Greenhalgh et al., 2005).

6.3.2 Search Strategy

The major academic databases (Scopus, Web of Science, ScienceDirect, and Google Scholar) have been used to conduct the literature search. It was complemented by specific reviews of pertinent New Zealand government publications, industry reports (e.g. BRANZ, MBIE) and standards documentation. The search strategy involved a Boolean operator of key words that had to do with zero-carbon and low-carbon building materials in the New Zealand construction environment. Sources written in English only were taken into consideration. It is emphasized that the academic and industry points of view should be combined in the assessment of sustainable material use in the construction (MBIE, 2020c).

6.3.3 Inclusion and Exclusion Criteria

Studies were included if they met the following criteria:

- Focused on building materials in the New Zealand construction industry or similar regions with temperate climate.
- Environmental, economic, or technical peculiarities, which are discussed regarding any of the six SWOT criteria.
- Provided evidence, expertise or judgment that may give advice on SWOT items.

The following were excluded:

- Articles that do not deal with building materials or construction uses.
- Publications that are not relevant to at least one out of the six target criteria.
- Documents or literature written in non-English and not publicly available.

6.3.4 Data Extraction and Categorization

All the studies reviewed were related, and they were 26 studies. The main qualitative and quantitative findings were identified and divided into either of the four SWOT areas in the six performance dimensions. To be clear and general, all the statements in the SWOT analysis were rewritten in a short, declarative statement. The material names were not used to maintain a neutrality so that the users could make an interpretation of the SWOT matrix by being flexible in its relation to various material options. The complete output will have 90 statements (7 statements in each SWOT quadrant as there are 6 criteria). One or more literature references were used to support each of the statements.

6.4 Cost-Effectiveness

Zero-carbon building materials are a complex feature concerning the cost-effectiveness, as it includes both a long-term monetary outcome and short-term economic issues (Pomponi & Moncaster, 2017). The literature includes information about the economic implication of the adoption of such materials, especially in the New Zealand environment where there are different regions in which the availability of materials, the maturity of the market, and the policy support.

6.4.1 Strength

- ✓ Zero-carbon materials are also known to have the potential of lowering the energy usage in operations. Greater thermal performance, which can be the result of high-performance insulation and envelope-tightening measures, will lead to substantial energy bill savings throughout the lifetime of the building (Mata et al., 2020). Nevertheless, empirical research does indicate that those savings can be small provided there is no simultaneous intervention on occupant behaviour and system inefficiencies, which curtails their direct cost benefit (Dixit et al., 2012).
- ✓ Swift of the decrease in maintenance requirements of most sustainable materials is a strength. Durable and environment-resistant materials may reduce the expenses of operation in the long term since such materials are used in environments that may be subjected to moisture or UV-radiation (Cabeza et al., 2014). Furthermore, the project, which uses these materials, can be eligible to receive financial incentives, such as rebates, tax credits, and favourable lending, developed to fasten the adoption of low-carbon constructions (MBIE, 2020a; World Green Building Council, 2013).
- ✓ Zero-carbon materials can also reduce life-cycle costs in the long-run, especially by considering energy savings and less material wastage (Cabeza et al., 2014). Additionally, in certain instances, their assistance in developing resilience will reduce insurance premiums particularly of those structures that are in a high-risk area (Tsantopoulos et al., 2018). Long-service life materials also assist in minimizing the number of replacements, which leads to more economic predictability throughout life, a factor of the building.
- ✓ In some markets, such materials contribute to green certifications such as Homestar and Green Star NZ, which can enhance resale value, reduce compliance costs, or unlock eligibility for green funding mechanisms (NZGBC, 2023a).

6.4.2 Opportunities

- ✓ New cost-sharing schemes - commonly led by government or public-private alliances - are meant to counter initial stage financial challenges of low-carbon building implementation (IEA, 2022). At the same time, bio-based and prefabricated material production are becoming easier using technological advances, with the cost decreasing gradually in the long term (Giesekam et al., 2016).
- ✓ With the increased demand towards zero-carbon solutions in the world, the market will probably enhance its cost-effectiveness by creating economies of scale. As an illustration, the wider implementation of cross-laminated timber has induced tremendous reductions in unit cost in sections of Europe and Australasia (Dixit et al., 2012). Green financing tools, including climate-aligned loans, can also help to promote this trend because they cut down the capital costs of the projects that incorporate sustainable materials (World Green Building Council, 2013).
- ✓ Integrated design tools also are making the calculation of costs more predictable, as it now is possible to model the effect of the material on the energy, carbon, and cost early (Mata et al., 2020). Government contracting and adoption by the public sector can further stabilize the demand and supply chains, and the developer-supplier relationship can minimize the procurement risk and harmonize the project costs throughout its lifecycle (NZGBC, 2023a).

6.4.3 Weaknesses

- ✓ Despite the long-term benefits, high initial cost of purchase is one of the greatest challenges to the adoption of zero-carbon materials, particularly in the traditional models of capital expenditure (Dixit et al., 2012; World Green Building Council, 2013). Moreover, the fact that specialized labour would have to be employed to build some materials, including hempcrete, hi-tech thermal panels or PV-integrated facades, may make the construction more expensive (Giesekam et al., 2016).
- ✓ Further expenses can also be incurred in transportation because most sustainable materials are imported or are scarce in the location. This leads to an increase in the carbon and cost footprint especially in rural or remote locations (Cabeza et al., 2014). Together with non-standard specifications and custom finishes, it adds to procurement and integration cost of developers that are not experienced with sustainable design systems (Zuo & Zhao, 2014).

- ✓ Additionally, the certification of green buildings is often accompanied by the need to perform other tests and make even more documents, which increase management overhead and extend timelines (NZGBC, 2023a). These compounded costs in the short-term financial analysis can present projects as less viable, although they can have good returns in the long-term (Dixit et al., 2012).

6.4.4 Threats

- ✓ External threats to the cost-effectiveness of the zero-carbon materials include market uncertainties. Unstable prices, especially in bio-based products and imported products, can jeopardize cost planning. Increased interest rates can also influence green financing access but this will unequally impact small-scale developers (IEA, 2022).
- ✓ Also, alternative materials like standard concrete and steel might still prevail due to short-term price benefits, even though they have a higher embodied carbon (Giesekam et al., 2016). During economic downturns, the investment in either experimental or eco-friendly superior products will generally decrease (World Green Building Council, 2013).
- ✓ The impacts of carbon pricing, although it is meant to internalize the environmental externalities, may lead to indirect cost increases of low-carbon alternatives under the regulation of supply chains (Mata et al., 2020). Policy adoption may be delayed due to a lack of an updated policy or incompatible regional regulations. Inflationary pressures are also a very important risk factor, although not always when the environmental value is not present in the market price structures (Mata et al., 2020).

6.5 Durability

The durability of zero-carbon building materials is critical in establishing the longevity of value and performance of the material (Uddin et al., 2025). It has a direct influence on lifecycle cost, material resilience, interventions frequency, including maintenance or replacement. Durability is not only a technical but also an economic necessity in climates like those of New Zealand that subject buildings to changing weather, high humidity, and earthquakes (Heffernan et al., 2015).

6.5.1 Strengths

- ✓ Durable materials are important to the structures of buildings as a whole and their durability. Most zero-carbon materials are very resistant to wear and tear, especially at moderate application and even in stable indoor conditions (Cabeza et al., 2014). These

materials are in other instances designed to endure harsh environmental factors such as thermal cycling, humidity, and ultraviolet radiation (Giesekam et al., 2016). Accordingly, they have a longer service life; therefore, there is less replacement and frequent intervention.

- ✓ Such materials can significantly decrease the cost of repair and negative effects on the environment by reducing the repair frequency, especially when well installed and maintained (Mata et al., 2020). Some of the low-carbon alternatives, including engineered timber or bio-based products with a treatment that supports resistance to biological degradation, including mould or insect infestation, also demonstrate this behaviour (BRANZ, 2020). A combination of these properties will contribute to a lower replacement rate and contribute to the stability of the structure in the long term.

6.5.2 Opportunities

- ✓ The lifespan of sustainable materials is more than ever being sustained owing to continuous studies on lifespan improvement and performance testing to ensure better confidence in the industry regarding the extended application of materials (Giesekam et al., 2016). Third-party certification such as life-cycle assessment and load testing in real-world conditions is becoming a trend and is providing green building certifications (NZGBC, 2023a).
- ✓ Moreover, the disaster-prone regions are also appreciating the use of durable and low maintenance materials to minimize the operation risk and enhance resilience of the buildings (Tsantopoulos et al., 2018). The insurance companies can consider providing more favourable prices to materials that reduce long-term structural damages (IEA, 2022). Consumers and builders are also shifting their preference to long-life products in the market that is being supported by long warranties issued by manufacturers and digital capabilities of predictive maintenance (IEA, 2022).

6.5.3 Weaknesses

- ✓ Certain products are not resistant to moisture or UV radiations, especially when they lack the necessary protection during installation (Cabeza et al., 2014). Consequently, protective coating can be a requirement, which increases the price, as well as complexity (Giesekam et al., 2016).
- ✓ Some materials might have poor performance with regard to abrasion resistance in places of high usage, making them less appropriate in a commercial or industrial application (BRANZ, 2020). Strength variability is also of issue particularly where

multiple suppliers provide the materials or it is produced in varied quality standards (Dixit et al., 2012). This may also make the designs less flexible to the needs of reuse or change in future renovations, as the emphasis on durability is sometimes made (Dixit et al., 2012).

- ✓ There is also a lack of documentation, where the behaviour of maintenance and degradation is not explicitly specified in technical datasheets (Zhang et al., 2011). Finally, the contact with fixings, coatings, or dissimilar materials may also cause unexpected performance concerns, especially when used in a hybrid construction environment (Zhang et al., 2011).

6.5.4 Threats

- ✓ Another group of external threats that can reduce the expected performance with time also influences durability (Mata et al., 2020). An example is the extreme weather conditions like heavy rainfall, heat waves or freeze thaw cycles, which might surpass the durability of a particular material, thus degrading it faster. Poor installation is one of the most frequent causes of durability accidents, which usually shortens the projected service life dramatically (Mata et al., 2020).
- ✓ It is also growing more worrisome that fake or uncertified materials are getting in the market and that they have not gone through independent testing of their durability (World Green Building Council, 2013). In cases where the manufacturers may say that it is very durable, it may not be confirmed on its own, which undermines the confidence of the buyers. In certain projects, materials can be over-specified to low-stress usage, which is increasing the costs unnecessarily and will not add value (World Green Building Council, 2013).
- ✓ Surface finishes or coating might get corroded by cleaning protocols or harsh chemicals and incompatibility of materials in composite assembly may decrease the overall lifetime. Such threats demonstrate the need to focus on quality assurance, compatibility on system level, and post occupancy monitoring performance (Asdrubali et al., 2012).

6.6 Buildability

An important factor in the feasibility of zero-carbon building materials is buildability, which is the ease and efficiency at which the materials can be managed, installed and combined on site. Material adaptability and labour issues are paramount in the case of the construction industry in New Zealand where both traditional and modular technology is a part of the construction sector (Pan et al., 2012).

6.6.1 Strengths

- ✓ Most of the low-carbon materials are easy to manipulate and handle, particularly the prefabricated, lightweight, and modular materials (Cabeza et al., 2014). Long-term physical capabilities like easy to cut, shape, or fix materials could increase the efficiency of on-site assembly (Cabeza et al., 2014). Specifically, lightweight materials minimize the chances of injury and fatigue among labourers and make it easier to work with it and minimise the use of special equipment (Dixit et al., 2012).
- ✓ An important point that is highlighted by many studies is the time savings that comes with the implementation of sustainable prefabricated components that may lead to a shorter time to set-up and low labour requirements (Giesekam et al., 2016). The materials that can be used with an off-site construction or building and modular system also contribute to this advantage by simplifying the construction schedule and minimizing waste (BRANZ, 2020). Moreover, a lot of zero-carbon products produce less on-site waste, which increases their efficiency, lowers disposal expenses, and decreases environmental disruption (Mata et al., 2020).
- ✓ A safer worksite environment is also provided by other materials, including wood and strawbale, which is not toxic, requires fewer methods using heat to install, and has lower dimensional tolerance, which means that human error is less likely to happen during use (IEA, 2022). All of these qualities render the zero-carbon materials interesting to implement into residential building systems and commercial ones (IEA, 2022).

6.6.2 Opportunities

- ✓ Various training and education programmes are taking shape to provide the skills unique to low-carbon materials among the contractors and installers to enhance the outcomes of buildability (MBIE, 2020a). Simultaneously, building codes are becoming more aware of innovative products, simplifying compliance and adding to their application (NZGBC, 2023a).
- ✓ Off-site production, such as volumetric modular systems and panelised assemblies, is growing at an alarming rate, and offers new possibilities when it comes to integrating sustainable elements efficiently (World Green Building Council, 2013). The integration of suppliers, contractors and researchers is also simplifying the installation, logistics and site safety protocols (World Green Building Council, 2013).
- ✓ Also, new technologies like 3D printing and CNC fabrication are improving the accuracy and reliability of parts, eliminating the mistakes during the installation process

and guaranteeing the improved work with the material (IEA, 2022). The solution of new fastening systems and special tools to these materials also facilitates easier adoption (IEA, 2022).

6.6.3 Weaknesses

- ✓ Despite these breakthroughs, there are several obstacles that still impact on the construction of zero-carbon materials. The installation may also be associated with special tools or methods that are not commonly available among small or local contractors (Giesekam et al., 2016). In addition, variation in quality, particularly of bio-based materials or imports may complicate on-site adjustment (Cabeza et al., 2014).
- ✓ Another significant weakness is that it may not be compatible with the current standards or practices in construction, and thus may require retraining or system re-design (Dixit et al., 2012). The possible customization on-site is also constrained by some materials, which are either fragile or rigid enough to make it harder to make last-minute change or retrofit (BRANZ, 2020). The absence of domestic knowledge of green material systems can slow down the implementation of a project and risks (BRANZ, 2020).
- ✓ Moreover, the sensitivity to weather is a repeated problem. Certain natural or made materials should be installed in dry, mild weather that will be cured, and that is not easy in New Zealand which has unpredictable climate (Jiang & Tovey, 2010). Lastly, integration with conventional materials may lead to gaps or other inefficiencies or discrepancies in tolerances during multi-material assembly due to technical issues (Jiang & Tovey, 2010).

6.6.4 Threats

- ✓ The sustainability of the materials can also be threatened by several external factors to its buildability. Lack of skilled labour, especially in rural or under-resourced regions, may slow down construction timelines and raise the expenses (IEA, 2022). The market penetration of novel materials is also restricted by opposition by the contractors to traditional systems (IEA, 2022). Malfunctions during the installation, particularly with the lack of training, may decrease performance or nullify warranties (Giesekam et al., 2016). Moreover, not all sustainable materials can be used with legacy systems, which results in a higher cost of retrofit or less structural coherence (Giesekam et al., 2016).
- ✓ There is a risk of incorrect or unfinished instructions on how to install the application, and this leads to more inconsistency in the results. On the regulatory level, construction planning and choice of materials can be influenced by delays in building consent

approvals (Likita et al., 2022). Weather-dependent installations Weather-based installation procedures may create seasonal constraints, particularly those that cannot be put in place during wet or cold weather, which has an impact on the project schedule and quality of construction (BRANZ, 2020).

6.7 Embodied Carbon

The greenhouse gas emissions that are related to the extraction, manufacturing, transportation, installation, and disposal of building materials (the so-called embodied carbon) have become one of the key issues in climate-resilient construction (Pomponi & Moncaster, 2017). Although operational emissions have been continuously decreasing by the means of better efficiency standards, the share of embodied emissions has grown considerably, especially in new constructions. This renders embodied carbon a vital prism of evaluation of zero-carbon materials (Pomponi & Moncaster, 2017).

6.7.1 Strengths

- ✓ Most zero-carbon materials have a much lower embodied carbon footprint than traditional materials, such as concrete, steel or PVC. This is because of low-impact raw materials or the manufacturing processes are energy efficient (Dixit et al., 2012). Renewable or recycled materials are included into some materials which minimizes the emission that occur during both extraction and processing stages, thus helping to achieve circular economy objectives (Cabeza et al., 2014).
- ✓ On a larger systems-level analysis, these materials allow reducing the whole building lifecycle emissions to ensure that they are in line with national and international decarbonization goals (Giesekam et al., 2016). In certain natural materials, one can also have carbon sequestration in the growth phase, which further neutralizes their effects on the environment, especially in bio-based material such as timber, or hemp (IEA, 2022).
- ✓ The attributes assist in meeting a green building rating scheme like the Green Star and Homestar that recognizes the use of low-carbon materials. Besides, low-carbon processing techniques also lower emissions but enhance the sustainability appearance in the eyes of the population (MBIE, 2020a). Above all, at least, resources with confirmed low embodied carbon can contribute to aligning the outcomes of the project with the national carbon reduction target of New Zealand, especially at the time when the country aims to reach net-zero emissions by 2050 (MBIE, 2020a).

6.7.2 Opportunities

- ✓ The expanding availability of carbon reporting tools, including Environmental Product Declarations (EPDs), is improving transparency and benchmarking of material emissions (NZGBC, 2023a). Emerging standards and protocols, such as ISO 21930 and the EC3 tool, are driving consistency in how embodied carbon is measured and reported (IEA, 2022).
- ✓ In the meantime, policy requirements, such as in the procurement of infrastructure by government, are driving the industry to use low-carbon materials. On the material development level, bio-based and recycled innovations still reduce the carbon intensity of a variety of new products (World Green Building Council, 2019).
- ✓ Embodied carbon reduction incentive can also be provided in the form of carbon credits, where the cost of saving the carbon is given a market value. This, in combination with the increasingly widespread public awareness of the effects of carbon, places pressure on suppliers and developers to implement transparent sustainable solutions. Lastly, the EPDs are becoming more available, and the entry barriers to the certified and low-carbon markets are decreasing (Giesekam et al., 2016).

6.7.3 Weaknesses

- ✓ Restrict the use of low-embodied-carbon materials. As an example, certain products that have sustainability labels have a lot of transportation or processing emissions, especially in imports or extreme processing (Cabeza et al., 2014). Also, the data inconsistency is a problem that is commonplace- lots of materials do not have published or trustworthy embodied carbon values and it is hard to compare them (Giesekam et al., 2016).
- ✓ It is common to have carbon metrics checked through third-party evaluation, which is unavoidably costly to smaller suppliers or developers (Dixit et al., 2012). In addition, carbon estimates can be misleading due to the presence of hidden emissions in the supply chain, including the upstream energy consumption or offshore manufacturing unless life-cycle assessments are performed in full (Dixit et al., 2012).
- ✓ The difference in production techniques, even within the same product type, may also result in the uneven effects of embodied carbon, making it difficult to generalize conclusions. According to some researchers, the low-impact materials can be compensated by post-construction activities (e.g., renovation, repair, or replacement) to recover the original carbon savings (IEA, 2022). Moreover, certain types of carbon

reduction might not be certified by all, particularly in relation to new materials or hybrid ones that do not have a standardized documentation (IEA, 2022).

6.7.4 Threats

- ✓ Externally, they can subvert the embodied carbon benefit of sustainable materials. Although the purpose of carbon pricing policies is to encourage low-carbon alternatives, they are volatile, and so there is an uncertainty in long-term planning (IEA, 2022). The case of greenwashing is also on the rise - false carbon claims that are made by suppliers undermine trust and make it difficult to compare the products (World Green Building Council, 2019).
- ✓ Lack of obligatory report requirements also makes the process of standardising the accounting of carbon in projects even more problematic. Along with that, low levels of carbon literacy in designers, contractors, and procurement professionals delay the uptake and increase the lack of knowledge (Giesekam et al., 2016). The global supply chains which are fragmented also lead to low emissions traceability, which degrades carbon transparency claims (Giesekam et al., 2016).
- ✓ Policy-related threats include reversals or delays in national decarbonization strategies, which may weaken market signals for sustainable procurement (Hawkins et al., 2013).
- ✓ Carbon verification is a very high cost that may not favour smaller developers and it may not be a good incentive to engage in low-carbon transitions despite their interest or willingness (de Silva et al., 2025).

6.8 Availability

The availability of zero-carbon building materials significantly influences their integration into mainstream construction projects. Availability is shaped not only by production and distribution systems but also by geography, policy environments, and supply chain resilience. In a New Zealand context, issues such as remoteness, local production capacity, and import reliance are especially relevant (Murtagh et al., 2020).

6.8.1 Strengths

- ✓ The access to more sustainable materials has been gradually increasing, especially with the involvement of local suppliers, eliminating the need to import materials internationally and improving the reliability of procurement (BRANZ, 2020). Consequently, stock quantities have become more predictable, and wait time has decreased, and construction scheduling results are better (IEA, 2022).

- ✓ Some zero-carbon materials, including timber, straw, or flax-based composites, are obtained using renewable or fast-renewable sources, and they promote the unlimited supply under sustainable management (Dixit et al., 2012). Due to the increase in demand in the area of sustainable products, scalable production systems are presented, which allow suppliers to satisfy the needs of small and large projects (Giesekam et al., 2016).
- ✓ The variety of materials, in regards to its use in a wide range of structural and non-structural functions, is useful in reinforcing the chain of supply, particularly where one material can be substituted by another (BRANZ, 2020).
- ✓ Lowly imported dependent materials also provide an extra point of stability in supply especially during global disruption or remaining volatile trade (Murtagh et al., 2020).
- ✓ The increase in the number of manufacturer networks (such as public- private venture) has also increased the distribution coverage and variety of suppliers (MBIE, 2020a).

6.8.2 Opportunities

- ✓ Although it has strengths at present, additional opportunities of improving material availability can be achieved with dedicated innovation and policy. A significant opportunity to strategically invest in domestic production capacity is to produce many zero-carbon materials, especially advanced composites or prefabricated components (IEA, 2022).
- ✓ Also, there are seasonal or regional limits on year-round availability, such as harvesting based on climate or small-scale production. As an example, growing season restrictions can be applied on hemp or straw bales. Long lead times may be experienced where the production is decentralized, which slows down procurement or adds to storage needs (IEA, 2022).
- ✓ Small-scale production systems might also not be able to cover the needs of large urban developments, which shows the necessity of a scaling infrastructure and capacity-building. The remoteness of geographical locations, especially rural New Zealand, can become a cost and emission contributor to delivery, which presents a logistical issue to an otherwise sustainable decision (MBIE, 2020a). The new suppliers can be prevented by barriers to market entry like certification and monopoly of suppliers in supply contracts, and the next generation availability can be affected by scarcity of resources due to environmental or geopolitical stressors (World Green Building Council, 2019).

6.8.3 Weaknesses

- ✓ Availability-related weaknesses are also usually based on indirect economic costs as opposed to supply per se. An example is that increased start-up charges on sustainably sourced or certified materials may limit their accessibility in the market especially where price is sensitive (Dixit et al., 2012). These materials might also not be easily accessible in all locations, which means that specialized labour and equipment might be not easily accessible, further decreasing the level of practicality (Giesekam et al., 2016).
- ✓ Even otherwise low impact materials can be a subject of concern in regions where the supply region is limited and the distances incurred during transportation, as well as associated carbon emissions. This can also increase the cost of transport, particularly into remote or offshore locations. Besides, the long payback period (because of the initial cost premiums) may cause financial reluctance, especially in smaller companies or governmental projects (Mata et al., 2020).
- ✓ Other issues are non-standard sizing and finish that may make the process of stock planning and procurement harder, and further certification requirements that cause documentation burdens. Within a financial analysis of short terms, a sustainable material can be priced reasonably higher than its counterpart, which is priced more reasonably in the long term (Giesekam et al., 2016).

6.8.4 Threats

- ✓ Outside the organisation, the availability landscape is affected by several threats. It may be volatile due to price volatility, which could be based on fuel prices, tariffs on imports, or the scarcity of raw materials and therefore discourage adoption. An increase in interest rates can render loans or financing sustainable projects less appealing, which indirectly slows down demand (IEA, 2022).
- ✓ Competition based on price only in flooded markets of cheaper, carbon-intensive materials can force zero-carbon choices out of the market. The wider economic recessions or recessions could lower the eagerness of the construction sector to invest in long-term sustainable solutions (World Green Building Council, 2019). Meanwhile, poorly implemented carbon pricing policies would also be a cost to production with no adequate incentives to counter these costs.
- ✓ Policy delays or reverses can also have an impact on financial planning particularly the incentive program or the rebate program. Lastly, the price of materials can be influenced

by inflationary factors because even sustainable materials can remain expensive even with their benefits in terms of environmental and performance (Dixit et al., 2012).

6.9 Aesthetics

Aesthetic value is still a very powerful determinant in the choice of materials particularly in architectural designs where aesthetic harmony, style, and perception by the users are very crucial. Although the performance and sustainability metrics usually take up the centre stage of decision-making frameworks, visual, textural and design-related features of materials can make a significant contribution to the user experience and marketability.

6.9.1 Strengths

- ✓ Zero-carbon materials: zero-carbon materials are progressively featuring unique visual properties, which attract both architects and clients. Natural textures and organic visual variation are found in many of these materials, rammed earth, cross-laminated timber, or straw-bale plastered finish, to improve the authenticity of architecture and are sought after in contemporary biophilic and minimalist architecture (Giesekam et al., 2016).
- ✓ Such materials tend to be versatile and can be used in a variety of architectural styles, including traditional and modern ones, which is why they can be named flexible in terms of being applicable within a broad range of architecture applications (Cabeza et al., 2014). Ability to customize such as tinting, surface etching, and coating gives the design flexibility, and the tactile qualities such as softness, warmth or natural roughness give the interior environment a perceived level of comfort (World Green Building Council, 2019).
- ✓ Notably, the process of natural aging or weathering of some natural materials gives aesthetic qualities to the materials instead of undermining the beauty. This is in line with the design philosophies that would prefer material honesty and lifecycle revelation. Lastly, the expressive and unpredictable results of sustainability design can be achieved through the multiple mechanisms of creativity of many sustainability materials and are becoming a more valued part of architecture award programs and the sustainable building displays (NZGBC, 2023a).

6.9.2 Opportunities

- ✓ There is a trend in the design community to adopt biophilic and nature-inspired building materials, and the industry and consumer shift toward the use of more authentic and environmentally conscious visual finishes (IEA, 2022). Advanced fabrication

techniques, such as CNC milling, additive manufacturing, and digital surface modelling, are expanding the design versatility of sustainable materials, enabling their use in complex architectural geometries (BRANZ, 2020).

- ✓ Public and professional education campaigns are slowly changing the perception of aesthetic value and repackaging sustainability as a design asset, but not as a compromise (World Green Building Council, 2019). Sustainability certifications are also shifting towards a more visual performance much like aesthetics is associated with more overall objectives, such as occupant well-being and environmental psychology (NZGBC, 2023a).
- ✓ Moreover, there are also interactions with the lighting, the patterns of ventilation, and superimposition of texture, which are also improving the visual effect of these materials in practical work. Major architects are also extensively demonstrating zero-carbon materials in high profile projects and this further justifies its use in design-oriented construction (NZGBC, 2023a).

6.9.3 Weaknesses

- ✓ With all these developments, there is still the issue of aesthetic constraints. Not every stylistic preference can be compatible with some zero-carbon materials, especially in the area of heritage or project which prefer high-gloss finishes (Cabeza et al., 2014). Such differences in appearance are natural and may be valued by some people, but they may be perceived as inconsistent or worse still inferior by others, particularly in an institutional setting or business.
- ✓ The scarcity of coating, textures, or finishes can limit the appeal in a case when the polished or controlled coloration of the surface is needed (Dixit et al., 2012). It can fade or be discoloured with time because of being exposed to sunlight, water, or pollution and requires repair or refurbishing. In other instances, cleaning or conditioning is required regularly to maintain the original visual effect, which increases the operational requirements.
- ✓ Aesthetic design freedom may be undercut by the technical properties of certain materials: rigidity or brittle materials cannot be used when this property is needed somewhere (to create a curve or inbuilt lighting, etc.). Also, the perceived rustic or unfinished materials are sometimes seen as low-end or unfinished construction, and therefore they are not used in the high-status developments (Giesekam et al., 2016).

6.9.4 Threats

- ✓ External externality of aesthetic uptake: Polished steel, aluminium, or painted plaster that is a dominant feature of urban and commercial design standards is biased. The unorthodox finishes can also have their approval restricted by zoning rules or heritage restrictions regardless of whether they are sustainable or not (MBIE, 2020a).
- ✓ Misconceptions regarding aesthetical inferiority in the market group can restrain the acceptance, and non-uniform supply can harm the colour or texture consistency particularly in bio-based products. Colour-matching or patterning might be a more costly option that is not used in projects where the budget is a major concern (IEA, 2022).
- ✓ Finally, aesthetic changes in architecture are habitually fast and therefore what looks beautiful today becomes a forgotten finish tomorrow. The perceptions might also be reinforced by negative media coverage or bad design implementations, particularly in the speculative housing or commercial projects where the focus on branding overshadows experimental experiments (IEA, 2022).

6.10 Discussion and Conclusion

This paper has reviewed existing literature to generate a SWOT analysis of building material of zero carbon in six major dimensions which are specific to the construction scenario in New Zealand. The discussion has demonstrated that these materials have a significant promise of achievement in climate-constructive development; however, the application is not possible because of the systemic and market-level barriers. This SWOT analysis is based on literature which offers a multi-facet analysis of zero-carbon building materials in relation to six major criteria: Cost-Effectiveness, Durability, Buildability, Embodied Carbon, Availability, and Aesthetics. The results indicate that even though zero carbon materials have significant long-term benefits, the implementation of such materials remains suppressed by cost-related, technical, logistical and perceptual factors. On all six dimensions, the most consistent strengths are associated with long-term environmental and operational benefits. As an example, it was shown that materials have high potential in reducing lifecycle emissions and the maintenance costs, which can be aligned with the targets of the low-carbon transition in New Zealand. The aspects of durability and embodied carbon became especially important, and considerable literature evidence that they help to maintain resilience, align with rating tools, and reduce the carbon content in a whole building (Giesekam et al., 2016; Mata et al., 2020).

Meanwhile, such relentless vulnerabilities and threats indicate that system-wide responses will be needed to promote widespread implementations. Issues like high initial expenses, non-standardisation, restricted availability within a region and specialised labour needs have been noted. These results are also corroborated by previous research that suggested that market uncertainty, disjointed supply chains, and regulatory inconsistencies still stand as significant hurdles (Dixit et al., 2012; World Green Building Council, 2019).

The opportunities, in their turn, are in technological, regulatory, and educational areas. New design tools, green financing platforms as well as policy requirements are starting to change the status quo in the industry, which is a way of mainstream acceptance. The increasing focus on aestheticist, manufacturing essence and carbon reporting transparency also signify the emergence of the culture shift in the construction industry towards appreciating low-carbon design. Table 6.1 has a summary of the SWOT of each criterion.

Table 6.1: summarizes the SWOT statements categorized for each criterion

Criterion	Strengths	Weaknesses	Opportunities	Threats
Cost-Effectiveness	Lower maintenance costs; eligibility for financial incentives; life-cycle savings; alignment with green certifications.	High upfront cost; need for specialized labour; transportation costs; admin burden of certifications.	Climate-aligned loans; cost-sharing programs; improved design tools for early cost prediction.	Price volatility; rising interest rates; competition with conventional materials; policy delays.
Durability	High resistance to UV and moisture; long service life; biological resistance; reduced repair frequency.	Degradation under exposure; need for protective coatings; inconsistent performance.	Disaster resilience premiums; extended warranties; predictive maintenance tools.	Harsh weather patterns; counterfeit materials; poor installation practices; cleaning chemical damage.
Buildability	Lightweight and easy to handle; compatible with off-site construction; reduces waste and on-site hazards.	Requires specialized tools; weather sensitivity; misalignment with current standards.	Training programs; regulatory updates; integration with digital construction (CNC, 3D printing).	Skilled labour shortage; resistance from contractors; retrofit incompatibility.

Embodied Carbon	Low-impact materials; support for circular economy; aligns with carbon targets.	Data inconsistency; hidden emissions in supply chain; high verification costs.	Rise of EPDs; carbon credit markets; new low-carbon innovations.	Carbon pricing volatility; greenwashing; poor carbon literacy; policy reversals.
Availability	Growth in local supply chains; versatility across applications; reduced import reliance.	High transport costs in rural areas; non-standard sizes; long lead times.	Scaling local production; innovation in decentralized systems.	Trade volatility; raw material scarcity; monopolized supply chains.
Aesthetics	Natural visual appeal; adaptability to design styles; customization flexibility.	Perceived rustic look; fading or discoloration; limited finish options.	Biophilic design trend; evolving certification standards; advanced fabrication tools.	Design trend shifts; bias toward conventional materials; approval constraints in heritage zones.

Nonetheless, the effectiveness of such implementation will rely on the capacity of the sector to overcome technical constraints in addition to refurbishing value in alignment with the lifecycle impact and not only the cost per se. In addition, policy and industry should facilitate the local production scale, standard carbon calculations, and the visual and design plasticity of zero-carbon materials to boost the consciousness of the citizens and professionals. The given SWOT framework is a strategic evidence base of the inception of future work in the field of MCDM tools (e.g., AHP, MCDA), which may assist the stakeholders to rank or compare materials by project-specific needs. The findings underscore the need of:

- Clear carbon performance data and verification standards,
- Education and upskilling within the construction workforce,
- Integration of zero-carbon options into regulatory and procurement frameworks, and
- Greater public and design-sector awareness of the aesthetic and functional value of sustainable materials.

This SWOT framework provides the future architects, engineers, developers, and policymakers with the foundations to develop further decision support systems that will assist them in selecting materials considering the pros and cons. As New Zealand approaches its 2050 net-

zero goals, formal review instruments like which will be valuable in closing the gap between environmental aspiration and construction sector practice.

The SWOT analysis extends the quantitative findings of Chapter 5 by showing why the six criteria may operate differently across actual construction contexts. Cost and availability, for example, are affected by market volatility and supply-chain conditions, while buildability depends on labour capability, regulatory acceptance, and compatibility with established systems. Chapter 7 uses the quantitatively assessed criteria as the computational structure of the DST, while retaining the SWOT findings as contextual evidence for interpreting rankings, limitations, and implementation risks.

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STATEMENT OF CONTRIBUTION
DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the student and the student's main supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the student's contribution as indicated below in the Statement of Originality.

Student name:	Ali Hashemi Araghi
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In which chapter is the manuscript/published work?	Chapter 7

Describe the contribution that the student and members of the supervisory team have made to the manuscript/published work:[1]

Conceptualization, A.H.A.; methodology, A.H.A.; software, A.H.A.; validation, A.H.A.; formal analysis, A.H.A.; investigation, A.H.A.; resources, A.H.A.; data curation, A.H.A.; writing—original draft preparation, A.H.A.; writing—review and editing, A.H.A., E.O.R., V.V. and J.S.; visualization, A.H.A.; supervision, E.O.R., V.V. and J.S.; project administration, A.H.A.; funding acquisition, E.O.R., V.V. and J.S. All authors have read and agreed to the published version of the manuscript.

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Chapter 7: Developing and validating the decision-support tool

This chapter is based on the MDPI -Civil Engineering Journal article, which is under review:

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7.1 Chapter Summary

This chapter detailed the development, implementation, and validation of a practitioner-oriented DTS designed to assist early-stage selection of low- and zero-carbon building materials within the New Zealand construction context. Grounded in MCDM theory, the chapter translated empirically derived practitioner priorities into an operational weighted-sum model incorporating six evaluation criteria: cost effectiveness, durability, buildability, embodied carbon, availability, and aesthetics.

The chapter first outlined the conceptual structure of the tool, including the derivation of criteria and weighting factors from a large-scale national survey of construction professionals. These weights were normalised and embedded directly into the scoring engine to ensure that material rankings reflect real-world practitioner decision logic rather than researcher-imposed assumptions. Each criterion was decomposed into clearly defined evaluation items and measured using five-level ordinal performance scales informed by standards, life-cycle assessment conventions, and industry practice.

The technical implementation of the tool was then described, including its Python-based architecture, Streamlit user interface, and transparent weighted-sum scoring algorithm. The design prioritised accessibility, interpretability, and reproducibility, enabling users to compare alternative materials and examine both aggregated scores and item-level contributions. Sensitivity analysis demonstrated that material rankings remain generally stable under moderate variations in criterion weights, supporting the robustness of the adopted aggregation approach for screening-level decision support.

Validation was conducted through a structured three-round Delphi process with a purposively selected panel of built-environment experts. The Delphi results confirmed consensus on the relevance and completeness of the evaluation criteria, the plausibility of the weighting structure, and the credibility of the tool's outputs. Areas requiring refinement were identified and addressed iteratively. Convergent validity was further supported by consistency between tool-generated material rankings and empirical survey results.

This chapter established the methodological rigour, transparency, and practical grounding of the proposed DTS. It provides a validated foundation for the results and discussion presented in subsequent chapters and demonstrates how empirically informed MCDM frameworks can be operationalised to support carbon-informed material selection in real-world construction practice.

7.2 Introduction

The global construction sector is undergoing a fundamental transition as nations accelerate efforts to meet net-zero emissions targets (Aeinehvand et al., 2021; Hashemi Araghi et al., 2022; Lamb et al., 2021). While operational energy has historically dominated decarbonisation strategies, embodied carbon now represents a rapidly growing share of total life-cycle emissions (Myint et al., 2025; Zhang et al., 2024). In high-performance, energy-efficient buildings, embodied emissions can exceed 50% of whole-life carbon, making material choices a decisive factor in climate-aligned design (Röck et al., 2023; Shindo et al., 2023). This shift places increasing emphasis on selecting building materials that minimise carbon intensity while maintaining structural, economic, and design performance (Baghaei Daemei & Jamali, 2022; Hashemi Araghi, 2014; Khotbehsara et al., 2018).

However, evaluating these trade-offs remains challenging for practitioners, as materials differ substantially in durability, service life, supply chain risks, aesthetic qualities, and long-term maintenance requirements (Liu & Leng, 2022; Röck et al., 2023). A growing body of literature highlights that reducing embodied carbon is particularly important in countries with pressing decarbonisation agendas and limited domestic manufacturing capacity, such as New Zealand (Bui et al., 2022; Bui et al., 2023). The country's construction sector faces distinctive constraints, including heavy reliance on imported materials, fragmented supply chains, and inconsistent availability of low-carbon alternatives, all of which complicate material specification and procurement decisions (Hashemi Araghi & Sakhaee, 2014; Myint & Shafique, 2024). At the same time, climate policy developments are placing new expectations on designers and clients to demonstrate carbon-informed decision-making (Bahrami et al., 2022; Hu et al., 2025).

Zero-carbon building materials such as engineered timber, hempcrete, rammed earth, and straw bale have gained international attention for their ability to drastically reduce life-cycle impacts while offering renewable or carbon-sequestering properties (Hashemi Araghi et al., 2025; Tong & Memari, 2025). Recent studies emphasise their performance benefits, including thermal stability, moisture regulation, and competitive structural characteristics when properly engineered (Kosiński et al., 2025; Xu et al., 2023). Nevertheless, widespread adoption remains

limited due to concerns related to supply chain maturity, workmanship skills, code compliance, and perceived construction risks (Le et al., 2024). This underscores the need for decision-support approaches that help practitioners systematically compare materials across environmental and practical criteria (Araghi et al., 2024; Bajwa et al., 2025).

In response to these challenges, multi-criteria decision-making (MCDM) frameworks have emerged as powerful tools to support material evaluation, enabling transparent weighting of factors such as embodied carbon, cost, durability, buildability, availability, and aesthetic value (Frahat et al., 2024). Integrating such frameworks into digital platforms further enhances accessibility, allowing designers, engineers, policymakers, and clients to assess material performance in real time (Collinge et al., 2022). However, recent reviews indicate that many existing tools lack contextual alignment with local industry realities, especially in small or geographically isolated markets (He et al., 2021). This gap is particularly evident in New Zealand, where region-specific data, practitioner preferences, and market constraints must be incorporated into decision models to ensure realistic and actionable outputs.

Recent research has extensively employed multi-criteria decision analysis (MCDA) frameworks to support sustainability evaluation across construction materials, structural systems, infrastructure projects, and broader production and supply chain contexts. For example, sustainability assessment of conductive concrete mixes for pavement deicing has been conducted using composite sustainability indices and the applied effect of changes intensity in each indicator (AECIEI), enabling systematic comparison of alternative mix designs under environmental, economic, and technical criteria (Shishegaran et al., 2021). Similarly, MCDA approaches combining life-cycle indicators with expert-derived weights have been applied to evaluate optimised structural systems for tall buildings, where TOPSIS and AECIEI were used comparatively to rank alternative lateral load-resisting systems based on sustainability performance (Shishegaran et al., 2022).

At the material scale, sustainability evaluation of artificial stone produced from industrial and hazardous waste streams has demonstrated the usefulness of MCDA for comparing recycled and conventional construction materials, again employing TOPSIS and AECIEI to capture environmental, technical, and economic trade-offs (Shishegaran et al., 2025). Comparable MCDA-based sustainability assessments have also been reported for large-scale transportation infrastructure, such as system interchanges, where environmental, social, and economic indicators were integrated to rank alternative development scenarios (Shishegaran et al., 2020). Beyond the construction sector, sustainability evaluation frameworks have further been

extended to agricultural production and supply chains, where multi-criteria approaches are used to balance environmental impacts, economic viability, and system transparency, often in conjunction with digital and computational intelligence tools (Rezaie & Shishegaran, 2025).

MCDM frameworks are widely used in construction and environmental decision-support because they decompose multi-dimensional problems into structured evaluation criteria. For example, Zavadskas et al. (2015) and Mardani, Jusoh, Zavadskas, et al. (2015) highlight the broad applicability of MCDM methods in construction engineering and energy planning. In the context of material selection, a single metric such as embodied carbon cannot capture technical, environmental, economic and practical considerations; MCDM provides a theoretical foundation to integrate diverse factors into a transparent and replicable decision process.

The weighted-sum model (WSM) is one of the simplest and most widely applied MCDM techniques (Mardani, Jusoh, Md Nor, et al., 2015; Triantaphyllou, 2000). It converts a multi-criteria problem into a single objective by assigning weights to each criterion and summing the weighted scores (Figueira et al., 2005). The WSM is popular because of its simplicity and ease of interpretation, making it well suited to early-stage design decisions (Huang et al., 2011). However, WSM assumes linear trade-offs between criteria and can be sensitive to the selection of weights, which may introduce subjectivity (Greco et al., 2016).

The WSM was selected because the purpose of the DST is to provide a transparent and readily interpretable screening-level comparison of candidate materials. The six criteria were assessed using a common five-point performance scale, and their normalised weights summed to 100%, making additive aggregation appropriate. The method also allows users to understand how each criterion contributes to the final score, which is important for practical use by architects, engineers, construction managers and other stakeholders.

Alternative weighting and MCDM methods were considered but were not adopted. The Analytic Hierarchy Process (AHP), for example, derives weights through pairwise comparisons. With six criteria, each participant would need to complete 15 pairwise comparisons, increasing respondent burden and requiring additional consistency testing. The survey conducted in this study collected direct importance ratings from 203 construction professionals rather than pairwise-comparison data; therefore, applying AHP retrospectively would not have been methodologically appropriate. Equal weighting was also rejected because it would disregard the differences in criterion importance identified by respondents. Purely data-driven weighting methods, such as entropy weighting, were not selected because the

purpose was to represent practitioners' expressed priorities rather than variation within the performance data.

Ranking methods such as TOPSIS were not adopted because they require the construction of ideal and anti-ideal alternatives and can be sensitive to the selected normalisation procedure. This additional complexity was unnecessary for the intended screening-level application, which required a clear explanation of how each criterion contributed to a material's final score. Similarly, outranking and fuzzy MCDM methods would require additional preference thresholds, membership functions or assumptions that were not supported by the available empirical data.

The WSM does assume preferential independence and compensability, meaning that stronger performance under one criterion can offset weaker performance under another. This limitation was addressed by using clearly defined scoring scales, empirically derived and normalised weights, sensitivity analysis, and Delphi expert review. The WSM was therefore considered the most appropriate balance of empirical grounding, transparency, usability and analytical rigour for the intended DST.

As such, this research aims to develop and validate a decision-support tool that enables practitioners to systematically compare zero-carbon building materials using a locally grounded MCDM framework. By integrating real-world industry data into a digital platform, the tool supports carbon-informed, practical, and contextually appropriate material selection for the New Zealand construction sector. The overarching aim of this study is to develop and validate a practitioner-oriented decision-support tool for evaluating low- and zero-carbon building materials within the New Zealand construction context. To achieve this aim, the study pursues the following specific objectives:

- (O1) To identify and structure a set of environmental, economic, and durability-related criteria relevant to early-stage material selection for low- and zero-carbon construction.
- (O2) To quantify practitioner preferences and priority trade-offs among these criteria using large-scale survey data.
- (O3) To calibrate and validate the evaluation framework through expert review using a Delphi process.

- (O4) To implement the framework within an operational multi-criteria decision-making (MCDM) tool and assess its internal consistency and alignment with practitioner judgment.

Together, these objectives ensure that the proposed tool is both methodologically grounded and practically relevant for screening-level material evaluation. Table 1 summarises the alignment between Objectives O1–O4, the methods used to address each objective, and the sections in which the associated outputs are presented. This mapping is intended to clarify the internal logic of the study and to support reproducibility and interpretability of the proposed decision-support framework.

Table 7.1: Mapping between research objectives, chapters, methods, outputs, and contributions to the DST

Research objective	**Chapter and methodological approach**	**Main output**	**Contribution to the DST**
O1: Investigate common low- and zero-carbon materials	Chapter 3: scoping review of academic and industry evidence	Candidate material categories and initial evidence concerning benefits and limitations	Defined the material domain and candidate alternatives
O2: Identify factors influencing material selection	Chapter 4: systematic literature review	Material-performance themes, evidence gaps, and areas requiring empirical investigation	Provided the conceptual evidence base for factor development
O2 and O3: Evaluate selection factors and their relationships with material adoption and carbon considerations	Chapter 5: practitioner survey, descriptive analysis, one-sample tests, and PLS-SEM	Empirical ratings, structural relationships, and baseline criterion weights	Supplied practitioner-informed criteria assessment and baseline weights
O2 and O3: Examine the contextual implications of the selection criteria	Chapter 6: literature-based SWOT analysis	Strengths, weaknesses, opportunities, and threats associated with the six criteria	Added contextual evidence concerning implementation barriers, risks, and enabling conditions
O4: Develop and validate the DST	Chapter 7: WSM implementation, sensitivity analysis, and three-round Delphi study	Operational digital tool, tested scoring logic, expert feedback, and validation evidence	Translated the preceding evidence into the final DST and identified areas for refinement

The SWOT analysis constituted the principal method used to address Research Objective 3. It did not independently generate or numerically weight the six selection criteria. Instead, it

examined the contextual strengths, weaknesses, opportunities and threats associated with each criterion. The findings informed the practical interpretation of the DST outputs by identifying implementation barriers, risks, enabling conditions and contextual trade-offs. The numerical criterion weights were derived separately from the practitioner survey reported in Chapter 5.

The SWOT analysis did not independently determine the numerical criterion weights. Its role was interpretive and contextual: it examined implementation conditions, risks, and opportunities associated with the six criteria after their quantitative evaluation in Chapter 5. These findings informed the interpretation of tool outputs and the contextual considerations presented to users and decision-makers. Numerical weights were derived separately from the practitioner survey and evaluated through sensitivity analysis and Delphi review.

From an industry perspective, the study responds to the need for practical, interpretable tools that support early-stage material comparison under time, cost, and regulatory constraints. The framework enables practitioners to consider embodied carbon alongside cost, durability, buildability, availability, and aesthetics within a single structured evaluation logic. This supports more informed trade-off reasoning and aligns material selection with both environmental targets and construction realities in the New Zealand context. More broadly, the study contributes a transferable methodological approach for embedding regional priorities into sustainability-driven decision-support systems. While the framework is calibrated to New Zealand conditions, the underlying structure may be adapted to other regulatory and market contexts where low-carbon material adoption is constrained by competing technical and economic demands.

In the New Zealand context, several resources support sustainable building decision-making, including regulatory guidance (e.g., Building Code requirements), advisory tools and calculators provided by government agencies, and technical guidance published by research organisations and industry bodies. These resources primarily focus on compliance, energy performance, or single-issue metrics, and typically address decisions at the building or system level rather than material-level trade-offs. While valuable, they do not provide an integrated, multi-criteria mechanism for comparing low- and zero-embodied-carbon materials based on practitioner-defined priorities at the early design stage.

This study addresses a critical gap between the growing availability of low- and zero-carbon construction materials and the limited decision-support capacity available to practitioners to evaluate these materials in a structured, transparent, and context-specific manner. While life-

cycle assessment and sustainability rating systems provide valuable environmental metrics, they are often too complex, costly, or disconnected from everyday design decision-making to be routinely applied by architects and builders. By translating empirically derived practitioner priorities into an operational multi-criteria decision framework, this study contributes to knowledge by demonstrating how stakeholder-driven weighting structures can be systematically embedded within material selection processes for low-carbon construction. In doing so, it strengthens the link between sustainability theory and real-world construction practice.

7.3 Material and Methods

Development of the DST involved six connected analytical stages. First, literature synthesis was used to define the candidate material-selection criteria and their sub-criteria. Second, a survey of New Zealand construction professionals evaluated the importance of the six criteria. Third, PLS-SEM was used to assess the measurement model and examine relationships between the criteria and material adoption. Fourth, the direct survey importance ratings were normalised to produce criterion weights for the decision model. Fifth, material-performance inputs were converted to common ordinal performance scores and aggregated using a Weighted Sum Model. Finally, Delphi review and sensitivity analysis were used to assess the relevance, clarity, and stability of the resulting framework. These stages served different purposes; in particular, the SEM coefficients were not used directly as the DST weights.

7.3.1 Overview of the Tool

The goal of the zero-carbon material evaluation tool is to provide architects, engineers and policymakers with a systematic means of comparing construction materials based on sustainability performance. To achieve this, the tool employs a MCDM framework that aggregates scores across six weighted categories: durability, cost effectiveness, buildability, embodied carbon, availability and aesthetics. MCDA methods are designed to balance multiple objectives and reduce bias by explicitly weighting criteria and structuring trade-offs. Figure 1 shows the interface where users select a material and rate its durability characteristics.

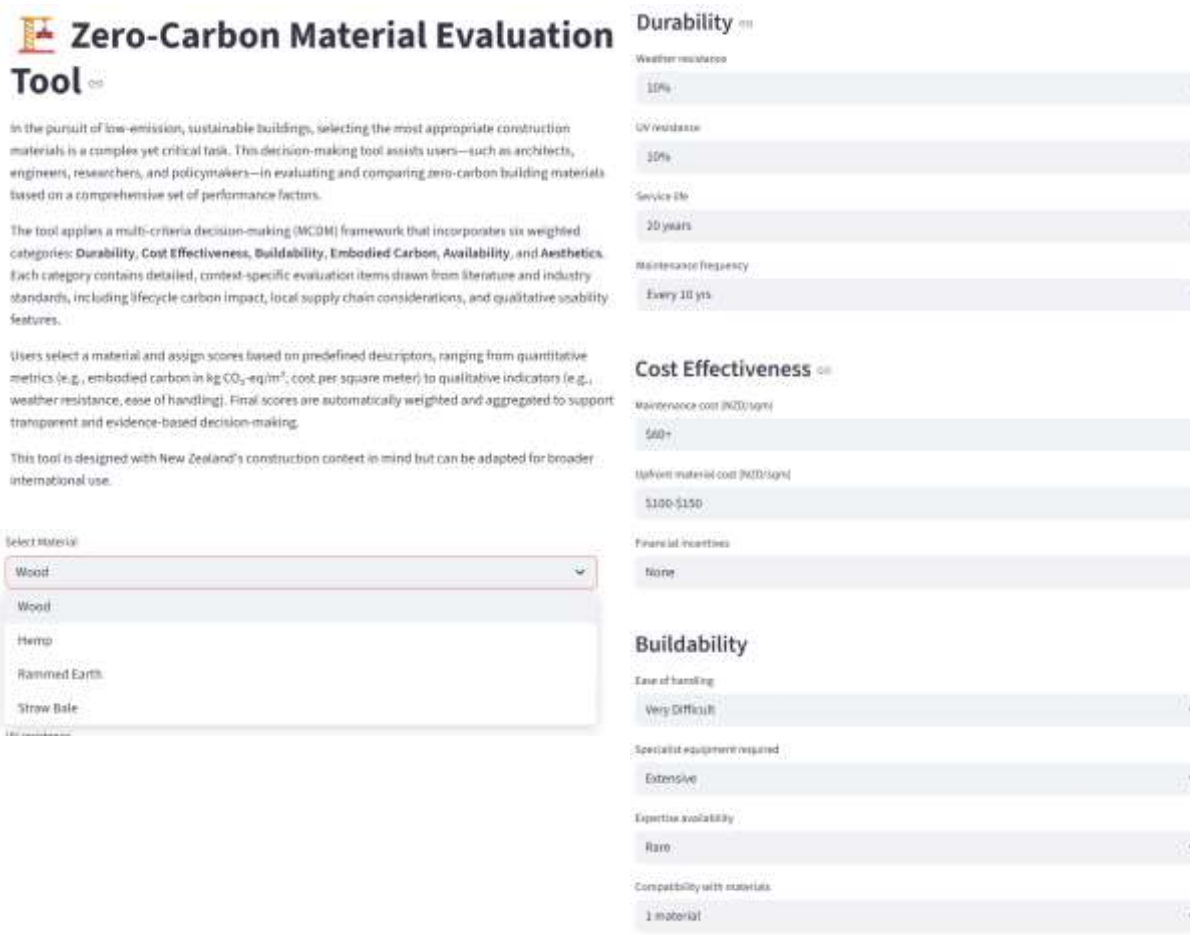


Figure 7.1: Some screenshots of the user interface of the zero-carbon material evaluation tool displaying the introduction and durability scoring fields (Source: the authors). For further details, refer to the URL provided in the Data Availability Statement at the (https://decision-tool-kebcwwd99cfqukfdbc7cue.streamlit.app/)

The zero-carbon material evaluation tool consists of a Streamlit-based user interface, a data input module, a weighted scoring module, and an output display module. Figure 2 illustrates the flow of data through these components, showing how user inputs are processed using predefined criteria and weights stored within the system, and how final material scores are generated and displayed.

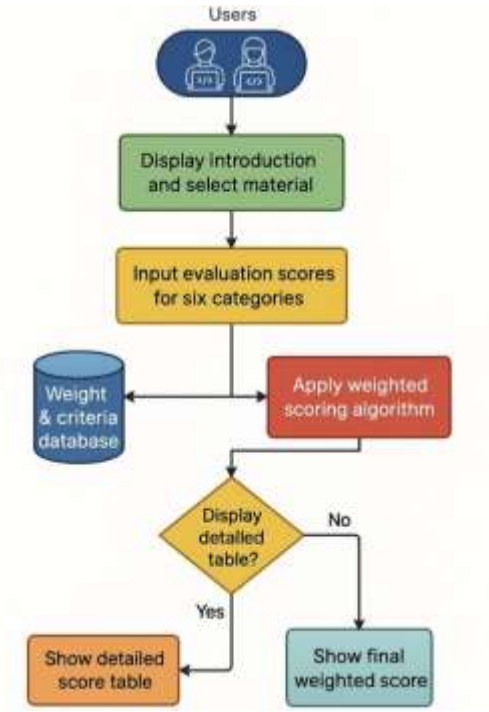


Figure 7.2: Flowchart of the zero-carbon material evaluation tool interface, showing the sequence of user interactions and processing steps (Source: the authors)

In this paper, the term "zero-carbon materials" is used in a screening-level embodied-carbon sense rather than implying absolute zero emissions across the full building life cycle. The assessment boundary is defined as cradle-to-gate (modules A1–A3), consistent with common practice in early-stage material comparison and the structure of most available environmental product declarations (EPDs). Modules beyond production, including transport to site, construction processes, use-phase impacts, and end-of-life scenarios (A4–C), are not explicitly modelled and are instead partially represented through proxy indicators such as durability, availability, and end-of-life recovery potential within the multi-criteria framework. Materials are considered "zero-carbon" where their reported cradle-to-gate embodied carbon intensity is very low relative to conventional alternatives, or where net-zero claims are supported by third-party verified disclosures, such as EPDs reporting offsetting or biogenic carbon storage. The tool does not independently verify offset quality or permanence; such claims are treated as input assumptions consistent with screening-level decision support.

7.3.2 Deriving Criteria and Weights

The weighting structure is derived from a national survey of 203 construction professionals conducted in New Zealand, including architects, engineers, construction managers, and sustainability practitioners. Participants were recruited using a purposive industry-based sampling strategy, and the survey instrument was empirically validated using structural

equation modelling, confirming the relevance and interrelationships of the six criteria (Araghi et al., 2025). Key sampling, response, and instrument quality details are summarised here; additional instrument development details are reported in [40]

Criteria selection was informed by a review of life-cycle assessment literature, New Zealand building standards, and prior survey research that examined practitioner perceptions of material selection priorities (Araghi et al., 2025). That analysis showed that embodied carbon and material availability had the strongest direct effects on material adoption, while cost effectiveness and durability were indirectly influential through their interactions with practical and environmental considerations. In that study, 203 construction professionals rated the importance of six material selection factors: cost effectiveness, durability, buildability, embodied carbon, availability, and aesthetics. These mean importance scores represent the relative strength of practitioner preferences. To convert these empirical preferences into a form suitable for use in a WSM, the mean scores were normalised so that their total equals 100%. This normalisation step is a standard requirement in additive MCDM models, where weights must be expressed on a common ratio scale to ensure mathematical consistency, interpretability, and comparability across criteria (Figueira et al., 2005; Malczewski, 2006; Triantaphyllou, 2000). Without normalisation, the resulting weighted scores would be scale-dependent and could distort trade-off relationships between criteria.

The weighting procedure deliberately separated construct validation from preference weighting. PLS-SEM was used in Chapter 5 to assess the measurement model and estimate relationships between the six criteria and material adoption. However, the SEM path coefficients were not used as DST weights because they are conditional regression-type estimates that depend on model specification, covariance among predictors, and the selected outcome variable. They do not directly represent the trade-offs that users are willing to make among decision criteria.

The final DST weights were instead derived from respondents' direct importance ratings. This approach was selected because all six criteria were evaluated using the same five-point response scale and the resulting means directly represented the aggregated priorities reported by 203 construction professionals. For each criterion *f*, the normalised weight was calculated as:

$$w_f = \frac{\bar{x}_f}{\sum_{k=1}^{6} \bar{x}_k}$$

Applying this procedure produced weights of 19.29% for cost-effectiveness, 19.13% for durability, 17.79% for buildability, 15.71% for embodied carbon, 14.41% for availability, and 13.66% for aesthetics. These values preserve the relative ordering of practitioners' stated priorities while placing all criteria on the common ratio scale required by the weighted-sum model.

The normalised weights were encoded directly into the DST's weighted-sum scoring algorithm. For each candidate material, its performance rating under each criterion was multiplied by the corresponding criterion weight. The six weighted values were then summed to calculate the material's overall score:

$$S_m = \sum_{i=1}^{6} w_i r_{mi}$$

In this calculation, S represents the overall score for a candidate material, W represents the normalised weight assigned to each criterion, and R represents the material's performance rating under that criterion. Candidate materials were ranked according to their overall weighted scores. Therefore, criteria with higher weights made proportionally greater contributions to the final results, while all six criteria remained represented in the decision.

The relatively narrow range of weights reflects the fact that respondents considered all six criteria relevant. Consequently, no single criterion dominates the DST output. This is appropriate for a screening-level tool intended to support balanced comparison, although it also means that the distinction between the most and least weighted criteria is modest. The weights represent aggregate practitioner preferences from the study sample, not universal or prescriptive values. Users may therefore recalibrate them for different project types, regions, or stakeholder priorities.

This approach, deriving weights from expert or stakeholder mean ratings and normalising them to unity (or 100%), is widely adopted in construction and sustainability decision-support studies (Huang et al., 2011; Mardani, Jusoh, Zavadskas, et al., 2015; Zavadskas et al., 2014). It preserves the relative preference structure expressed by respondents while translating subjective importance judgements into quantitative weights compatible with additive aggregation. Following this standard procedure, the normalised weights obtained were 19.29% for cost effectiveness, 19.13% for durability, 17.79% for buildability, 15.71% for embodied carbon, 14.41% for availability, and 13.66% for aesthetics. These weights represent the

empirically derived priority ordering of criteria within the New Zealand construction context and are encoded directly in the tool's scoring engine. This ensures that the final material rankings reflect real practitioner decision logic rather than researcher-imposed assumptions.

The weighting structure was derived from a survey of 203 New Zealand construction stakeholders. Eligibility criteria required respondents to have professional experience working within the New Zealand construction sector and involvement in construction-related decision-making (e.g., design, engineering, project delivery, sustainability, or procurement).

Recruitment was conducted through professional associations, industry mailing lists, industry events, and targeted outreach to construction firms and consultants. A total of 266 surveys were distributed, including 60 online invitations and 206 in-person invitations, resulting in 203 valid responses and an overall response rate of approximately 76%.

Respondents represented architecture, engineering, construction management, and sustainability-related roles. Instrument quality was previously validated using structural equation modelling, with acceptable internal consistency (Cronbach's $\alpha > 0.70$ across all constructs) and satisfactory model fit indices reported in the original validation study [40].

Potential sources of bias include self-selection and geographic concentration within New Zealand. However, comparison of respondent and non-respondent characteristics (professional role and years of industry experience) revealed no meaningful differences, reducing concerns regarding systematic non-response bias. The resulting weights are therefore considered suitable for representing aggregated practitioner preferences within the New Zealand construction context. To support reproducibility and enable assessment of potential bias associated with the survey-derived weighting structure, Table 2 summarises the key characteristics of the underlying practitioner survey, including recruitment approach, participant profile, instrument reliability indicators, and identified sources of bias.

Table 7.2: Summary of survey characteristics underpinning weighting derivation

Item	Description
Invitations sent	266
Modes	online + in-person
Response rate	76% (203 valid) construction stakeholders
Sample size	203 construction professionals

Recruitment	Industry associations, mailing lists, direct contacts
Disciplines	Architecture, engineering, construction management, sustainability
Experience	NZ Work Experience
Instrument validation	SEM-based CFA
Reliability	Cronbach's $\alpha > 0.70$ (all constructs)
Primary bias risk	self-selection, geography, mode effects, NZ-specific professional sample

7.3.3 Deriving Criteria and Weights

The Weighted Sum Model was selected after considering the analytical requirements and intended use of the DST. The tool is intended to support transparent, early-stage screening rather than detailed optimisation or final regulatory approval. It combines economic, environmental, technical, and qualitative indicators that have been converted to a common performance scale. It must also allow practitioners to understand how each criterion contributes to the final score, modify weights when required, and recalculate results without specialist decision-analysis expertise.

WSM was suitable for these requirements because it provides a direct and traceable relationship between criterion performance, criterion weight, and total material score. Each output can be decomposed into criterion-level contributions, making the ranking process easier to audit and communicate. The method is also computationally simple, readily implemented in a web application, and compatible with the survey-derived weights available from the preceding empirical phase.

The choice of WSM was therefore driven by fitness for purpose rather than a claim that it is universally superior to other MCDM methods. More complex methods can provide additional analytical capabilities, but they also require forms of preference data, threshold parameters, or comparison judgements that were not collected in this study (Table 7.3).

Table 7.3: Deriving criteria and weights

Method	**Main capability**	**Why it was not selected**
WSM	Transparent additive aggregation using explicit criterion weights	Selected because it matches the survey data, supports rapid screening, and produces easily traceable scores

AHP	Derives weights through pairwise comparisons and tests judgement consistency	The survey collected direct importance ratings, not pairwise comparisons; adopting AHP would require new data collection
TOPSIS	Ranks alternatives by distance from ideal and worst-performing solutions	Requires a stable decision matrix and additional normalisation choices; less transparent for an interactive user-scoring tool
ELECTRE/PROMETHEE	Supports outranking, vetoes, and non-compensatory decisions	Requires preference, indifference, and veto thresholds that were not elicited in the study
ANP	Models dependence and feedback among criteria	Requires extensive pairwise influence judgements and substantially increases elicitation and interpretation complexity
Entropy/CRITIC weighting	Derives weights from variation in performance data	Would measure data dispersion rather than practitioner priorities and is unsuitable for the mixed, partly ordinal demonstration dataset
BWM/FUCOM	Derives weights using structured comparisons with fewer judgements than AHP	Still requires a dedicated comparative elicitation procedure that was not included in the practitioner survey

AHP would have required at least 15 pairwise comparisons for the six principal criteria alone, with substantially more comparisons if sub-criteria and material alternatives were incorporated. More importantly, pairwise-comparison judgements and consistency ratios cannot be reconstructed from the direct Likert-scale importance ratings collected in this study. Retrospective application of AHP would therefore create an additional, unsupported dataset rather than provide a valid alternative analysis of the existing evidence.

7.3.4 Defining Evaluation Items

The development of the evaluation items for the decision-support tool was grounded in a comprehensive empirical investigation of the key factors influencing zero-carbon building material selection in the New Zealand construction sector. Based on a large-scale industry survey and structural equation modelling analysis, six primary decision-making criteria were identified as the most influential: cost effectiveness, durability, buildability, embodied carbon, availability, and aesthetics. These criteria and their interrelationships were previously validated using responses from 203 construction professionals across New Zealand (Araghi et al., 2025).

Each criterion represents a core dimension of sustainable material performance that integrates environmental, technical, economic, and practical construction considerations. To operationalise these criteria within the present digital tool, each was decomposed into multiple context-specific evaluation items capturing both quantitative and qualitative attributes.

Durability reflects long-term material performance and resistance to environmental degradation. It includes resistance to weather exposure and ultraviolet radiation, expected service life, and maintenance frequency. Durability is consistently identified as a core determinant of sustainable construction because materials with longer service lives reduce life-cycle resource consumption and replacement emissions.

Cost effectiveness captures both economic feasibility and financial accessibility. It includes upfront material cost, maintenance cost over the service life, and the presence of financial incentives or subsidies. This criterion reflects the persistent dominance of economic constraints in construction decision-making, particularly in residential markets.

Default cost values used in the tool were pre-populated as indicative ranges reflecting typical New Zealand market conditions at the time of development. These ranges were informed by a synthesis of publicly available construction cost guides, material supplier price lists, and industry reports commonly used in New Zealand practice. The values are intended for early-stage screening and comparison, rather than for detailed cost estimation, and can be modified by users to reflect project-specific conditions or updated market prices.

Buildability represents construction practicality and implementation feasibility on site. It includes ease of handling, required specialist equipment, labour expertise, and compatibility with conventional construction systems. Buildability is critical because materials with strong environmental performance may still face adoption barriers if they require highly specialised skills or disrupt established construction workflows.

Embodied carbon captures life-cycle greenhouse gas emissions associated with material production and end-of-life performance. It includes cradle-to-gate carbon intensity as well as recyclability, reuse, and recovery potential. This criterion directly reflects national and international decarbonisation targets and forms the environmental backbone of zero-carbon material assessment.

Availability reflects supply-chain resilience and logistical accessibility. It includes the strength of local supply chains, transport costs, import dependency, production scalability, and material

scarcity. In the New Zealand context, availability is particularly critical due to geographic isolation and market reliance on imported construction materials.

Aesthetics captures architectural and market acceptance considerations, including the range of finish options and design adaptability. Although typically ranked lower than technical and economic factors, aesthetic compatibility remains essential for mainstream market uptake and regulatory approval.

Each evaluation item is measured using a five-level ordinal performance scale, ranging from worst to best performance. These scales are derived from relevant standards, sustainability assessment frameworks, and peer-reviewed literature, allowing diverse performance metrics, such as kg CO_2-eq/m^2, years of service life, and relative cost categories, to be converted into a consistent scoring structure. This enables direct comparison across qualitative and quantitative indicators within a unified decision-making model.

Importantly, the present study does not propose a new theoretical set of material selection criteria. Rather, it translates an empirically validated decision framework into an operational computational tool that enables structured, transparent, and user-driven evaluation of zero-carbon construction materials for practical decision support (Araghi et al., 2025).

7.3.5 Scoring Algorithm

The scoring algorithm implemented in the tool follows the classical Weighted Sum Model (WSM), a widely used MCDM method for evaluating alternatives across multiple weighted criteria (Malczewski, 2006; Triantaphyllou, 2000) . In this approach, each alternative is evaluated by aggregating weighted performance scores across all criteria, allowing transparent comparison between competing options.

First, the user selects a construction material from a predefined list (wood, hemp, rammed earth, and straw bale). The user then assigns a performance score to each evaluation item using five-level qualitative descriptors. For cost-related criteria, default cost values are pre-populated for each material to reduce cognitive burden and enhance consistency across users, a common practice in decision-support systems (Greco et al., 2016).

All qualitative scores are converted into numerical values ranging from 1 to 5. Each score is then multiplied by its associated criterion weight and normalised by dividing by the maximum possible score (5), following the standard WSM formulation (Triantaphyllou, 2000). The weighted contributions are subsequently summed across all criteria to generate a final

composite performance score for each material. Materials can then be ranked based on their total weighted scores, enabling direct and interpretable comparison.

The weighted-sum approach is extensively adopted in sustainability, construction, and material-selection studies due to its computational simplicity, transparency, and suitability for stakeholder-driven decision environments (Cabeza et al., 2014; Zavadskas et al., 2018). Accordingly, this study adopts an established and well-validated MCDM structure rather than proposing a new algorithmic framework.

The scoring scales are informed by international standards, sustainability assessment frameworks, and empirical ranges reported in the literature. Rather than prescribing fixed thresholds, these sources were used to define relative performance bands suitable for early-stage screening. Environmental criteria draw on EPD and LCA conventions (e.g., EN 15804; ISO 14040/44), durability anchors reflect service-life concepts in construction standards (e.g., ISO 15686), and the overall indicator structure aligns with built-environment sustainability frameworks (e.g., ISO 21929-1). Cost bands are based on indicative ranges from construction cost guides and industry practice, with final anchors refined through expert review.

7.3.6 Tool Implementation

The tool is implemented in Python using the Streamlit framework to provide an interactive, browser-based user interface. Streamlit is an open-source Python library designed for rapid development and deployment of data-driven web applications directly from analytical scripts, without requiring front-end programming in HTML, CSS, or JavaScript (Streamlit Inc., 2023). This design enables computational models and decision logic to be exposed through reactive graphical interfaces using only Python code, supporting rapid prototyping and transparent interaction with analytical workflows (George, 2021).

In this study, Streamlit functions as the presentation layer of the zero-carbon material decision-support system. It captures user inputs for material selection and scoring, passes these inputs to the weighted-sum MCDM engine implemented in Python, and dynamically displays final material scores and detailed breakdown tables in real time. Such browser-based interfaces are increasingly adopted in decision-support research due to their accessibility, transparency, and ease of dissemination (Perkel, 2018). This architecture enables transparent interaction with the decision model while maintaining full computational reproducibility.

Pandas is used for internal data handling, including storage of factor weights, evaluation criteria, default cost values, and output tables. Pandas is a widely adopted data analysis library in

scientific computing and supports robust manipulation of structured datasets (McKinney, 2010). Plotly is included to enable future visualisation extensions such as radar plots and comparative bar charts; interactive visualisation frameworks such as Plotly have been shown to enhance interpretability of multi-criteria decision outputs (Plotly Technologies Inc., 2023). The application source code is hosted publicly on GitHub to ensure transparency, version control, and replicability, consistent with open and reproducible computational research practices (Perkel, 2018). Deployment is achieved through Streamlit Cloud, allowing users to access the tool via a standard web browser without local software installation.

The five-level scoring anchors were defined as screening-level performance bands rather than precise thresholds. Anchor ranges were informed by a synthesis of (i) publicly available construction cost guides commonly used in New Zealand practice (e.g., national quantity surveying cost handbooks and supplier price lists), (ii) embodied-carbon intensity ranges reported in third-party verified environmental product declarations (EPDs) accessed via established databases, and (iii) reference values reported in peer-reviewed life-cycle assessment studies and relevant international standards. The anchors therefore represent relative performance categories intended to support early-stage material comparison rather than normative or universal benchmarks.

7.3.7 Data structure and scoring algorithm

For each selected material, users input or select performance levels for all evaluation items. The tool assigns a numerical score between 1 and 5 based on the position of the selected option on the ordinal performance scale. Each decision factor comprises multiple evaluation items; for example, the *durability* factor includes weather resistance, ultraviolet resistance, service life, and maintenance frequency. This hierarchical structuring of criteria and sub-criteria is consistent with standard value-focused multi-criteria decision analysis practice (Keeney & Raiffa, 1993).

For a given factor f, the weighted contribution of item i, with score $s_i$and factor weight W_f, is computed as:

1) $$\text{contribution}_i = \frac{s_i}{5} \times W_f$$

2) $$\text{Total Score} = \Sigma\ (s_i\ /\ 5\ *\ W_f)$$

Normalisation by the maximum possible score (5) transforms all item ratings to a common 0–1 scale prior to aggregation, ensuring dimensional consistency across heterogeneous indicators. The total weighted score for each material is then obtained by summing the contributions across all items and factors. This formulation corresponds to the classical additive value model, which is one of the most widely applied scoring structures in MCDA due to its transparency, interpretability, and low computational complexity (Edwards & Barron, 1994; Fishburn, 1970).

The weighted-sum model assumes preferential independence among decision factors, meaning that preferences for performance on one criterion are not contingent on the levels of other criteria. This assumption is a formal requirement for additive value aggregation (Keeney & Raiffa, 1993). In the present application, this assumption is considered reasonable because durability, cost, constructability, embodied carbon, availability, and aesthetics represent conceptually distinct dimensions of material performance. Nevertheless, if strong interdependencies were suspected, such as systematic coupling between cost and durability, non-additive aggregation methods would be required.

7.3.8 Technology stack

The tool is implemented in Python using a set of open-source scientific computing libraries to ensure accessibility, transparency, and reproducibility. Python was selected as the core programming environment due to its widespread adoption in sustainability research, decision-support systems, and data-driven modelling, as well as its extensive ecosystem of validated scientific libraries (Millman & Aivazis, 2011; Rossum, 1995). Streamlit was used to develop the interactive web-based user interface. Streamlit enables rapid transformation of Python scripts into browser-accessible applications without the need for front-end development in HTML, CSS, or JavaScript. This design paradigm has been shown to substantially lower the technical barrier for deploying data-driven decision-support tools while preserving tight coupling between the analytical model and the user interface (Grus, 2019; Streamlit Inc., 2023). In the context of this study, such rapid prototyping capability is essential for facilitating iterative testing of material selection logic with domain experts.

Tabular data handling and output formatting are implemented using the Pandas library. Pandas provides efficient data structures for managing heterogeneous datasets and is widely regarded as a foundational tool for reproducible scientific data processing in Python-based research workflows (McKinney, 2010). The final scoring outputs and item-level breakdowns are displayed to the user in the form of Pandas DataFrames, supporting transparent interpretation of model behaviour. Plotly is included within the software environment to enable future

extensions involving interactive data visualisation. Interactive plotting frameworks such as Plotly have been shown to improve the interpretability of multi-criteria evaluation outputs by allowing users to explore trade-offs dynamically across competing criteria (Sievert, 2020). Although advanced visualisation is not central to the present implementation, its inclusion supports future scalability of the tool.

To support computational reproducibility, all software dependencies are explicitly declared in a *requirements.txt* file. Formal specification of computational environments is a recognised best practice in open and reproducible research, as it enables independent users to recreate identical analytical conditions and verify reported results (Sandve et al., 2013). The supplementary materials include a snapshot of this dependency file, showing that the environment relies exclusively on Streamlit, Pandas, and Plotly.

The core decision logic is implemented within a single Python script. This script encodes the empirically derived factor weights, evaluation item definitions, and default cost values for four materials (wood, hemp, rammed earth, and straw bale). User interaction is handled through graphical selection widgets that guide users through material choice and performance scoring. For cost-related items, default price values representative of typical New Zealand market conditions is pre-populated to reduce cognitive load and to support consistency across user evaluations. Once all inputs are provided, the script computes weighted contributions using the additive scoring model and displays both the final material score and a full item-level contribution breakdown. This explicit exposure of intermediate and results supports transparency, traceability, and user trust in the decision-support process.

7.3.9 Validation and testing

The tool was validated through multiple complementary procedures. First, functional testing was conducted to verify that the scoring algorithm correctly implemented the weighted-sum model and that the user interface responded consistently across different web browsers. Second, a pilot evaluation was undertaken with the full Delphi panel of 14 experts, who evaluated the clarity of the evaluation items, weighting structure, scoring descriptors and plausibility of the generated outcomes. Their evaluations were compared across the Delphi rounds using medians, interquartile ranges and Kendall's coefficient of concordance to assess agreement and consensus stability. The dependability of the results was further examined through sensitivity analysis and comparison of the tool-generated material rankings with the ordering obtained from the practitioner survey.

The panel size was consistent with recommended sample sizes for Delphi studies in specialised technical domains. Methodological guidance indicates that panels of approximately 10–18 experts can achieve stable consensus when participants are selected based on subject-matter expertise rather than statistical representativeness (Hsu & Sandford, 2007; Okoli & Pawlowski, 2004). In this study, the Delphi process was used to validate the relevance, clarity and coherence of the criteria, weights and scoring descriptors rather than to generate statistically generalisable findings. Accordingly, panel adequacy was evaluated based on the relevance of participants' expertise and the stability of consensus across rounds rather than sample size alone.

The experts confirmed that the selected criteria captured the key dimensions relevant to zero-carbon material assessment and suggested minor refinements to the wording of several evaluation descriptors. Third, a sensitivity analysis was performed (see Section 3.1) to examine the impact of weight variations on material ranking stability. Finally, the tool's default output rankings were compared with the empirical material ratings obtained from the practitioner survey (e.g., wood = 4.96, hemp = 4.21). When default values were applied, the tool ranked wood highest, followed by hemp, with rammed earth and straw bale ranked lower, reproducing the ordering observed in the survey data.

In addition to expert and survey-based validation, functional testing was conducted during tool development to ensure internal consistency and correct operational behaviour. This testing involved applying the tool to a series of representative material scenarios with systematically varied inputs to verify scoring logic, aggregation behaviour, and sensitivity to changes in individual criteria. These tests confirmed that the tool responds predictably to input variations, does not produce counterintuitive rankings under controlled conditions, and maintains stability under moderate changes in weights and scores.

The validation strategy adopted in this study primarily addresses face validity and convergent validity. Face validity was established through iterative expert review via the Delphi process, which assessed the conceptual soundness, clarity, and relevance of the criteria and scoring structure. Convergent validity was examined by comparing tool-generated rankings with mean importance ratings derived from a large practitioner survey, demonstrating alignment between the tool's outputs and prevailing practitioner preferences. These forms of validation are appropriate for early-stage decision-support tools intended for screening-level use.

7.4 Delphi evaluation

The Delphi method is a structured, iterative technique used to obtain reliable consensus from a panel of experts through multiple rounds of questionnaires and controlled feedback (Skulmoski et al., 2007). Its defining features include anonymity, iteration, statistical aggregation of group responses, and controlled feedback, all of which help reduce dominant-voice bias and promote independent expert reflection (Hsu & Sandford, 2007). The Delphi technique is particularly suitable in contexts where the evidence base is incomplete, emerging, or requires expert judgement rather than empirical measurement (Li et al., 2018).

In this study, the Delphi method was used to validate the structure, weighting, and relevance of the zero-carbon material evaluation tool. Because the tool integrates heterogeneous criteria (e.g., economic, environmental, technical, and qualitative) a structured consensus approach was needed to confirm whether:

i. the six categories captured all essential sustainability dimensions;
ii. the sub-criteria and scoring descriptors were meaningful and clear;
iii. the weighting scheme aligned with expert judgement (Okoli & Pawlowski, 2004).

The controlled, multi-round Delphi process allowed experts from architecture, engineering, construction management, and sustainability to iteratively review the tool, highlight areas needing refinement, and converge toward agreement on priorities (Diamond et al., 2014). This approach follows best practice in decision-support research, where Delphi validation is often used to refine MCDA criteria, enhance transparency, and strengthen the credibility of tools before real-world deployment.

7.4.1 Expert Panel and Participant Selection

For this study, an "expert" was defined as an individual who satisfied both an experience criterion and a domain-relevance criterion. Eligible panellists were required to have at least five years of professional experience in the built environment and demonstrated involvement in at least one area directly relevant to the decision-support tool. Relevant areas included architecture and sustainable design; civil or structural engineering; construction or project management; quantity surveying, cost estimation or procurement; building-material specification; life-cycle assessment; green-building certification; environmental assessment; and sustainability consulting. Expertise was therefore determined through relevant professional experience and subject-matter involvement rather than professional title alone. Panellists were not required to

possess expertise in every area because the multidisciplinary panel was designed to provide complementary technical, economic, environmental and practical perspectives.

Fourteen eligible experts participated in the Delphi process. Purposive maximum-variation sampling was used to obtain perspectives from architecture, civil or structural engineering, construction management, environmental sustainability, material specification, life-cycle assessment, and green-building certification. This disciplinary range was required because the tool evaluates economic, technical, environmental, and practical dimensions of material selection. The final panel size (n = 14) is consistent with established Delphi methodology, where expert judgement is prioritised over large sample size. Previous methodological studies indicate that heterogeneous Delphi panels typically operate effectively with 10–20 experts and that consensus reliability depends more on iterative stability than on the absolute number of participants (Beiderbeck et al., 2021; Okoli & Pawlowski, 2004). The demographic characteristics of the Delphi expert panel are summarised in Table 3.

Table 7.4: Expert Panel Demographics (n = 14)

Characteristic	**Category**	**n**
Primary Discipline	Architecture	2
	Civil / Structural Engineering	3
	Construction Management	4
	Environmental / Sustainability Specialist	5
Years of Professional Experience	5–10 years	2
	11–20 years	9
	>20 years	3
Primary Professional Role	Consultant	5
	Academic / Researcher	4
	Industry Practitioner	2
	Policy / Advisory	4
Main Area of Expertise	Material Specification	3
	Life-Cycle Assessment (LCA)	4

	Green Building Certification	2
	Sustainable Design	5
Geographical Practice Base	Auckland	12
	Wellington	2
	Other	N/A
Gender	Male	8
	Female	6

7.4.2 Ethical Considerations

Participation was voluntary and anonymised to minimise bias and ensure independent expert reflection. Experts provided informed consent, and the study followed Massey University's ethical guidelines for research involving human participants.

7.4.3 Delphi Procedure and Rounds

A three-round Delphi process was implemented to iteratively refine expert agreement and validate the structure of the zero-carbon material evaluation tool. The Delphi method is a structured expert consensus technique developed to support systematic judgement under conditions of uncertainty through controlled feedback and repeated rating cycles (Dalkey & Helmer, 1963; Hsu & Sandford, 2007). It is widely applied in sustainability assessment, construction research, and decision-support development where empirical benchmarks are incomplete and expert knowledge is essential (Okoli & Pawlowski, 2004).

Round 1 focused on the initial evaluation of the proposed framework. Experts rated the relevance of the six main criteria, allocated weighting percentages, and provided qualitative feedback on the clarity, completeness, and appropriateness of indicators and scoring descriptors. This exploratory round corresponds to the classical Delphi function of problem structuring and variable refinement.

In Round 2, participants were presented with anonymised, aggregated feedback from the first round and were asked to evaluate seven structured statements addressing the tool's overall structure, weighting logic, indicator relevance, clarity of scoring descriptors, perceived interface suitability for practitioner use, and potential adaptability beyond the New Zealand context. This controlled feedback mechanism is a defining feature of Delphi methodology and enables participants to reflect on group trends without direct peer influence.

Round 3 focused on confirming convergence by asking experts to rank improvement priorities, establish consensus thresholds, and identify essential refinements, such as the inclusion of New Zealand–specific benchmarks and expanded circularity metrics. Across all rounds, controlled feedback was provided in the form of anonymised summaries to support iterative reflection while minimising dominance bias and group pressure, consistent with established Delphi good practice. The process continued until stability in median ratings and reductions in interquartile ranges indicated adequate convergence towards consensus.

Multi-round Delphi procedures following this same structure have been widely used to validate sustainability indicators and decision-support frameworks in the built environment, particularly where expert judgement is required to operationalise complex performance constructs (e.g., (Darko & Chan, 2016)). Although overall agreement was achieved on the relevance of the criteria, lower consensus was observed for several scoring descriptors, particularly those related to cost ranges, durability interpretation, and embodied carbon framing. Delphi panellists indicated that some descriptors were too narrowly specified or relied on implicit technical assumptions that could be misinterpreted by non-expert users. In response, descriptors were revised between rounds to use broader performance bands, plain-language explanations, and contextual examples aligned with common construction practice. These revisions were intended to improve clarity and interpretability for early-stage decision-making contexts.

7.4.4 Instruments and Data Collection

Data collection was conducted through online questionnaires administered via Qualtrics, with each Delphi round serving a distinct evaluative purpose. In the first round, experts appraised the preliminary framework by rating the relevance of each category on a 1–5 Likert scale, allocating weighting percentages across the six criteria, and providing open-ended comments on the clarity and suitability of both the criteria and their associated scoring descriptors. The second round focused on structured evaluation, in which participants reviewed anonymised feedback from Round 1 and rated their level of agreement with seven statements addressing the adequacy of the categories, the appropriateness of the weighting scheme, the relevance of indicators, the clarity of scoring descriptors, the perceived credibility of the tool's outputs, perceived interface suitability for practitioner-oriented use, and the potential for adaptation beyond the New Zealand context. In the final round, experts completed forced-ranking exercises to identify priority areas for improvement and to confirm consensus thresholds, such as retaining criteria only when at least 70% of respondents rated them 4 or higher. All responses

were submitted anonymously to minimise peer influence and preserve the independence of expert judgments (see Figure 3).

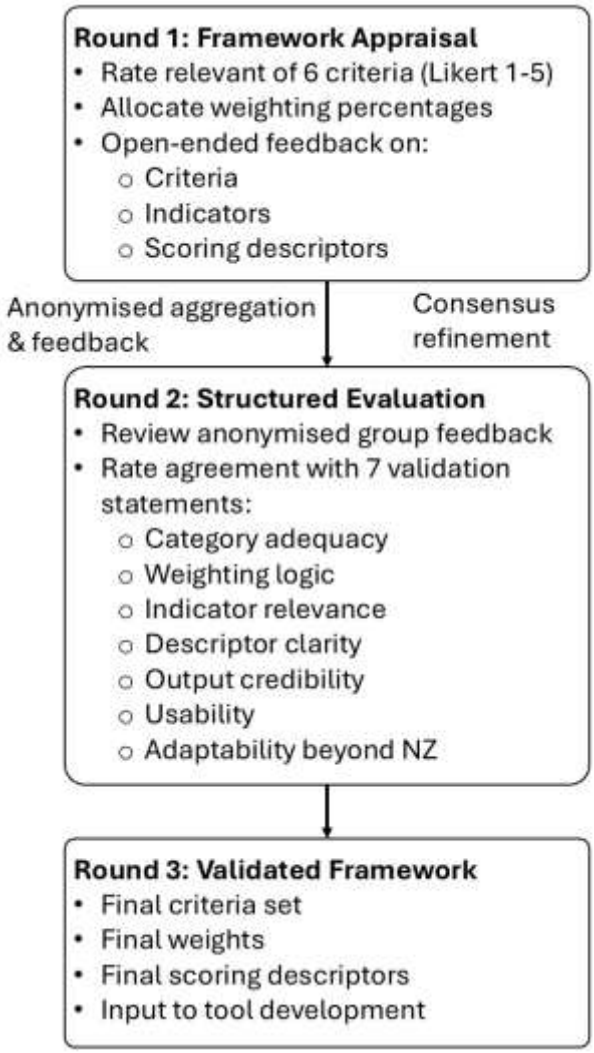


Figure 7.3: Three-round Delphi data collection and validation process for the zero-carbon material evaluation framework (Source: the authors)

7.4.5 Consensus Measurement

Consensus among the expert panel was evaluated using a combination of **median values, interquartile range (IQR)**, and Kendall's coefficient of concordance (W), which provides a standard quantitative indication of the level of agreement among Delphi panellists. The **median** was used as the primary measure of central tendency because Delphi data are typically derived from ordinal Likert-type scales. The median is preferred over the mean in this context as it is less sensitive to extreme values and provides a more reliable indication of collective expert judgement for ordinal ratings (Hsu & Sandford, 2007; von der Gracht, 2012). The **interquartile range (IQR)** was used to quantify the dispersion of expert responses and, by extension, the degree of agreement. The IQR reflects the range within which the middle 50% of responses fall

and is widely recommended as a stable and interpretable indicator of consensus in Delphi research (Diamond et al., 2014; Rayens & Hahn, 2000). In this study, an **IQR ≤ 1.0** was adopted as the operational threshold for consensus, indicating that at least half of the expert ratings fell within one scale point of each other. This threshold is consistent with commonly applied consensus criteria in methodological and applied Delphi studies (Diamond et al., 2014; von der Gracht, 2012).

To assess the overall level of agreement across ranked statements, **Kendall's coefficient of concordance (W)** was computed in Round 2. Kendall's W is a non-parametric statistic used to evaluate the degree of agreement among multiple raters when ranking a common set of items (Legendre, 2005). Values of W range from 0 (no agreement) to 1 (complete agreement). In this study, Round 2 produced **W = 0.48**, which indicates a **moderate level of consensus** according to standard interpretation guidelines (Schmidt, 1997). This level of agreement was deemed sufficient to proceed to a final refinement round, consistent with established Delphi practice where full consensus is not always expected or required. The combined use of **median values, IQR thresholds, and Kendall's W** is widely recognised as best-practice for statistically defensible consensus measurement in Delphi research. Together, these measures capture both the **stability of central judgements** and the **degree of dispersion and concordance** among experts, thereby providing a rigorous basis for determining convergence across successive Delphi rounds (Diamond et al., 2014; von der Gracht, 2012).

7.4.6 Data Analysis

Quantitative responses (e.g., relevance ratings, statement agreement, weight allocations) were analysed using descriptive statistics (median, mean, standard deviation, IQR). Kendall's coefficient of concordance (W) was used in Round 2 to examine the level of agreement among experts' rankings of the validation statements (Keeney et al., 2011). Qualitative comments were analysed thematically. Feedback was coded to identify concerns regarding clarity, indicator relevance, need for regional benchmarks, circularity metrics, and potential refinements to scoring descriptors. These insights informed revisions to criteria definitions, scoring thresholds, and explanatory text within the tool.

7.5 Results

7.5.1 Description of the Developed Tool

This section presents the functional characteristics, internal scoring behaviour, weighting structure, sensitivity performance, and data structure of the developed zero-carbon material

evaluation tool. The tool operationalises a multi-criteria decision-making framework that allows users to compare construction materials based on six weighted sustainability and practical performance criteria. The tool enables the evaluation of four materials (wood, hemp, rammed earth, and straw bale) using six criteria: cost effectiveness, durability, buildability, embodied carbon, availability, and aesthetics. These criteria are decomposed into multiple evaluation items based on literature, engineering standards, and domain expertise. Each item is measured using a five-point ordinal performance scale, where higher levels indicate better performance. All ordinal inputs map directly to numeric scores from 1 to 5, enabling unified aggregation across heterogeneous indicators.

The four materials evaluated in this study (wood, hemp, rammed earth, and straw bale) were selected to demonstrate tool functionality and validation rather than to provide a comprehensive material library. These materials were chosen because they represent diverse low-embodied-carbon construction typologies with differing cost, durability, and performance profiles, thereby enabling meaningful comparison during tool development.

For demonstration purposes, the tool was populated with four commonly used material categories to illustrate functionality rather than to provide an exhaustive comparison. Default cost values were specified as indicative ranges derived from publicly available New Zealand construction cost guides, supplier price lists, and industry reports, reflecting typical market conditions at the time of tool development. Performance-related inputs, including embodied carbon intensity and durability characteristics, were informed by environmental product declarations (EPDs), life-cycle assessment databases, and peer-reviewed literature. These values were used consistently across all demonstrations to ensure comparability and transparency.

7.5.2 Weighting Impact

Because the weights are derived from practitioner preferences, factors such as cost effectiveness and durability typically contribute more to the final score than aesthetics or availability. For example, if two materials are equal on all criteria except cost, the material with lower cost will achieve a higher final score due to the 19.29 % weight assigned to cost effectiveness. Sensitivity checks indicate that moderate variations in weights (±20 %) do not substantially alter the ranking of materials when differences in performance are large, demonstrating robustness of the weighted-sum approach.

7.5.3 User Experience and Flexibility

Informal functional walkthroughs conducted during tool development with sustainability consultants and architects provided preliminary feedback on interface clarity and workflow logic. These walkthroughs were exploratory in nature and were not designed as formal usability tests employing standardised evaluation metrics. Default cost values and structured descriptors were designed to support interpretability during early-stage use. The ability to display a detailed scoring table is intended to support transparency and traceability of the decision logic and may facilitate discussion among stakeholders. Although designed with New Zealand data and standards, the tool's structure allows adaptation to other contexts by adjusting weights and descriptors.

7.5.4 Deriving the weights

To translate the survey findings into a usable weighting scheme, we normalised the mean scores of each factor so that their sum equals 100 %. The mean importance scores from Hashemi Araghi et al. (2025) were divided by the total of all six means and multiplied by 100. The resulting weights are listed in Table 1. For example, the cost-effectiveness mean of 4.91 yields a weight of $4.91/25.46 \times 100 \approx 19.29\,\%$. This approach preserves the relative preferences expressed by professionals and converts them into numeric weights suitable for the weighted-sum model. See Table 4 for weighted factors based on survey responses.

Table 7.5: Weighted factors for material selection based on survey responses (Source: the authors)

Criterion	**Survey mean**	**Final DST weight**	**SEM coefficient**	**Delphi mean weight**	**Role in DST**
Cost-effectiveness	4.91	19.29%	0.132	22.1%	Baseline weight
Durability	4.87	19.13%	0.094	15.8%	Baseline weight
Buildability	4.53	17.79%	0.074	19.2%	Baseline weight
Embodied carbon	4.00	15.71%	0.397	15.1%	Baseline weight
Availability	3.67	14.41%	0.368	18.0%	Baseline weight

Aesthetics	3.48	13.66%	0.058	9.7%	Baseline weight

SEM coefficients are reported for explanatory comparison only. They were not normalised or used as DST weights. Delphi allocations were used to assess the plausibility and sensitivity of the survey-derived weighting structure.

These weights are encoded in the tool as a Python dictionary, ensuring transparency and reproducibility. Users can later adjust the weights if their context or priorities differ from the survey averages. A discrepancy was observed between the criterion weights derived from the large-scale practitioner survey and the median weights suggested by the Delphi expert panel. This difference reflects the distinct roles of the two groups within the study design. The survey weights capture aggregate practitioner decision behaviour and were therefore selected as the primary inputs for the operational tool, consistent with the study's aim of supporting real-world, practitioner-facing decision-making. In contrast, the Delphi-derived weights represent expert-normative perspectives and were used to validate the plausibility and robustness of the survey results rather than to override them. The consistency in relative ranking patterns between the two weighting sources supports the validity of the final weighting scheme despite numerical differences.

7.5.5 Sensitivity analysis

Sensitivity analysis was conducted to examine the stability of material rankings under variations in criterion weights. A one-at-a-time (OAT) perturbation strategy was employed, whereby each criterion weight was independently varied while all other weights were held constant. Weight values were perturbed by ±10% and ±20% relative to their baseline survey-derived values, with weights subsequently normalised to maintain a unit sum. For each perturbation scenario, material rankings were recalculated and compared with the baseline ranking. The sensitivity analysis was limited to moderate (±20%) one-at-a-time weight perturbations and therefore evaluates local stability rather than global robustness under extreme or joint parameter uncertainty. To support assessment of the framework's sensitivity, Table 5 summarises the observed ranking behaviour under all one-at-a-time weight perturbation scenarios (±10% and ±20%), including the occurrence of any rank reversals.

Table 7.6: Material ranking stability under one-at-a-time weight perturbations

Criterion perturbed	Weight change	Rank reversals	Top-ranked material changed
Cost effectiveness	±10%	0	No
Cost effectiveness	±20%	0	No
Durability	±10%	0	No
Durability	±20%	1	No
Buildability	±10%	0	No
Buildability	±20%	1	No
Embodied carbon	±10%	0	No
Embodied carbon	±20%	0	No
Availability	±10%	0	No
Availability	±20%	1	No
Aesthetics	±10%	0	No
Aesthetics	±20%	0	No

Across all one-at-a-time perturbation scenarios, the top-ranked material remained unchanged, and rank reversals were limited to swaps between adjacent, closely scored materials. This pattern is indicative of local ranking stability rather than global robustness and is consistent with the intended screening-level application of the tool.

7.5.6 Definition of sub-criteria and scoring scales

Each factor was decomposed into evaluation items based on literature review, engineering standards and domain expertise. The items were chosen to capture both quantitative measures (e.g., carbon intensity, cost per square metre) and qualitative aspects (e.g., ease of handling). To promote comparability, each item uses a five-point ordinal scale, where higher levels represent better performance. Table 6 summarises the sub-criteria and the meaning of each level.

Table 7.7: Summary of the sub-criteria and the meaning of each level

Factor	Evaluation item	Five-level scale (from lowest to highest performance)
Durability	Weather resistance	Weather resistance (performance retained under severe weather exposure): 50%, 60%, 70%, 80%, 90% performance retained.
	UV resistance	UV resistance (performance retained after UV exposure):

		50%, 60%, 70%, 80%, 90% performance retained.
	Service life	20 years, 30 years, 50 years, 100 years, > 100 years.
	Maintenance frequency	Maintenance required every 10 years, 20 years, 30 years, 50 years, > 50 years.
Cost-effectiveness	Maintenance cost	> NZD 60/m^2, 40–60, 30–40, 20–30, < 20.
	Upfront material cost	> NZD 150/m^2, 100–150, 70–100, 40–70, < 40.
	Financial incentives	None, low, moderate, high, very high incentives/subsidies.
Buildability	Ease of handling	Very difficult, difficult, moderate, easy, very easy.
	Specialist equipment required	Extensive, high, moderate, low, none.
	Expertise availability	Rare, limited, some, common, very common.
	Compatibility with other materials	Compatible with 1, 2, 3, 4 or ≥5 materials.
Embodied carbon	Production carbon intensity	> 100, 75–100, 50–75, 25–50, < 25 kg CO_2-eq/m^2.
	End-of-life: recycle	Never, rarely, sometimes, often, always recyclable.
	End-of-life: reuse	Never, rarely, sometimes, often, always reusable.
	End-of-life: recovery	Never, rarely, sometimes, often, always recoverable.
Availability	Local supply chains	None, limited, moderate, strong, very strong local supply.
	Transport costs	Very high, high, moderate, low, very low logistics costs.
	Production scalability	None, low, moderate, high, very high production scalability.
	Material scarcity	Very rare, rare, moderate, common, very common.
Aesthetics	Finish options	Very limited, limited, moderate, varied, extensive finishes.
	Design adaptability	Very rigid, rigid, moderate, flexible, very flexible designs.

The ordinal scales map directly to numeric scores (1–5), with higher scores signifying better performance. Although the scales are coarse, they provide a structured means of capturing expert judgement and enable aggregation across heterogeneous indicators. The five-level scoring anchors were defined as screening-level performance bands rather than fixed regulatory thresholds. Cost-related anchors were informed by commonly used New Zealand construction cost guides and quantity surveying handbooks, supplemented by publicly available supplier price lists. Embodied carbon anchors were derived from cradle-to-gate values reported in third-party verified environmental product declarations (EPDs) accessed through established databases and aligned with reporting conventions in EN 15804 and ISO 14040/44. Durability and service-life anchors were informed by concepts used in ISO 15686 and related building performance guidance. These sources were synthesised to define relative performance bands suitable for early-stage material comparison rather than normative benchmarks.

7.6 Tool Evaluation

7.6.1 Weights and relevance

Weights. The weight distribution (Table 8) reflects strong emphasis on cost effectiveness and buildability. Aesthetics received the lowest median weight (5 %) but exhibited a wide IQR (9.75 %), indicating diverse views. Durability and embodied carbon were moderately weighted. The relevance ratings paralleled weight allocations (Table 9): cost, buildability and durability were rated highest; embodied carbon and availability received moderate ratings; aesthetics was lowest

Table 7.8: Example evaluation items and scales

Criterion	Evaluation items and five-level anchors
Durability	Weather resistance (10 % → ≥ 50 % retention under severe weather); service life (20 years → > 100 years); maintenance frequency (every 10 years → > 50 years).
Cost effectiveness	Upfront cost (> NZ$150 m² → < NZ$40 m²); maintenance cost (> NZ$60 m² → < NZ$20 m²); financial incentives (none → very high).
Buildability	Ease of handling (very difficult → very easy); need for specialist equipment (extensive → none); expertise availability (rare → very common).
Embodied carbon	Production carbon intensity (> 100 kg CO_2e m² → < 25 kg CO_2e m²); recyclability (never → always); reuse and recovery potential (never → always).
Availability	Local supply chains (none → very strong); transport costs (very high → very low); material scarcity (very rare → very common).
Aesthetics	Range of finish options (very limited → extensive); design adaptability (very rigid → very flexible).

Table 7.9: Weight allocations (n = 14)

Criterion	Mean (%)	Median (%)	IQR (%)
Cost effectiveness	22.1	25.0	5.75
Buildability	19.2	20.0	2.75
Availability	18.0	20.0	5.0
Durability	15.8	15.0	0.75
Embodied carbon	15.1	15.0	2.5
Aesthetics	9.7	5.0	9.75

Table 7.10: Relevance ratings (n = 14)

Criterion	Mean (1–5)	Median	IQR
Cost effectiveness	4.70	5.0	1.0
Buildability	4.83	5.0	0.0
Availability	3.80	4.0	0.0

Durability	4.30	4.0	1.0
Embodied carbon	3.80	4.0	0.0
Aesthetics	2.77	3.0	0.0

Delphi round 2 – Structured statements

Medians for five of the seven statements were 4 / 5 (Table 10). Scoring descriptor clarity and adaptability beyond New Zealand received lower median ratings (3 / 5), indicating areas needing improvement. IQRs were about 1.0 for most statements, reflecting some diversity of views. Kendall's W for the ranking of statements across participants was 0.48, indicating moderate consensus.

Table 7.11: Round-2 statement ratings

Statement	Median	IQR	Interpretation
Categories capture key factors.	4.0	1.0	Consensus.
Weighting reflects importance.	4.0	1.0	Consensus.
Indicators are relevant.	4.0	1.0	Consensus.
Scoring descriptors are clear.	3.0	0.0	No consensus.
Outputs are credible.	4.0	1.0	Consensus.
Tool is user-friendly.	4.0	1.0	Consensus.
Tool can be adapted beyond NZ.	3.0	1.75	Disagreement.

Delphi round 3 – Improvement priorities

Participants ranked defining quantitative thresholds and New Zealand benchmarks as the top priority, followed by integrating local data and adding circularity and regulatory criteria. Approximately two-thirds supported including financial incentives as an informational cross-cutting factor. The majority favoured retaining criteria when at least 70 % of respondents rated them ≥ 4 / 5.

7.7 Discussion

The zero-carbon material evaluation tool developed in this study applies MCDA to support material selection in sustainable construction. By explicitly weighting criteria and structuring trade-offs, the approach reduces reliance on intuition and makes decision logic transparent. A weighted-sum model (WSM) is implemented, as it is well established for aggregating multi-criteria performance and is appropriate for early-stage screening where practitioners often work with incomplete information and require rapid, interpretable comparisons. The WSM assumes compensatory, approximately linear trade-offs and preferential independence among criteria. In the present context, these assumptions represent a pragmatic approximation of practitioner

reasoning: survey results indicate that respondents generally prioritised balanced performance across criteria rather than accepting extreme sacrifices in cost or durability for gains elsewhere.

However, additive aggregation has known limitations. In real projects, some conditions are non-compensatory where poor performance on a single criterion cannot be offset by strengths in others. In addition, criteria may be partially interrelated (e.g., cost–durability or cost–carbon linkages), and preferential independence was not formally tested. These limitations should be considered when interpreting outputs and motivate future extensions incorporating minimum thresholds or hybrid decision rules for later-stage material selection. Alternative MCDM methods could address some of these limitations. For example, the Analytic Hierarchy Process (AHP) allows pairwise comparison of criteria and can capture subjective preference structures more explicitly; however, it becomes cognitively demanding as the number of criteria increases and is less suited to rapid, practitioner-facing tools. Non-compensatory approaches, such as outranking or rule-based filtering methods, can explicitly model veto thresholds but often reduce transparency and interpretability for non-expert users. Given the study's objective of developing an accessible, practitioner-oriented screening tool grounded in empirical industry preferences, the weighted-sum model represents a pragmatic balance between analytical rigour, interpretability, and transparency.

The Delphi validation process demonstrated moderate consensus regarding the relevance of the six evaluation categories and their overall contribution to early-stage material selection. Participants consistently endorsed the inclusion of embodied carbon and life-cycle cost as critical decision factors and provided constructive feedback to refine individual metrics, such as aligning durability considerations more closely with New Zealand Building Code requirements. While agreement was achieved on the relevance of most criteria, lower consensus was observed for the clarity of some scoring descriptors and for cross-jurisdictional adaptability, indicating that further refinement of descriptor wording and contextual calibration may be required to support broader adoption beyond the New Zealand context.

Sensitivity analysis indicated that moderate variations in criterion weights do not substantially alter material rankings, supporting the stability of the framework for screening-level comparison. However, the Delphi panel was relatively small and geographically concentrated, with most experts based in Auckland. Although this aligns with recommended Delphi practice, it may bias the resulting weights toward urban construction contexts. Broader stakeholder participation, including contractors, building owners, and Indigenous community representatives, could capture a wider range of perspectives and values in future iterations.

Regional variation within New Zealand may influence both the relative importance of decision criteria and the performance of specific materials. Factors such as material availability, transport distance, climatic conditions, and local construction expertise vary across regions and may affect assessments of cost effectiveness, durability, and buildability. Applying a nationally uniform weighting structure therefore represents a simplification that may obscure meaningful regional differences in material selection logic.

The framework also exhibits several methodological strengths. The use of default cost values promotes consistency and reduces user burden, while allowing user overrides maintains flexibility. Implementation through a web-based interface supports accessibility for practitioners without programming expertise, and public release of the source code enhances transparency and reproducibility. Future enhancements could include hybrid or non-additive decision rules, expansion of the material database to include additional low-carbon alternatives, and project-based case study applications to assess real-world decision impact. These extensions would strengthen the framework while preserving its intended role as a screening-level decision-support tool. The Delphi expert panel comprised 14 participants, most of whom were based in Auckland. While this reflects the dominance of Auckland within the national construction market, it may bias validation outcomes toward urban conditions and supply-chain realities specific to that region. Regional variation in climate, material availability, and construction practice across New Zealand is therefore not fully captured, and this should be considered when interpreting the validation results.

For embodied carbon, the highest-performance band (<25 kg CO_2e/m^2) corresponds to the lower range of cradle-to-gate values commonly reported for bio-based and low-carbon wall systems in EPD datasets and recent life-cycle assessment literature, while higher bands reflect progressively more carbon-intensive conventional alternatives. Because the weighting structure is derived from a voluntary practitioner survey, it may reflect self-selection bias and the priorities of respondents who are more engaged with sustainability-related decision-making. In addition, although the sample size was sufficient for stable estimation of mean importance scores, the resulting weights reflect aggregated preferences within the New Zealand construction sector and may not generalise to other regulatory or market contexts. These considerations align with the intended use of the tool as a context-specific, screening-level decision aid rather than a universal optimisation model.

Although the panel included construction-management professionals, quantity surveying and specialist construction-cost consultancy were not separately represented in the recorded

disciplinary categories. The validation of cost-related indicators and scoring bands should therefore be interpreted as preliminary. Future validation should include registered quantity surveyors or construction-cost consultants, particularly when recalibrating upfront cost, maintenance cost, and life-cycle cost thresholds.

7.8 Conclusion

This study presents the development and validation of a zero-carbon material evaluation tool designed to support evidence-based decision-making in sustainable construction. By integrating survey-derived weights, context-specific evaluation items, and a transparent weighted-sum scoring model, the tool provides a systematic approach to comparing materials across six key criteria: durability, cost effectiveness, buildability, embodied carbon, availability, and aesthetics. The Streamlit implementation provides an accessible digital platform, while open-source code supports reproducibility and future adaptation. Validation through a three-round Delphi process confirmed the relevance of the criteria and identified priority areas for refinement, particularly in scoring descriptor clarity and contextual calibration for New Zealand**.** Sensitivity analysis indicated that the weighted-sum model is stable under moderate weight variations, and comparison with practitioner survey patterns supported the credibility of the tool's rankings. While the tool provides a practical and transparent structure for early-stage material evaluation, its generalisability is constrained by the composition of the expert panel, the limited number of materials tested, and the availability of local data. Future work should expand the material database, incorporate updated regional benchmarks, and involve a broader and more diverse range of stakeholders. Applying alternative MCDA techniques or integrating real-time data sources may further enhance the tool's analytical power. Despite these limitations, the study provides a valuable foundation for decision-support systems in sustainable construction and underscores the potential of MCDM-based approaches to guide low-carbon material choices in practice.

Chapter 8: Discussion

8.1 Chapter Summary

In this chapter, the key findings of the thesis have been synthesised, the scalability and usability of the DTS examined, the possible role of government subsidies and support considered as well as the issues that the tool is meant to solve. The capability of the tool to combine several criteria in a transparent and flexible framework makes it a helpful resource to the practitioners that must cope with the challenges of the zero-carbon material selection. The foundations of scalability are in modular architecture and methodological rigour, but it demands localisation of data and integration with digital platforms. The simplistic nature of the interface is an advantage of usability, which may be improved by customisation, training and accessibility. The impact of the tool would be increased with the government assistance in the form of data infrastructure, financial incentives and regulatory integration that would enhance the shift to low-carbon construction. The tool will improve the policy-practice bridge by addressing data fragmentation, data uncertainty, and cognitive load and help to achieve the net-zero aspirations of New Zealand. The research in the future must be aimed at widening the tool scope, improving the quality of data and the possibility of synergetic relations between the technology, policy and the culture of industry.

8.2 Overview

This chapter puts the results of the previous chapters into perspective of the research aim and objectives, evaluates the importance of the DTS created to support the zero-carbon material selection, and considers its implications for theory, practice and policy in general. Combining the results of literature review, empirical analysis of factors, SWOT analysis, and validation of the tool, this discussion gives a holistic reflection of how this research contributes to the transformation of low- and zero-carbon construction in New Zealand. It also pinpoints constraints and opportunities in the future, alongside the scalability and usability of the tool, the possibility of government subsidies and assistance, and how the tool can impact the solution of chronic issues in the selection of materials.

8.3 Integration of Findings Across Research Phases

This research was designed as a sequential and integrative programme of inquiry, in which each empirical phase informed and constrained subsequent stages. The findings from Chapters 3 to 7 should therefore not be interpreted in isolation, but as interdependent components of a coherent decision-support framework for zero-carbon material selection in New Zealand.

Chapter 3 the scoping review of zero-carbon materials, identified the practical materials as applicable to the New Zealand context. Instead of conceptualizing the material choice as a theoretical practice, this chapter limited the study to materials, which are locally available, technically feasible, and are either current or developing in industry practice. This underpinning was necessary to escape abstract optimisation that is not attached to actual construction conditions.

It is based on this synthesis that the systematic literature review (Chapter 4) identified a set of recurring performance dimensions that prevail internationally in the field of low- and zero-carbon building materials, namely cost-effectiveness, durability, buildability, embodied carbon, availability, and aesthetics. Nevertheless, the review also revealed an important limitation in the existing body of research, namely that material performance is commonly analysed in isolation from practitioner decision-making behaviour and contextual constraints. In response to this gap, the empirical investigation presented in Chapter 5 was directly informed by these identified dimensions and sought to examine how they are prioritised and weighted by construction professionals in the New Zealand context.

The systematic literature review (Chapter 4) identified two principal weaknesses in the existing body of research on low- and zero-carbon building materials. First, material performance is predominantly examined through isolated technical or environmental criteria—most notably embodied carbon, durability, or thermal performance—resulting in a fragmented, mono-dimensional understanding that does not reflect the multi-criteria nature of material selection in practice. Second, material performance is commonly analysed without explicit consideration of practitioner decision-making behaviour and the contextual constraints under which material choices are made.

This second gap directly motivated the empirical investigation presented in Chapter 5. A survey of construction practitioners, analysed using structural equation modelling (SEM), revealed that material selection decisions are influenced by a hierarchy of factors, with cost-effectiveness and durability ranked as the most influential determinants, followed by buildability and availability, while embodied carbon, although considered important, was prioritised alongside—rather than above—these practical considerations. Aesthetics was consistently rated as the least influential factor. These findings empirically demonstrate that environmental performance alone is insufficient to explain material choice in practice and that material selection is shaped by trade-offs among economic, technical, and contextual factors.

This insight challenges simplistic carbon-optimisation models commonly used in material assessment studies and reinforces the need to conceptualise material selection as a multi-dimensional socio-technical decision-making process. The qualitative SWOT analysis in Chapter 6 further extended these findings by revealing implementation-level constraints—such as regulatory uncertainty, supply-chain fragility, limited availability of skilled labour, and market acceptance—that are not captured by quantitative models but significantly mediate the translation of material potential into actual adoption. Collectively, these results explain the persistent under-utilisation of technically promising low-carbon materials despite their favourable environmental performance.

Lastly, Chapter 7 conceptualised these combined understandings into a digital decision-support model. The developed tool is based on empirically derived weights and explicitly models trade-offs, unlike previous versions based on MCDA, which make weight-based assumptions or participate in a fixed set of criteria, and thus can be re-calibrated as priorities change. The Delphi validation also proved the applicability of the criteria, as well as the interpretation and applicability of the tool to professional processes. Combined, these results prove that the problem of efficient zero-carbon material selection cannot be addressed by the isolated performance indicators or after-design certification programs. It involves rather an evidence-based, open and flexible decision-support mechanism that mirrors technical performance, as well as professional decision-making realities.

8.4 Significance of the Research Findings

The results of this study indicate that the task of material selection with zero carbon is a multidimensional decision-making problem, and it should not be viewed as a single-objective optimisation task but as one that involves technical, environmental, economic, and social factors (Akadiri et al., 2013; Govindan et al., 2015). With the help of the synthesis of international and New Zealand-specific literature and empirical survey evidence, the study proves the salience of six criteria, including cost-effectiveness, durability, buildability, embodied carbon, availability, and aesthetics, to the practitioners who work in the context of the New Zealand construction environment (Araghi et al., 2025; Braulio-Gonzalo et al., 2022). The weighting obtained in the survey shows that the cost and durability continue to dominate the decision drivers as well as portray the industry-old priorities, and the embodied carbon and availability inclusiveness reveals the increasing sensitivity to the environmental performance and supply chain limitations (Hertwich, 2021; Skillington et al., 2022). The findings of the SEM also indicate interdependence of criteria, and the results show that the performance on one

dimension (e.g., embodied carbon) could affect the perceptions of practitioners on other dimensions (e.g., cost or durability) as a result of the results, which aligns with the previous research on the subject (trade-off behaviour in sustainable construction decision-making) (Wang et al., 2009; Zavadskas et al., 2016).

These insights are operationalised through the integrated decision-support framework developed in this thesis, implemented as a weighted-sum model within a user-friendly digital tool. Such aggregation-based MCDM approaches are widely recognised for their transparency and suitability for early-stage decision contexts where clarity and interpretability are essential (Behzadian et al., 2012; Huang et al., 2018). Validation through a multi-round Delphi process involving a heterogeneous expert panel confirms that the tool captures relevant criteria, applies rational weighting logic, and generates plausible material rankings, aligning with established best practice for decision-support system evaluation under conditions of uncertainty (Okoli & Pawlowski, 2004; Hsu & Sandford, 2007). Furthermore, analysis demonstrates that material rankings remain stable under moderate variations in criteria weights, supporting the robustness, reliability, and generalisability of the proposed framework (Triantaphyllou & Sánchez, 1997).

From a theoretical perspective, this study contributes to the MCDM literature by contextualising the weighted-sum model for application in a small, geographically isolated construction market, where data availability, supply constraints, and regulatory conditions differ from those assumed in many international studies (Araghi et al., 2025; Li et al., 2019). The integration of survey-based weighting with Delphi-refined scoring descriptors offers a structured balance between empirically observed practitioner priorities and expert judgement, addressing a commonly identified limitation in sustainability-oriented decision models (Akadiri et al., 2013; Govindan et al., 2015). More broadly, the research advances the zero-carbon construction literature by reinforcing the critical role of early-stage material selection and by providing a repeatable, evidence-based framework that helps bridge the persistent gap between high-level policy ambition and project-level implementation in sustainable building practice (Van Soest et al., 2021; Bajwa et al., 2025).

8.5 Scalability of the Decision-Support Tool

Scalability means that the tool can include more materials, criteria, geographic situations and user groups without redesigning (Malczewski, 2006). Several features of the tool architecture and methodological basis ensure scalability, and some features would suggest ways to improve the tool in the future.

8.5.1 Expanding Material Options and Criteria

The existing application of the decision-support tool considers four materials, including timber, hemp, rammed earth, and straw bale, which are selected based on their applicability to the New Zealand construction market and a long-standing presence in the low-carbon building research (Araghi et al., 2024; Cabeza et al., 2022). Nevertheless, the supporting weighted-sum model and data architecture (factor definition, criteria weights, scoring scales, etc.) is purposefully created to be made scalable, so that additional materials could be added without modifying the fundamental decision logic. The earlier research underline that modular MCDM structures increase flexibility and long-term usability of the decision-support tools within dynamic constructions markets (Behzadian et al., 2012; Zavadskas et al., 2016). An introduction of new materials, in practice, demands the definition of default cost parameters, quantitative performance values, and qualitative descriptors, and slight changes in the user interface, which aligns with the best practices in extensible decision-support system design (Huang et al., 2018). Such extensions are supported in the modular Streamlit-based implementation that is based on dictionary-based data structures and provides transparency and computational stability.

In addition to material growth, scalability also includes the capacity to add new assessment standards or re-calibrate the old ones according to the changing sustainability priorities. Since the ideas of circularity, climate resilience, and occupant health and well-being have become a significant part of the sustainable construction discussion, the subsequent versions of the tool can introduce a set of criteria associated with recyclability, reuse, indoor air quality, or thermal comfort (Cabeza et al., 2022; Pomponi and Moncaster, 2017). In the same way, criteria weights can be re-estimated in case of updated survey data or when the tool is used in other geographic or regulatory settings where practitioners' priorities may not be the same as those that were identified in New Zealand (Govindan et al., 2015; Li et al., 2019). Notably, the normalisation process inbuilt to the weighting algorithm makes sure that the weights of all the criteria add up to 100 per cent and thus internal consistency and methodological integrity maintains even with the introduction or revision of criteria (Triantaphyllou and Santos, 1997).

8.5.2 Geographic Transferability and Data Localisation

One of the guiding principles of the decision-support tool development is that the process of material selection is a context-specific matter that can be conditioned by the local weather conditions and climate, protection regulations, market forms, and the priorities of practitioners (Akadiri et al., 2013; Li et al., 2019). Thus, criteria weights and scoring descriptors that were used within this study are based on the perception of New Zealand construction professionals,

local climate factors, and regulatory standards, as well as supply-chain realities. To be applicable in a cross-geographic context, the data inputs of the tool need to be localised systematically and not copied into another area. Previous research highlights that the success of MCDM-based systems of decision support relies upon the conformity to area-specific cost models, carbon levels, and regulatory and cultural environments (Govindan et al., 2015; Zavadskas et al., 2016).

The tool must be localised thus through parallel empirical research in the areas of interest, such as the re-definition of the criteria significance by conducting surveys among the practitioners, adjusting cost and embodied-carbon data to local market environment, and recalibration of qualitative rating scales descriptors to be indicative of the regional standards and climatic areas (Hertwich et al., 2020; Pomponi and Moncaster, 2017). The methodological approach employed in the present thesis, including the systematic literature review, the survey-based weight, the qualitative SWOT analysis and the use of the Delphi-based expert validation is a replicable model of such localisation processes. The tool can provide context-sensitive decision support in a wide variety of geographic contexts without affecting methodological consistency or transparency by maintaining the same decision architecture but replacing context-specific data and expert inputs (Behzadian et al., 2012; Triantaphyllou and Sánchez, 1997).

8.5.3 Integration with Digital Platforms and Databases

The interoperability with external digital platforms and data structures is also a factor that determines the scalability of the decision-support tool, instead of using only internal datasets, which are not updated. Although the current prototype implementation uses fixed dictionaries to cost, embodied carbon, and performance values, which can be appropriate when evaluating and validating them is the goal, long-term adoption would be enhanced with connection to dynamic and authoritative data, including national embed-carbon databases and the environmental product declaration (EPD) repositories (Hollberg et al., 2020; Soust-Verdaguer et al., 2017). Application programming interfaces (APIs) to update embodied-carbon factors, cost indices, and supply-chain data have been broadly found as a key facilitator of data accuracy and relevance in the digital sustainability decision-support systems (Antón and Diz, 2014; Cavalliere et al., 2019).

Integration with building information modelling (BIM) platforms is another way of increasing usability and traceability, with direct material data transfer between design models and the decision-support environment allowing to minimize manual input and help to provide more consistent early-stage material appraisal (Eastman et al., 2011; Santos et al., 2022). According

to prior studies, such interoperability needs an organization in line with open data standards, uniform semantic definitions, and resilient information-exchange protocols to ascertain reliability among software environments (ISO, 2018; O'Donnell et al., 2020). Meanwhile, greater connectivity brings up issues on governance, security, and privacy of data, which need to be considered to promote and uphold professional trust and regulatory measures when implementing at scale, decision-support tools (Rezgui et al., 2013). These integration issues are also key to evolving the proposed tool as a tested prototype to a deployable low- and zero-carbon material decision-making digital infrastructure.

8.5.4 Adoption across User Groups and Project Scales

Scalability also encompasses the capacity of the decision-support tool to be adopted by diverse stakeholder groups and applied across projects of varying scale and complexity. While the current prototype has been evaluated primarily by architects, engineers, and sustainability consultants, the underlying decision logic and interface are equally relevant to policymakers, contractors, and clients, who increasingly influence material decisions through regulatory, procurement, and investment mechanisms (Akadiri et al., 2013; Govindan et al., 2015). Prior research highlights that decision-support systems designed around transparent, criteria-based logic are more readily adopted across interdisciplinary teams, particularly when they align with existing professional workflows and decision responsibilities (Huang et al., 2018; Rezgui et al., 2013).

At larger project scales—such as commercial developments or infrastructure projects—the tool can be extended from evaluating individual materials to assessing assemblies or building systems (e.g., wall or roof systems), an approach commonly recommended in life cycle and systems-based sustainability assessment (Cabeza et al., 2022; Hollberg et al., 2020). Furthermore, the framework can support scenario analysis involving hybrid or mixed-material solutions by aggregating weighted scores across multiple components, reflecting real-world construction practices where composite systems are prevalent rather than single-material solutions (Pomponi & Moncaster, 2017; Santos et al., 2022). Such extensions are consistent with prior work on scalable MCDM applications that adapt decision granularity according to project scope and design maturity (Zavadskas et al., 2016).

Beyond professional practice, the tool also holds potential as an educational and capacity-building resource within university curricula and professional training programmes. Decision-support tools have been shown to enhance sustainability literacy by making trade-offs explicit and enabling experiential learning through scenario-based exploration (Ding, 2008; Kibert,

2022). In this context, the proposed framework can contribute to developing future practitioners' competence in low- and zero-carbon material selection, thereby extending its impact beyond individual projects to broader industry capability development.

8.5.5 Usability Considerations

The usability can be described as the measure of how a decision-support tool could be learned, understood, and used by the targeted users to attain their goals, which is commonly considered a decisive factor in adoption and long-term effects (ISO, 2018; Nielsen, 1994). The concept of usability is especially crucial in the context of sustainable construction decision-support systems since users are supposed to be able to interpret a complex set of trade-offs with time and cognitive constraints (Hollberg et al., 2020). In line with the foregoing, the proposed tool is designed to be simple, transparent and user empowered in a way that both evaluation logic, criteria weightings and aggregated scores are visible and understandable other than hidden and inaccessible by their algorithms (Behzadian et al., 2012). Nevertheless, previous studies point out that the concept of usability is not a fixed design attribute, but it is an iterative process that must be repeatedly refined according to user feedback, varying circumstances of this decision, and technological change (Norman, 2013; Rezgui et al., 2013). Although the existing implementation shows preliminary usability due to a systematic interface and well-defined scoring system, continued functionality requires continuous user-based testing and constant enhancement. User experience has to be paid attention to in order to support ease of use, however, it is also necessary to promote trust, lessen cognitive load, and offer the practitioners the opportunity to utilize decision-support outputs in the real-world material selection processes (Huang et al., 2018; Ding, 2008).

8.5.6 Intuitive User Interface

An intuitive user interface is an important facilitator of a successful decision-support, especially in the sustainability context where users are required to analyse a variety of criteria and trade-offs within budgetary constraints of time and cognitive limitations (Norman, 2013; Nielsen, 1994). The interface that is currently used is deliberately minimal and enables the user to choose the materials and evaluate the assessment items by using structured drop-down lists, which is aligned with the usability principles and puts more emphasis on clarity, learnability, and fewer cognitive load requirements (ISO, 2018). According to the feedback of the experts participating who participated in the Delphi validation, this simplicity helps the first interaction and understanding, which is why designing transparent interaction is so critical in a professional decision-support solution (Hollberg et al., 2020). However, the previous studies point out that

intuitive design is not limited to visual simplicity, and it needs progressive revelation of information to serve users with different expertise levels (Norman, 2013). Additional improvements to come in the future might involve contextual aids like tooltips or pop-up definitions that would help people with less technical background to become more acquainted with the technical terminology and scoring descriptions without necessarily simplifying the logic behind it (Nielsen, 1994). Moreover, visual feedback systems, including colour-codings or benchmarking comparisons have been found to increase interpretability and facilitate quick sense-making in a multi-criteria evaluation situation (Few, 2013; Behzadian et al., 2012). It can also be enhanced with the integration of comparative visualisations, e.g., bar charts or radar plots, which will help users to gain insights into relative material performance on criteria, which will enhance the transparency of the decision outcomes and their confidence (Huang et al., 2018). All these interface improvements would increase user experience and maintain analytical integrity of the decision-support framework.

8.5.7 Customisation and Flexibility

The usability characteristics of decision-support tools that are significant in the context of construction include customisation and flexibility because the needs and objectives of a project, their constraints, and stakeholder priorities often differ significantly (Govindan et al., 2015; Zavadskas et al., 2016). In the existing application, the criteria weights are determined using survey outcomes that are obtained empirically, and the scoring descriptions are globalised in terms of the common situations within the New Zealand construction industry. This will be consistent and comparable across any given project, but past studies indicate that perceived relevance and practical applicability of MCDM-based tools can be improved by permitting the controlled user-driven modification of parameters (Triantaphyllou and Sanchenz, 1997; Behzadian et al., 2012). Future extensions of the tool may thus be able to accommodate a project-specific customisation, e.g., allowing the user to modify weights of criteria using interactive controls to reflect certain project design priorities or subjective judgments, but the inherent weights used in the surveys remain a transparent reference point (Wang et al., 2009). In the same way, optional input fields would enable practitioners to replace default cost or embodied-carbon values with project-specific data where available local data can be relied upon, such as the ability to replace local data with contextual accuracy in sustainability-oriented decision-support systems (Hollberg et al., 2020). Notably, the literature highlights that flexibility should be followed by a clear statement of its implication that should include warnings or visual cues on how the change of default parameters affect the rankings and

comparability (Norman, 2013). Much of this protection assists in maintaining transparency, reducing abuse, and making sure that greater flexibility does not weaken but instead makes results of decisions more credible and interpretable.

8.5.8 Training and Support

User confidence, institutional support and access to organised learning material have a high impact to adopting digital decision support tools especially in professional areas that are risk based in decision making like construction and sustainability (Rogers, 2003; Ding, 2008). In order to improve the usability and uptake, the proposed tool can be supplemented with explicit tutorials, user manuals, and demonstrative case studies to illustrate how the tool can be applied in ordinary project situations. According to previous studies, these supporting materials are necessary to reduce barriers to entry, perceived complexity, and meaningful interaction with decision-support systems (Hollberg et al., 2020; Norman, 2013). The professional bodies and the industry organisations are very important in facilitating the diffusion of the new tools and practices. Activities such as workshops, webinars, and continuous professional development could facilitate familiarisation of practitioners, as well as create feedback that can improve the subsequent refinement of the tool (Rezgui et al., 2013; Rogers, 2003). Moreover, constant peer-peer support can be established by creating online communities of practice, help desk or forums so that users can get to share experiences, clear up doubts and share best practices and this has been proven to enhance long term adoption and learning (Wenger, 1998). With the development of the tool, version control and visible changelogs are critical to save the trust, traceability, and the possibility of analysis reproducibility. Documentation of updates clearly enables the user to learn how changes can have an impact on the results and, when needed, repeat past analyses (Sandve et al., 2013). Combined, these training and support mechanisms situate the decision-support tool as not just a technical artefact, but as a component of a larger knowledge infrastructure that will be used to build sustained capability in the area of zero-carbon selection of materials.

8.5.9 Technological Accessibility

Technological accessibility is a critical condition for the widespread adoption of digital decision-support tools, particularly in professional settings characterised by heterogeneous user capabilities, devices, and infrastructure (Rogers, 2003; Rezgui et al., 2013). The web-based deployment of the proposed tool reduces entry barriers by requiring only a standard web browser and internet connectivity, a delivery model that has been shown to support broader reach and lower technical overhead in construction-related decision-support systems (Hollberg

et al., 2020). Nevertheless, prior studies emphasise that effective accessibility extends beyond platform availability to include performance optimisation for low-bandwidth environments and compatibility with mobile devices, which are increasingly used by practitioners in on-site and remote contexts (Santos et al., 2022). In addition, internationalisation features are essential for extending the tool's applicability beyond English-speaking regions and for enabling equitable access across diverse cultural and regulatory settings (ISO, 2019). Compliance with recognised digital accessibility standards, including the Web Content Accessibility Guidelines, is also necessary to accommodate users with visual, auditory, or cognitive impairments and to ensure inclusive design practice (W3C, 2018). Addressing these accessibility considerations strengthens the ethical and practical foundations of the tool and aligns its deployment with broader principles of inclusive, user-centred digital decision support.

8.6 Government Support and Subsidies

Proactive policy decisions and financial incentives will probably improve the implementation and effects of the use of the DTS. Although the study was done without the involvement of the government sponsorship, one can make a number of arguments why the central and local governments of New Zealand should sponsor and provide subsidies to the implementation of the tool.

8.6.1 Aligning with National Climate Objectives

The requirement to achieve net-zero carbon emissions by 2050 as outlined in the Climate Change Response (Zero Carbon) Amendment Act 2019 is further bolstered by the fact that New Zealand is serious about the building sector, and any effective way that both operational and embodied carbon emissions should be reduced must be developed. The Building for Climate Change (BfCC) initiative by the Ministry of Business (MBIE, 2020b), Innovation and Employment (MBIE) is focused on the reduction of emissions by changing regulations as well as the participation of industries though it only offers high-level advice on the selection of materials at present. The adoption and promotion of the DTS by the government would therefore offer practical support to those in the industry who will want to adhere to the new carbon reduction demands. Subsidies may be in form of development grants, licensing that enable free access by small or medium enterprises (SMEs), or as a part of the official BfCC resources of MBIE.

8.6.2 Supporting Data Infrastructure and Standardisation

Government support is critical for addressing persistent data-related barriers that undermine the accuracy, credibility, and comparability of embodied-carbon assessments in material selection. As discussed in earlier chapters, environmental product declarations and life-cycle inventory datasets available for New Zealand–based construction materials are often incomplete, inconsistently reported, or derived from international averages that do not reflect local production methods, energy mixes, or supply-chain conditions (Strazza et al., 2016; Vierra, 2016). Such limitations constrain the reliability of carbon-informed decision-making and weaken practitioner confidence in quantitative comparison tools. International experience demonstrates that public investment in coordinated national data infrastructure can substantially improve the consistency, transparency, and usability of embodied-carbon data for material selection (Hollberg et al., 2020; Anderson & Moncaster, 2020). Establishing a New Zealand–specific embodied-carbon database, aligned with local manufacturing processes and regulatory conditions, would enhance the precision of material assessments and reduce reliance on proxy assumptions. In parallel, government-led standardisation of reporting requirements for material suppliers, including harmonised EPD templates and disclosure protocols, would support interoperability and enable integration with open digital platforms and decision-support tools (ISO, 2017; Pomponi et al., 2022). Such alignment would not only strengthen the performance of the decision-support tool developed in this thesis but also contribute to a broader ecosystem of data-driven sustainability instruments across the construction sector. Evidence from jurisdictions such as the United Kingdom indicates that coupling standardised data infrastructures with financial incentive schemes—for example, grants or tax mechanisms linked to demonstrable embodied-carbon reductions—can accelerate low-carbon material adoption more effectively than voluntary or non-monetary measures alone (Rosenow et al., 2020; UK Green Building Council, 2021). Collectively, these policy-driven data interventions provide a necessary foundation for scalable, transparent, and credible low-carbon material decision-making.

8.6.3 Financial Incentives for Low-Carbon Adoption

In the short term, cost premiums, market immaturity, and supply-chain constraints can discourage developers from adopting low-carbon construction materials such as rammed earth or straw bale, despite their environmental benefits (Pomponi & Moncaster, 2017; Cabeza et al., 2022). Empirical evidence from sustainability transitions literature indicates that such early-stage barriers can be effectively mitigated through targeted financial incentives, including

grants, tax credits, and green public procurement policies, which reduce perceived risk and encourage experimentation with alternative materials (Rosenow et al., 2020; Rogge & Reichardt, 2016). When financial incentives are coupled with an evidence-based decision-support tool, subsidies can be more transparently aligned with demonstrable embodied-carbon reductions rather than generic material categories. This linkage enhances accountability by ensuring that incentive recipients base their choices on informed, comparable assessments of environmental and practical performance (Hollberg et al., 2020). Furthermore, integrating such decision-support mechanisms into public procurement processes for government-funded projects can help institutionalise low-carbon material selection, raising baseline sustainability performance while signalling best practice to the private sector (Testa et al., 2016; UK Green Building Council, 2021). Beyond immediate market stimulation, the alignment of financial incentives with regulatory frameworks and professional education can contribute to longer-term capacity building. Embedding low-carbon material evaluation within training programmes and public-sector project requirements supports learning-by-doing and accelerates the diffusion of sustainable construction practices across the industry (Ding, 2008; Rogers, 2003). Together, these measures position financial incentives not merely as short-term subsidies, but as strategic instruments for fostering informed, durable transitions toward low-carbon construction.

8.6.4 Regulatory and Educational Integration

Beyond financial incentives, decision-support tools can be embedded within regulatory and educational systems to more systematically mainstream low-carbon material selection. Prior research highlights that regulatory mechanisms play a decisive role in shaping early-stage design decisions, where embodied-carbon impacts are largely determined (Hertwich et al., 2020; Pomponi et al., 2022). Integrating the decision logic underpinning the proposed tool into building-code compliance routes or performance-assessment processes would formalise the consideration of embodied carbon alongside cost, durability, and constructability during planning approval, thereby shifting low-carbon evaluation from a voluntary practice to a routine procedural requirement (Ding, 2008; Anderson & Moncaster, 2020). In parallel, educational integration represents a longer-term strategy for building industry capability. Incorporating decision-support tools into tertiary curricula and professional education programmes has been shown to enhance understanding of multi-criteria decision-making, sustainability trade-offs, and data-driven design reasoning among future practitioners (Kibert, 2022; Wiek et al., 2011). Early exposure to such tools can support the development of a workforce that is more

comfortable with quantitative sustainability assessment and evidence-based material selection. At the policy level, aggregated and anonymised outputs generated through tool use could provide valuable insights into market behaviour and adoption patterns. When used appropriately, such data can support evidence-informed policymaking, enabling governments to identify structural barriers, target incentive schemes more effectively, and monitor the impact of regulatory interventions over time (Rosenow et al., 2020; Rogge & Reichardt, 2016). In this way, regulatory and educational integration extends the role of the tool beyond project-level decision support to a broader governance and learning function within the low-carbon construction transition.

8.7 Problems Addressed by the Decision-Support Tool

The tool that is discussed in this thesis is dealing with some chronic issues of the modern process of selecting materials when constructing low-carbon buildings. It offers a vehicle of going beyond subjective or ad-hoc decision making by building a transparent framework through integrating empirical evidence and practitioner needs systematically, to reduce the obstacles to the use of low-carbon materials.

8.7.1 Fragmented Decision Processes

A recurring problem identified in both the literature, and the empirical findings of this study is the fragmentation of material selection decision-making across multiple stakeholders, including architects, engineers, contractors, clients, and product suppliers (Akadiri et al., 2013; Ding, 2008). These actors often operate with differing priorities, evaluative criteria, and information bases, while coordination and communication between disciplines remain limited, particularly during early design stages (Rezgui et al., 2013). Such fragmentation can lead to inconsistent assumptions, misaligned objectives, and increased potential for conflict or redesign. The decision-support tool developed in this research addresses this challenge by providing a shared evaluative structure, within which relevant criteria are explicitly defined, weighted, and aggregated. By presenting trade-offs through a common numerical and conceptual framework, the tool supports cross-disciplinary dialogue and comparison, enabling stakeholders to discuss material options using a shared vocabulary and transparent logic. Prior research suggests that structured, criteria-based decision-support environments can improve collaborative decision-making by reducing ambiguity and making underlying assumptions explicit, rather than relying on informal or discipline-specific judgement alone (Govindan et al., 2015; Zavadskas et al., 2016).

8.7.2 Data Inconsistencies and Uncertainties

A second major problem addressed by the decision-support tool is the inconsistency and uncertainty of locally relevant data related to material costs, embodied carbon, and performance characteristics. As highlighted in earlier chapters and widely reported in the literature, available datasets are often incomplete, heterogeneous, or based on international averages that do not accurately represent local production methods or market conditions (Strazza et al., 2016; Anderson & Moncaster, 2020). These limitations undermine confidence in quantitative comparison and contribute to scepticism toward carbon-informed material selection. The tool mitigates these challenges by consolidating available data into a structured database and by enabling users to substitute default values with project-specific inputs where reliable information is available. In addition, the emphasis on relative scoring and weighted comparison, rather than absolute optimisation, reduces sensitivity to individual data points and supports decision-making under conditions of uncertainty. Similar approaches have been shown to be effective in sustainability-oriented MCDM applications, where data precision is often limited but comparative reasoning remains possible (Triantaphyllou & Sánchez, 1997; Behzadian et al., 2012). Nonetheless, as discussed previously, the effectiveness of such tools ultimately depends on continued improvement of national data infrastructure and standardisation efforts led by industry and government.

8.7.3 Cognitive Burden and Time Constraints

Material selection decisions are frequently made under time pressure and resource constraints, particularly in small practices or early project phases, where detailed life-cycle analysis of multiple alternatives is impractical (Hollberg et al., 2020). In such contexts, practitioners may rely on heuristics or prior experience, increasing the risk of suboptimal or poorly justified choices (Norman, 2013). The proposed decision-support tool addresses this problem by reducing cognitive burden through automated aggregation of criteria weights and performance scores, presenting results in a concise and interpretable format. The interactive interface supports rapid iteration across alternatives, while the availability of default cost values and standardised scoring descriptors lowers the effort required for data input. Research in decision-support and human–computer interaction indicates that such features can significantly improve decision efficiency by externalising complex calculations and supporting sense-making, particularly where users face multiple competing objectives (Nielsen, 1994; Huang et al., 2018).

8.7.4 Bridging Policy and Practice

Lastly, the tool helps bridge the gap between high-level policy objectives and operational decision-making in practice. By integrating embodied carbon considerations into a format that is accessible to practitioners, the tool translates the core policy objectives and implementation intent of initiatives such as the Zero Carbon Act (Ministry of the Environment, 2019) and the BfCC programme (MBIE, 2020b) into actionable guidance. In doing so, it supports the mainstreaming of carbon awareness and facilitates a shift in industry practice towards evidence-based sustainability.

8.8 Implications

The above discussion has various implications to research, practice and policy. To begin with, the methodological framework offers the template to other areas and sectors planning to make context-specific DTS. The survey and the Delphi processes might be repeated in other countries in the future, and the weights and criteria obtained were to be compared and cross-cultural differences between material selection priorities were to be examined. It might also be of interest to researchers to examine non-additive MCDM models (e.g., multiplicative or outranking methods) to consider the interactions between multiple criteria or to use qualitative preferences in another way.

Second, it is essential to develop data infrastructure. Creating national repositories of embodied carbon and life-cycle cost data, along with standardised formats of EPDs and supply-chain reporting, would not only support the described tool in this thesis but also a bigger ecosystem of sustainability analytics. Government agencies should work with researchers and industry in developing such databases, the quality of data, transparency, and accessibility.

Third, the tool has a promising future of innovation through integration into the digital design workflow. Connections with the BIM software Parametric design engines and life-cycle assessment tools may be useful in connecting the tool with BIM software and automated analysis of design options and enable real-time feedback in the course of architectural modelling. Experts in the field of artificial intelligence and machine learning can make predictive analytics to suggest the best material mixes, depending on the project restrictions and user preferences.

Fourth, policy measures are necessary to establish favourable terms to use low-carbon materials. Carbon pricing, procurement policies, subsidies and regulatory requirements can change the nature of the market, however, they have to be supported by easy-to-use mechanisms that assist

practitioners navigate the ensuing environment. The decision-support tool introduced in this thesis can be used to assist in evidence-based policy making as it offers a summary of insights on the way materials are selected and where the obstacles exist. Lastly, education and cultural change of construction industry is a need that needs to be continuous. Even though the tool can ease the cognitive load and enhance the transparency, its implementation relies on the readiness of practitioners to accept new practices and challenge the traditional ones. Integrating the tool into professional development programmes, university curricula and industry guidelines will assist in the establishment of a sustainability literacy and continuous improvement culture.

Chapter 9: Conclusion and Future Research

9.1 Introduction

This chapter is the conclusion of the thesis as the main findings of all the stages and chapters of the research are synthesised, and the role of research objectives and questions is reflected. It subsequently presents the major theoretical, methodology and practical contributions of the work, the limitations of the study as well as its future research directions. The chapter ends by restating the importance of the developed DST to the development of the zero-carbon material selection in the New Zealand construction industry.

9.2 Summary of Key Findings

This study aimed at filling a significant gap between the New Zealand zero-carbon policy aspirations and the reality of material choice in construction projects. The study produced evidence at various levels, material, factor, criteria, and decision-framework levels, to formulate informed and transparent zero-carbon material choice.

To begin with, the thesis has given and critically analysed the usual zero-carbon and low-carbon materials of building to use in the New Zealand setting, such as timber-based products, straw bale, rammed earth, adobe, cork, stone, and earth-based substitutes (Chapter 3).

Although these materials show great potential in reduction of embodied carbon, their use is limited by uncertainty issues of durability, constructability, regulatory compliance, availability, and familiarity on the market. Second, an internationally specific and New Zealand-specific PRISMA-compliant systematic literature review (Chapter 4) summarised the evidence on zero-carbon material performance. This review has pointed to the lapsed and uncoordinated application of selection criteria in research and further validated the importance of a multi-criteria decision-support solution as opposed to single performance evaluations.

Third, an empirical survey of construction stakeholders (Chapter 5) revealed six prevailing factors that can affect sustainable material selection in New Zealand: cost-effectiveness, durability, buildability, embodied carbon, availability, and aesthetics. It was established through SEM that the decision of the type of materials selected is a multi-dimensional concept which cannot solely be justified by environmental performance.

Fourth, a qualitative SWOT-based analysis (Chapter 6) offered a deeper interpretive analysis of each of the selection criteria and revealed practical risks, implementation challenges, and

contextual trade-offs usually ignored by quantitative models. This step enhanced the construct validity and practicality of the decision framework.

Lastly, these combined results were operationalised into a multi-criteria DTS (Chapter 7) which was implemented as a digital application and tested with academics, industry, and policy experts in a three-round Delphi process (Chapter 7). The Delphi findings showed high agreement on the applicability, understandability and usefulness of the tool which validates its practical use in the early material selection decisions.

9.3 Research Contributions

The primary contribution of this thesis lies in reframing zero-carbon material selection from a predominantly environmental optimisation problem into a multi-dimensional decision process shaped by technical, economic, and contextual constraints. While previous studies have identified low-carbon materials or proposed conceptual MCDA frameworks, few have empirically grounded decision logic in practitioner priorities or translated findings into validated, usable artefacts. This research addresses that gap by combining mixed-method empirical analysis with design science research to deliver a functioning, adaptable decision-support tool tailored to the New Zealand construction context.

9.3.1 Theoretical Contributions

The research contributes to theoretical knowledge in sustainable building using the reframing of zero-carbon material selection as a MCDM problem, as opposed to an environmental or even technical optimisation problem. The research adds to the increasing literature on the need to consider many measures of sustainability assessment by empirically validating the interaction between the economic, technical, environmental, and contextual factors in sustainability assessment. Moreover, the thesis also adds to the decision-support theory within the built environment showing that abductive-deductive reasoning may be applied to combine literature-based constructs with empirical data and expert opinion in a consistent approach.

9.3.2 Methodological Contributions

The research methodologically shows an excellent use of research design science in the construction and sustainability research. The methodological template of systematic review, survey-based modelling, qualitative SWOT analysis and Delphi validation can be used in a sequential manner to give a replicable template of decision support research in the built environment in the future. The combination of survey-derived criterion weights, SEM-based construct assessment, Delphi review, sensitivity analysis, and transparent digital

implementation provides a reproducible methodological pathway from empirical evidence to an operational decision-support artefact.

The survey-derived weights reflect the aggregated preferences of the achieved sample and should not be treated as nationally representative or universally applicable. Their use as baseline DST weights is appropriate for prototype development, but regional or sector-specific applications require recalibration using more diverse samples. Future research should employ stratified sampling across regions and professional groups, including architects, contractors, quantity surveyors, sustainability consultants, Māori built-environment practitioners, local authorities, clients, and material suppliers.

9.3.3 Practical Contributions

The main practical contribution of this thesis is the creation of the proved practitioner-focused DTS on zero-carbon material selection and that specific to the New Zealand scenario. The DST in contrast to certification schemes or post-design assessment tools encourages the use of early-stage decision-making, where the stakeholders can compare materials in a systematic way before decisions have been locked in on design. The tool provides the architects, engineers, policymakers, and educators with value because the tool is able to translate complex evidence regarding sustainability in accessible and transparent decision logic. It is also a basis of industry- research partnership and policy-congruent application of zero-carbon building plans.

Preferential independence among the six criteria was not formally tested, and the SEM results indicate that some criteria may be related. The additive model therefore represents a pragmatic screening approximation rather than a complete representation of real project-level trade-offs. Future research should compare the WSM results with AHP, TOPSIS, outranking, or hybrid models using preference data specifically collected for those methods. A hybrid system combining mandatory threshold filters with weighted additive ranking may be particularly appropriate for criteria involving regulatory compliance, safety, or maximum acceptable embodied carbon.

9.4 Limitations of the Study

In spite of its contributions, this research has various limitations that need to be acknowledged. Such limitations can be attributed to methodological decisions, limitations on the availability of data, and the extent to which the tool is currently being put to use. Being aware of them gives the transparency as well as emphasizing the areas where the future work will enhance the study findings. Future research should extend the DST through six connected streams: resilience,

cultural relevance, regional calibration, methodological comparison, expansion of the material evidence base, and real-world validation. These extensions should not simply add more criteria to the existing model. Each proposed criterion must be conceptually defined, supported by appropriate evidence, operationalised through measurable indicators, evaluated for overlap with existing criteria, and validated with the stakeholder groups affected by its use.

9.4.1 Cross-Sectional Design and Temporal Dynamic

The cross-sectional design was applied to gather the empirical data by capturing the perceptions of the stakeholders at one time. Although suitable to the extent of determining salient decision factors and setting up of base weights, this method is incapable of explaining industry knowledge, change in policies and changing market situations. Such priorities as that of embodied carbon will probably become more significant with the development of regulatory frameworks and the implementation of carbon pricing. Equally, the perception of material availability and cost might change due to supply chain disruption or technological advancement. A longitudinal study or repeated surveys would help the researchers to trace such a temporal dynamic and modify the decision framework to suit the same.

9.4.2 Sample Composition and Generalisability

Despite the multicultural representation of the stakeholders on the survey and the Delphi panels, the sample sizes, especially on the expert validation, could not be large because of the topic in question being a specialist one. The Delphi panel of fourteen experts was sufficient to build consensus but is not capable of representing the broadness of experiences of the construction industry of New Zealand. There are some sub sectors that may have other priorities (e.g. residential vs. commercial developers, regional councils, indigenous building practitioners) which are not reflected in the current weighting. Further research might expand on the participation by focusing on specific sampling approaches, associating with industries, and working with professional organisations to raise the generalisability. Also, the comparison between the situations in various countries or regions would be used to define whether the weighting framework and criteria can be used outside of the New Zealand situation.

The survey findings have limited generalisability because the respondents were recruited using purposive sampling and were not proportionally representative of the New Zealand construction industry. Most respondents were located in Auckland, and engineers formed the dominant professional group. The results should therefore be interpreted as evidence from the achieved sample rather than as nationally representative estimates. Future validation should include

larger and more geographically and professionally balanced samples, including greater representation from regional centres, architects, contractors, quantity surveyors, clients, construction managers and sustainability specialists.

9.4.3 Data Availability and Modelling Assumptions

The DTS is based on the existing data and expert judgment assumptions instead of complete life cycle assessment (LCA) data sets of all materials. The inconsistency of environmental products declarations and the scarcity of New Zealand-specific embodied carbon data are a challenge that is still present. Cost and carbon values of certain materials were determined based on small samples or international data sets that had been adjusted to local conditions. Moreover, the weighted sum model presupposes the preferential independence of criteria- i.e. the importance of one criterion does not depend on the performance of another criterion. In practice, trade-offs can be more complicated: a material with low embodied carbon can be used to offset increased cost or poorer performance in a particular project. Although the weighted sum model is transparent and easy to use, it would be better to consider other multi-criteria approaches (e.g., multiplicative models, outranking methods) and consider more comprehensive LCA information to enhance resilience.

9.4.4 Validation Approach and Real-World Implementation

The tool has not been tested by a significant real-world application, but on the evaluation of the experts. Although the usability, relevance and logical behaviour were verified by professionals, the adoption rates and behavioural effects in real building projects were not assessed in the study. The time pressure, budget constraints, client preferences, and organisational culture can be influential factors, but they were out of the scope of this thesis. A live design project or pilot of the tool using a collaboration with design firms or project pilot would give a good understanding of the user behaviour, decision pathways, and barriers to adoption. An addition of this feedback of such pilots might expose more usability issues and training requirements.

9.4.5 Socio-Technical and Behavioural Factors

The study concentrates on technical and environmental standards but fails to delve into socio technical aspects of adoption, including organisational preparedness, cultural perspective on innovation or power relations in design teams. The strength of practitioners weighing the environmental benefits against the costs or buildability issues may be affected by the behavioural factors, risk aversion, familiarity bias, aesthetic preferences. Additional qualitative

study (e.g., interviews, ethnographic research) might illuminate these points and assist in tailoring the DTS to other organisational contexts.

9.4.6 Policy and Market Interactions

Lastly, the assumption of the research is a rather stable policy and market environment. As a matter of fact, the landscape can soon shift as government incentives, building-code changes, and market upheavals track their course. As an example, low-carbon material subsidies or high-embodied-carbon product fines may change decision priorities. Similarly, material availability and pricing might be influenced by a shortage in supply or alternation of international trade. It will be necessary to update the data and the weighting within the tool and continuously monitor the policy developments and the market trends to ensure it is relevant.

9.4.7 Resilience and adaptation

The current DST focuses primarily on economic feasibility, durability, buildability, embodied carbon, availability, and aesthetics. Future research should examine whether resilience should be introduced as a separate criterion or represented through additional sub-criteria. Potential dimensions include resistance to flooding, moisture, wildfire, earthquakes, extreme temperatures, and coastal exposure, as well as repairability, replaceability, supply-chain continuity, and recovery following disruption. These dimensions are particularly relevant in New Zealand, where climatic conditions and natural hazards vary considerably by region.

Developing a resilience criterion would require a systematic review of resilience indicators, consultation with structural, material, climate-adaptation, emergency-management, and insurance specialists, and validation against relevant New Zealand standards and hazard data. Researchers should also test whether resilience is sufficiently distinct from durability and availability. If substantial conceptual overlap exists, resilience may be better incorporated through revised sub-criteria rather than added as another independently weighted factor.

9.4.8 Māori and Pacific cultural values

Future development should investigate how cultural values influence the suitability and acceptance of building materials, particularly for Māori and diverse Pacific communities. This research should be conducted through co-design rather than by researchers assigning cultural scores to materials without community involvement. Appropriate participants may include iwi and hapū representatives, mana whenua, Māori architects and construction professionals, Māori housing providers, Pacific architects and practitioners, community organisations, and building users.

The objective would be to determine which cultural considerations are relevant to material-selection decisions and how they should be represented. Possible areas for investigation include relationships with place and natural resources, intergenerational stewardship, collective wellbeing, cultural identity, local knowledge, material provenance, community capability, and the social consequences of extraction and production. These dimensions should not be collapsed prematurely into a single generic "cultural value" criterion. Māori and Pacific communities are not homogeneous, and the tool may require community-specific decision profiles, qualitative guidance, or locally governed criteria rather than one nationally standardised cultural weight.

Future studies should use culturally appropriate and participatory research approaches and establish clear governance over how cultural knowledge is collected, interpreted, stored, and incorporated into the DST. The relevant research protocols and terminology should be developed with participating communities and supported by appropriate New Zealand scholarship.

9.4.9 Regional access, availability, and pricing

Regional calibration is necessary because the survey-derived weights predominantly reflect Auckland-based respondents, while material prices, transport distances, labour capability, climatic exposure, supplier networks, and regulatory implementation differ across New Zealand. Future studies should collect regionally stratified data from Auckland, Wellington, Canterbury, Waikato, Bay of Plenty, Otago, Northland, and other relevant areas rather than applying a single national profile.

Regional versions of the DST should incorporate local supplier coverage, transport distance and cost, lead times, labour and installation costs, specialist expertise, production capacity, and exposure to supply disruption. Cost and availability information should be time-stamped because both can change rapidly. Geographic information systems and periodically updated supplier or quantity-surveying databases could support location-sensitive estimates.

Regionally stratified surveys could then test whether criterion weights differ by location, profession, project type, and level of experience. Where the measurement structure is comparable across groups, multi-group analysis could be used to determine whether observed differences represent statistically meaningful regional variation. This would allow users to select an appropriate regional profile rather than relying on the current Auckland-dominated baseline.

9.4.10 Comparison of weighting and ranking methods

Further methodological research should compare the current survey-weighted WSM with alternative approaches using data collected specifically for each method. These may include AHP or Best–Worst Method for structured preference elicitation, TOPSIS for distance-to-ideal ranking, and ELECTRE or PROMETHEE for decisions involving thresholds or non-compensatory preferences. Objective weighting approaches, such as entropy or CRITIC, could also be examined where sufficiently complete quantitative performance data are available.

These methods should be compared using the same material alternatives and evaluation dataset. Relevant outcomes include ranking agreement, rank reversal, sensitivity to normalisation, consistency of participant judgements, cognitive burden, completion time, ease of explanation, and perceived usefulness among practitioners. This would determine whether WSM remains the most suitable method for practitioner-facing screening or whether a hybrid model provides stronger decision support.

A particularly useful extension would combine mandatory eligibility thresholds with subsequent weighted ranking. Materials that fail regulatory, structural, fire-safety, moisture, or maximum-carbon requirements would first be excluded. The remaining materials could then be ranked using the weighted model. This would prevent strong performance on cost or aesthetics from compensating for unacceptable performance on non-negotiable criteria.

9.4.11 Expansion of materials, assemblies, and evidence

The current prototype evaluates four material categories. Future research should include additional bio-based, recycled, and low-emission materials and progress from individual materials to complete building assemblies, such as wall, floor, and roof systems. Assembly-level evaluation would better represent real construction decisions because material performance depends on thickness, connections, finishes, insulation, protective layers, transport, maintenance, and end-of-life scenarios.

Future versions should also extend the environmental boundary beyond cradle-to-gate embodied carbon where data permit. Integration of modules covering transport, construction, use, maintenance, replacement, and end of life would provide a more complete life-cycle comparison. Default values should be linked to traceable EPDs, New Zealand-specific life-cycle inventories, current cost sources, and documented uncertainty ranges.

9.4.12 Real-world and longitudinal validation

The DST should be tested within live design and procurement projects involving architects, engineers, quantity surveyors, contractors, clients, sustainability consultants, and relevant community stakeholders. Comparative studies could examine decisions made with and without the tool and measure decision time, confidence, transparency, selected materials, predicted embodied carbon, projected cost, and changes made during later project stages.

Longitudinal research should examine whether DST-supported recommendations are retained through procurement and construction and whether predicted benefits are realised. Such research would distinguish perceived usability and expert approval from actual decision impact. Repeated surveys would also allow criterion weights to be updated as material markets, regulations, carbon policies, and professional knowledge change.

9.4.13 Prioritisation

The immediate research priorities are regional recalibration of cost and availability data, correction and comparative testing of the weighting and aggregation procedure, and real-project validation. Resilience and culturally grounded criteria should then be developed through dedicated studies with the appropriate technical specialists and community partners. These elements should not be added to the existing tool as unvalidated fields because doing so would increase apparent comprehensiveness without establishing measurement validity or decision relevance.

9.5 Directions for Future Research

There are several ways future studies can progress based on this study.

Future research should further validate and refine the six literature-derived material-selection factors using broader and more diverse practitioner samples. While the present survey identified cost-effectiveness as the highest-rated factor among the surveyed New Zealand construction professionals, this represents the empirical prioritisation of a pre-specified literature-derived factor rather than the identification of a new factor. Future studies should examine whether the relative importance of cost-effectiveness and the other five factors remains consistent across different regions, stakeholder groups, project types, and changing market conditions. Such studies may also investigate whether additional context-specific factors emerge that warrant consideration in future versions of the decision-support tool. Future application of the DST

longitudinally could examine the behaviour of material selection across time and whether the sustained use resulted in measurable improvements in the outcome of embodied carbon. It would also be beneficial to develop the tool further to include dynamic data on life-cycle assessment, carbon pricing, or regulatory levels to increase its analytical power.

The framework can be also scaled to other national settings or typologies of buildings and allow cross national comparison of zero-carbon material strategies. Moreover, the combination of the DST and Building Information Modelling (BIM) systems or AI-based recommendation systems is also a possible way of expanding its real-world influence.

Lastly, the issue of how DTS are influencing the professional learning, risk perception, and sustainability culture of construction organisations can be explored in the future and this way, the contribution made by technical decision-making can be expanded into behavioural and organisational change.

9.6 Concluding Remarks

This thesis shows that the possibility to reach zero-carbon construction in New Zealand cannot be achieved through the conventional power to find alternative materials or policy intent only. It needs well-organized, clear, and evidence-based decision-support systems to reconcile environmental goals with the real-life professional limitations. This study adds a viable direction of converting zero-carbon intentions into a material selection decision through the creation and validation of a multi-criteria DTS based on empirical data and expert opinion. Through this, it contributes to academic knowledge and professional practice and helps in the transition of New Zealand to a more sustainable and resilient built environment.

Appendix A: Summary of the findings from the selected studies

Sources	Studied Material(s)	Research Themes	Proportional of the material(s)	Building's Elements/types	Methods	Summary of Findings	Other Consideration
(Mutani et al., 2020)	Straw Bale	Thermal performance	515 mm thick walls	Two houses	Experimental measurement	The main results or findings regarding the thermal performance of straw bale walls include good insulating performance and high thermal inertia, the ability to offer energy savings and be used in green buildings, low cost, eco-sustainability, and potential for local economic development.	N/A
(D'Alessandro et al., 2017)	Straw Bale	Durability and Indoor Comfort, Sound Insulation, and Energy Performance	N\A	Wall (A pilot sample building)	Laboratory evaluation	The results demonstrated that the Life Cycle Assessment demonstrates that the use of straw bales in walls can reduce the energy and carbon embodied in the building. The results also showed that the tested façade had quite poor performance compared with a traditional heavyweight or lightweight wall.	Yearly thermal energy and electricity consumption per 1 m^2 of the wall in the winter season were measured by 8.19 and 2.34 kWh/m2/year, respectively. In conclusion, the study showed that straw bales have the potential for profitable use in the building sector, but several problems were also identified: the influence of moisture on the durability of the straw, the fire hazard during construction, the limited dynamic thermal performance and sound insulation.
(Alcorn & Donn, 2010)	strawbale and timber	CO_2 emissions, Life Cycle Analysis, conventional insulation, and energy performance	N\A	The whole house (Eighteen 200m^2 houses)	Experimental measurement	The results showed that the building with strawbale, timber frame, and concrete floor, (41.7 GJ and 2.197 kg) compared to the standard house with code insulation, timber frame, and concrete floor (37.9 GJ and 1.903 kg) could drop the annual energy and annual Co_2-e by about 9% GJ and 13% kg, respectively.	Also, they compared strawbale, timber frame, concrete floor and strawbale, timber frame, and suspended timber floor (36.9 GJ and 1.707 kg). The findings revealed that a building with suspended timber floors could reduce the annual energy and CO_2 by about 2.5% GJ for energy and 10% kg for CO_2. The total annual CO2-e reductions for strawbale insulation were 491 kg and 29%.
(Buchanan & Levine, 1999)	Wood	CO_2 emissions	N\A	Whole house (Two single-storey portal-frame buildings)	A comparative study	An analysis of typical forms of building construction shows that wood buildings require much lower process energy and result in lower carbon emissions than buildings of other materials such as brick, aluminium, steel and concrete.	The study reveals that a 17% increase in wood usage in New Zealand's building industry could cut carbon emissions by 20%, equivalent to about 1.5% of the nation's total emissions. This reduction mainly results from substituting wood for materials like brick, aluminium, steel, and concrete, which require more energy. Consequently, there would be a

							corresponding 1.5% decrease in total national fossil fuel consumption. These findings have significant implications for global forestry and construction, highlighting the need for increased forest management for sustained wood production.
(Resendiz et al., 2020)	Straw and wool	Insulation: Thermal resistance Vapour resistance	N\A	Wall (Three prefabricated wall panel)	The calculations have been manually conducted	The findings indicated that the thermal resistance and Vapour resistance of Panel 1 (straw) were about 7.2 m^2K/W and 4.714 MNs/g, which means straw could reduce these amounts by about 17%. However, the vapour resistance was slightly different, nearly 1%, compared to Panel 2.	Panel 2 combines wool's low density and superior insulative properties with straw's ability to support the bio-based vapour-permeable material of clay plaster. Panels 1 and 2 seek to improve upon existing prefabricated straw panels by increasing the thermal resistance and decreasing the weight of the panel by incorporating pure wool insulation.
(Umubyeyi et al., 2023)	Rammed earth	Durability	450 mm thick wall	Wall	Field measurement	The results showed that the estimated lifespan of the freestanding unsterilised rammed earth wall with minimal protection from natural climatic conditions in a temperate climate is between 37 and 75 years.	N/A
(Ciurileanu & Bucur Horvath, 2012)	wood, earth and straw	Thermal performance	550 mm thick wall	Modular wall, using a prefabricated system	Experimental tests	The thermal resistance of the wood, rammed earth, and straw bale are 0.17, 0.17, and 0.061 W/mK, respectively.	Local earth from the site can be used for one- or two-level house buildings.
(Swan et al., 2011)	Earth and Straw	Durability	N\A	N\A	Review analysis	In areas that experience up to 635 mm (25 in.) of rain per year, unsterilised earthen walls left unprotected are likely to erode at a rate of 25.4 mm (1 in.) in 20 years on vertical surfaces and 50–75 mm (2–3 in.) per year on horizontal surfaces	N/A
(Mi et al., 2020)	Transparent Wood	Aesthetics and thermal conductivity	60 mm × 60 mm × 2 mm	Wood block	Experiment	The results showed that aesthetic wood exhibits a thermal conductivity of 0.24 $W\ m^{-1}\ K^{-1}$ in the radial direction, which is a lower thermal conductivity than that in the axial direction	The aesthetic wood with perpendicular lumina possesses a high transparency of ~80% with excellent UV-blocking properties and a high optical haze of ~93%, which leads to good anti-glare performance and light guiding to create a comfortable space contrasting with glass. It also had a low thermal conductivity.
(Høibø et al., 2015)	Wood compared with other materials	Durability and Environmental Impact	N\A	Using wood materials indoors.	Questionnaire	The findings indicate that consumers in the Oslo area often prefer materials other than wood for various housing features.	N\A

(Bui et al., 2009)	Stabilised and unstabilised rammed earth	Durability	about 50 cm thickness in general	Walls	Stereo-photogrammetry	The stabilised wall with 5% hydraulic lime showed no significant changes in quality after 20 years, with minor vertical cracks at the edges. Unstabilised, showed erosion, especially on the top two-thirds of the wall portion.	Unstabilised with fine soil, it exhibited multiple cracks due to shrinkage, but only on the surface. Upper parts of walls are less eroded due to roof protection, and variation in density across compacted layers influences erosion.
(Venkatarama Reddy & Prasanna Kumar, 2010)	Cement-stabilised rammed earth (CSRE)	Energy Consumption	155mm 600mm 700mm	Wallette	Experimental Analysis	It was found that CSRE walls with 8% cement showed a 17% higher compressive strength compared to brick masonry, and increasing the cement content to 12% resulted in a 60% increase in CSRE strength.	The study compared the embodied energy in CSRE walls with 8% cement content to that of burnt clay brick masonry walls. It was found that the embodied energy in CSRE walls with 8% cement was only about 15-25% of the embodied energy in burnt clay brick masonry walls.
(Upton et al., 2008)	Wood-based and concrete-based	Energy Performance	N/A	Wall	CORRIM assessment: Life Cycle Inventories	The corresponding energy benefit associated with wood-based building materials is approximately 132PJyear^{-1}. These estimates represent about 22% of embodied energy and 27% of embodied greenhouse gas emissions in the residential sector of the US economy over 100 years.	Transitioning to wood-based construction could lead to substantial energy savings, with estimated reductions of 95PJ/year (wood vs. concrete) and 170PJ/year (wood vs. steel), averaging 132PJ/year. These figures represent approximately 10–34% (averaging 22%) of the 0.5–1.0EJ/year of embodied total energy associated with the US residential sector.
(Yan et al., 2024)	straw bale, wood, and bamboo	carbon emissions and economic performance (cost)	N/A	A Net-zero energy building (Wall)	Simulation: EnergyPlus (DesignBuilder)	Biomass materials, which occupy most of the building structure, accounted for 36.01% of the total carbon emissions. Biomass materials have a better carbon footprint than non-biomass materials. For individual materials, the straw bale, wood bits, bamboo, and other wood products accounted for 2.85%, 1.15%, 0.15%, and 31.87%, respectively.	The total was ¥490686 ($71114) and ¥3556 ($515) per square meter. The cost of labour was not considered in the calculations. The cost of biomass material accounted for 36.39% of the total cost. The straw bale, wood bits, bamboo, and other wood products accounted for 2.65%, 0%, 0.87%, and 96.48%, respectively. Therefore, wood and wood products accounted for the vast majority of the cost of all biomass materials. Non-biomass materials accounted for most construction costs.
(Thomson & Walker, 2014)	straw bale	Durability (humidity level)	total thickness of 35 mm	Walls	Exposure test (Experimental)	The findings show that the three-year-old straw did not support any significant new microbial growth. However, a rapid increase in CO_2 concentrations	During the experimental period, the hygrothermal conditions exceeded levels where degradation of the straw is understood to occur. This suggests that the

						was observed for the fresh straw, indicating rapid microbial growth.	conditions may have supported significant mould growth, which can impact the durability of the straw panel.
(Ashour et al., 2011)	straw bale	Durability (moisture content and pH) and thermal stability	total thickness of 50 cm	Wall	Laboratory measurements	The study found that relative humidity in the straw bales initially increased steeply, reaching 76.4% after 450 hours, compared to the surrounding humidity of about 78%. The difference between surrounding and internal humidity decreased from 3.44% at 400 hours to 2.55% by the end of the 450-hour test.	Average temperatures within the wall ranged from 12.7°C to 13.7°C initially. After 24 hours, temperatures increased towards the wall interior, with differences of 0.04°C to 2.11°C compared to outside temperature. After 96 hours, temperature percentages between ambient and wall interior varied (11.25% to 29.7%). Temperatures inside the straw were higher than outside plaster, showing superior insulation.
(Jové-Sandoval et al., 2024)	earth-straw	Thermal Performance	20-cm-thick	adobe walls	Experiment	Adobe exhibited a thermal transmittance 2.5 times higher than lightened boards, with board 2 showing the lowest thermal transmittance among the boards. Board 2 showed the highest temperature differences between both sides due to its insulating capacity, reaching the initial core temperature of 20°C first.	Boards with long length (12 cm) showed higher thermal transmittance than those with short length (1-5 cm), possibly due to differences in panel density caused by the incorporation of slip during execution. Adobe exhibited a thermal transmittance 2.5 times higher than lightened boards, with board 2 showing the lowest thermal transmittance among the boards.
(Wall et al., 2012)	straw bale	Sound insulation and thermal performance	3.6 m wide by 2.7 m high	Panel	Experiment	In the first test, emitting 100 dB of 'white noise' to the house's exterior resulted in a sound level drop, Rw value of 44 dB. In a subsequent test, emitting the same sound level to the house's exterior resulted in a sound level drop, Rw value of 48 dB. These values indicate that the prototype house had good sound insulation performance.	The thermal survey on the prototype house revealed areas of conductive heat loss, thermal bridging, and building defects. Thermal images identified heat loss around doors and air infiltration around windows and door frames. Specific areas for improvement include refining internal ply strips, panel junctions, and internal corners of timber frames.
(Kariyawasam & Jayasinghe, 2016)	rammed earth	Durability and energy performance	1000 x 160 x 650 mm	Wall Panels	Experiment	The durability problems identified in cement-stabilized rammed earth (CSRE) construction are related to shrinkage cracks, thermal cracks, and erosion. The erosion rate of CSRE specimens with different cement contents shows that erosion rate reduces with higher stabilizer content.	The embodied energy of cement-stabilized rammed earth (CSRE) walls was studied in comparison to burnt clay brick masonry. The study found that the embodied energy of CSRE is lower, ranging from 15-25% of burnt clay brick masonry. The contribution to operational energy is also discussed, indicating that rammed earth construction can lead to lower energy demand for thermal comfort, with about a 3°C reduction in indoor temperature compared to cement block wall

(Taylor et al., 2008)	rammed earth	Thermal comfort and energy performance	N/A	A two-storey building	Questionnaire (subjective), field measurement, and simulation (TRNSYS)	The building did not adequately achieve thermal comfort during occupied hours. Operative temperatures in two out of the three offices measured were outside the comfort zone for over 20% of the time in the summer evaluation period. In the winter, the situation was worse, with the two top-floor offices providing thermal comfort only 70% of the time and the ground-floor office only 13% of the time.	The building had a larger energy intensity than the target specified by the Australian Building Codes Board. The low electricity use did result in low greenhouse gas intensity. The installed solar system did not perform as intended. Computer modelling suggested that increasing the R-value of external walls through external insulation could improve energy efficiency. Unwanted air exchange, infiltration rates, and inadequate night purging affected thermal comfort and energy performance.
(Kallavus et al., 2017)	Wood-based construction panels	Moisture (mould growth)-Durability	N/A	Sample boards	Experiment	Construction materials, especially wood-based panels, can be vulnerable to moisture-related problems and mould growth, which can lead to "Sick Building Syndrome" and poor indoor air quality. Simulated laboratory conditions revealed that construction plates were already contaminated with mould spores before arrival at the construction site, indicating the potential for mould growth on untreated surfaces.	Wood-based construction plates made from materials like pinewood, oriented strand board, and waterproof birch plywood showed better resistance to mould growth compared to environmentally friendly wood-based panels.
(Singh et al., 2019)	Softwood-engineered wood products such as cross-laminated timber and laminated veneer lumber	Wood decay-Durability	900 x 45 x 90 mm	Wood panels	Experiment	Laminated veneer lumber samples showed minimal mycelium spread and localized damage compared to severe decay in untreated solid wood.	Laminated veneer lumber demonstrated better resistance to decay compared to cross-laminated timber. Definitions and ratings for mould growth on wood samples, ranging from no perceivable mould to severe mould covering more than 50% of the surface (ratings from 1 to 5).
(Nofal & Kumaran, 2011)	Engineering wood (oriented strand board)	Mold growth and wood decay	12 mm thickness	Exterior walls	Mathematical model (Hygrothermal models and damage functions)	The study indicates that mould growth increases with higher air leakage rates and decreases as the wall dries	The results suggest that the wood-rotting model shows the wall would start rotting from the bottom upward, emphasizing the significance of maintaining wood below the fibre saturation point for construction integrity.
(Chaussinand et al., 2015)	Straw bale	Thermal behaviour and energy performance	800 mm thickness	A building	Thermal-dynamic simulation	Straw bale buildings exhibit low heat capacity, making them prone to quick overheating in summer. Adding a clay wall coating can reduce heating demand but has minimal effect on overheating. The study highlighted the importance	The ECO46 straw bale building demonstrated efficient energy consumption compared to standard buildings. Utilizing solar panels, double-flow ventilation, and insulation contributed to the sustainability and energy efficiency of the building.

						of managing solar gains and using external blinds to improve comfort in the building.	The study concluded that straw bale buildings can be a sustainable alternative in the construction industry due to their low embodied energy and excellent thermal performance.

*Thickness × width × height

Appendix B: Survey of Zero Carbon Building Materials



Zero Carbon Building Materials

Survey Zero Carbon Building Materials

Thank you for participating in this survey. Your response will help us identify the most commonly used zero-carbon materials in the New Zealand construction industry. Moreover, your response will help us understand the key factors contributing to the choice of building materials in the industry.

This project has been evaluated by peer review and judged to be low risk- Ethics Notification Number : 4000027896. Consequently, it has not been reviewd by one of the University's Human Ethics Committies. The researcher named in this documnet is reponsible for the ethical conduct of this research.

Please answer the following questions to the best of your knowledge and based on your experience. Your answers will remain anonymous and confidential.

Should you require further information about the research, please contact:

Researcher
Ali Hashemi Araghi
Email: ahashemi@massey.ac.nz

1. By clicking the button below, you agree to participate in this research. If you do not wish to participate, please close the page to end your survey.

- ◯ I consent, begin the study

2. Please select your role in the construction industry

- ◯ Architect
- ◯ Developer
- ◯ Engineer
- ◯ Building Manager
- ◯ Contractor
- ◯ Client
- ◯ Other (please specify)

3. For how many years have your worked in the New Zealand Construction Industry:

- ◯ Less than 1 year
- ◯ 1 - 5 Years
- ◯ 5-10 years
- ◯ 10-20 years
- ◯ Over 20 years

4. Where are you located?

- ◯ Auckland
- ◯ Wellington
- ◯ Christchurch
- ◯ Dunedin
- ◯ Palmerston North
- ◯ Tauranga
- ◯ Other cities (Please specify)

5. What type of construction projects are you primarily involved in? (Select all that apply)

- ◯ Residential (single-family homes, apartments, etc.)
- ◯ Commercial (offices, shopping centres, etc.)
- ◯ Industrial (warehouses, factories, etc.)
- ◯ Institutional (schools, hospitals, etc.)
- ◯ Infrastructure (bridges, roads, etc.)
- ◯ Other (please specify)

Appendix C: Delphi Survey – Zero-Carbon Materials Evaluation Tool

This Delphi study aims to refine and validate a DTS for zero-carbon construction materials. Experts are invited to provide ratings and justifications across several rounds. Your responses will help us reach consensus on the most important criteria, indicators, and practical features of the tool.

Round 1 – Open Exploration

1. Relevance of Criteria

To what extent do the following six categories capture the most important decision factors for zero-carbon materials in construction (Durability, Cost Effectiveness, Buildability, Embodied Carbon, Availability, Aesthetics)?

• Rating: 1 = Not at all … 5 = Very extensively
• Follow-up: Please explain your rating. Which categories, if any, are over- or under-emphasised?
• Are there any additional criteria you believe should be included? Please list and briefly justify.

2. Weighting and Importance

Distribute 100 points across the six categories to reflect their relative importance. Please explain your distribution. Which categories should have more or less influence, and why?

3. Indicators and Metrics

Do the evaluation items (e.g., weather resistance, embodied carbon cradle-to-gate, local supply chains) accurately represent the categories?
• If not, which indicators would you add, revise, or remove? Please give a short explanation.

4. Scoring System

How clear and measurable are the scoring descriptors (e.g., ‘Very High,’ ‘Rigid,’ ‘Extensive’)? (1 = Not clear, 5 = Very clear).
• Please suggest changes to improve clarity, measurability, or balance between qualitative and quantitative aspects.

5. Usability and Practicality

How user-friendly is the tool in its current form? (1 = Not at all, 5 = Very).

• Could decision-makers realistically apply it in practice? Please explain.

6. Credibility and Transparency

To what extent does the aggregated score reflect a credible and transparent picture of material performance? (1–5 scale).

• How well does the tool balance evidence-based rigor with ease of use?

Round 2 – Structured Rating (Consensus Building)

Please rate each statement on a 1–5 Likert scale (1 = Strongly Disagree, 5 = Strongly Agree):

• The six categories represent the key factors for zero-carbon material evaluation.

• The weighting of categories reflects their real-world importance.

• The evaluation items/indicators are relevant, sufficient, and evidence based.

• The scoring descriptors are clear, realistic, and easy to apply.

• The tool produces outputs that are credible and decision useful.

• The tool is user-friendly and practical for different stakeholders.

• The tool can be adapted effectively beyond New Zealand's context.

Optional: If your rating differs substantially from the group median (shared after Round 1), please provide a brief justification.

Round 3 – Prioritisation & Final Consensus

1. Please rank the top 3 improvements that must be addressed before practical implementation of the tool.

2. Should financial incentives be included as a core factor across all materials? Please explain your reasoning.

Appendix D: Human Ethics Low Risk Notification

TE KUNENGA KI PŪREHUROA | MASSEY UNIVERSITY
UNIVERSITY OF NEW ZEALAND

20/08/2023

Dear: Ali Hashemi Araghi

Re: Low Risk Notification - 4000027896 - The Development of a Decision-Support Tool (DST) for Selecting Best-fit Zero-Carbon Building Materials; The Case of New Zealand Building Industry

Thank you for submitting a low risk notification for your research/teaching/evaluation.

This email is to acknowledge receipt of the low risk notification and to inform you that the details of your project have been recorded in our database for inclusion in the annual reports to the Health Research Council Ethics Committee (HRCEC) and the Massey University Research Committee (URC).

You may proceed with your research, though it is advisable to provide a couple of weeks before commencing, as all low risk notifications are checked for completeness and clarity by a Research Ethics Advisor. You may be contacted if your application is incomplete and/or further clarification is required.

The low risk notification for this project is valid for a maximum of three years.

Please notify me if situations subsequently occur which cause you to reconsider your initial ethical analysis.

If a sponsoring organisation, funding authority (e.g., the Health Research Council) or a journal require evidence of ethical approval from a Human Ethics Committee (with an approval number), you need to complete a full Massey University Human Ethics application to be reviewed and approved by one of our Human Ethics Committees. Applications must be submitted and approved prior to the commencement of the research.

Please note that travel undertaken by students must be approved by the supervisor and the relevant Pro Vice-Chancellor and be in accordance with the Policy and Procedures for Course-Related Student Travel Overseas. In addition, the supervisor must advise the University's Insurance Officer.

If you have any concerns about the conduct of this research that you want to raise with someone other than the researcher(s), please contact the Research Ethics Office, email humanethics@massey.ac.nz. "

Please include the following statement on all public documents (e.g., information sheet, consent form) related to your project:

> ***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 above are responsible for the ethical conduct of this research.***
>
> ***If you have any concerns about the ethical conduct of this research that you want to raise with someone other than the researcher(s), please contact Massey University Human Ethics by email: humanethics@massey.ac.nz.***

I wish you all the best in your research, teaching or evaluation activities and appreciate your thoughtful consideration of ethics principles and practices.

Ngā mihi nui,



Professor Tracy Riley
Acting Chair, Research Ethics Chair's Committee

Research Ethics, Graduate Research School and Ethics
Massey University, Private Bag 11 222, Palmerston North, 4442, New Zealand
E humanethics@massey.ac.nz; animalethics@massey.ac.nz
www.massey.ac.nz/research/ethics

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