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Identifying Critical Criteria on Assessment of Sustainable Materials for Construction Projects in New Zealand Through the Analytic Hierarchy Process (AHP) Approach

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Abstract: New Zealand’s goal of achieving net-zero greenhouse gas emissions (GHG) by 2050 highlights the urgent need for integrating sustainable practices into the construction industry. Since the construction industry makes a major contribution to GHG emissions, this study aims to address this need by identifying and prioritizing the critical criteria relevant to the effective selection of sustainable construction materials for New Zealand’s construction industry. The research employs a multi-stage approach, including a comprehensive literature review, expert interviews, and industry surveys. Initially, 80 criteria were identified through the literature review. Subsequently, expert interviews and industry surveys led to the identification of 30 critical criteria, which were categorized into environmental, technical, economic, and social impacts, and were ranked based on their importance. This study utilizes a 5-point importance index and Analytic Hierarchy Process (AHP) to rank these criteria. This study notably integrates technical impacts with the three traditional sustainability pillars—environmental, economic, and social—providing a nuanced evaluation of construction material selection. The results indicate that environmental and technical criteria received the highest priority weights (32% each), followed by economic (19%) and social impacts (17%). The findings offer valuable insights for industry stakeholders, assisting them in applying these critical criteria to improve material selection practices in alignment with New Zealand’s sustainability objectives.

Keywords: construction materials; sustainable construction materials; material selection; sustainable and green construction; eco-friendly construction practices; life cycle assessment



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1. Introduction

The principle of sustainability has become a cornerstone across various sectors, with the construction industry emerging as a pivotal domain in this global shift. The construction sector’s rapid expansion is driven by accelerated urbanization and population growth, positioning it as one of the most dynamically evolving industries worldwide [1]. In New Zealand, the construction industry has experienced notable growth, with residential and non-residential construction increasing by 3.1% and 4.9%, respectively, according to Stats NZ [2]. Despite its economic importance, the sector has a substantial environmental footprint [3]. In 2018, NZ’s building and construction sector was responsible for 7.4 metric tons of CO₂ emissions, accounting for 9.4% of the nation’s GHG emissions; moreover, this figure exceeds 15% when excluding biogenic methane [4]. This underscores the urgent need to prioritize environmentally sustainable construction practices [5–7].

Recognizing the significant environmental repercussions associated with construction activities, particularly in terms of pollution and waste, resulting from material and energy consumption [8], New Zealand has implemented the Emission Reduction Plan. The overarching vision of this plan is to attain near-zero building-related emissions by 2050, concurrently ensuring that buildings contribute to providing healthy living and working environments for both current and future generations [4].

A significant challenge within the industry is that 40% of GHG emissions arise from the use of imported materials [4]. For instance, cement, a commonly used material in concrete production, contributes approximately 8% of global CO₂ emissions from the 4–4.1 billion tons produced annually [9]. Replacing cement with alternative materials is a key strategy for reducing emissions [10]. However, selecting suitable replacement materials is crucial, as it impacts embodied energy, CO₂ emissions, energy consumption during production, and the overall environmental impact throughout the material's life cycle [11,12]. Consequently, the process of selecting sustainable building materials has become increasingly complex and significant [10,12–14].

While previous research has developed criteria for selecting sustainable construction materials using various rating systems [15], there is a notable gap in studies addressing the specific context of New Zealand's construction projects [16]. Unique geographic and logistical challenges, combined with New Zealand's relatively small economy and high industrial standards, affect purchasing power and material logistics [17]. Therefore, designers in New Zealand must carefully consider logistics, purchasing capacity, and material lead times in their material selection processes.

This paper aims to address this gap by identifying and prioritizing the critical criteria relevant to New Zealand's construction industry. By doing so, it seeks to enhance material selection practices in alignment with New Zealand's sustainability objectives, contributing to more effective and environmentally conscious construction practices.

2. Literature Review

Numerous research investigations have explored sustainability in construction, sustainable construction materials, frameworks for selection, and tools to assess sustainability during construction activities [18]. A bibliometric analysis was conducted to explore the prior research efforts in the realm of sustainable construction materials. Over 3000 research studies, sourced from the Scopus database, were scrutinized. The analysis utilized prevalent keywords from research papers on sustainable construction material assessment over the past decade. These keywords were automatically categorized into clusters using VOSviewer, with each cluster being labeled according to its most representative terms. Studies within each identified cluster often show greater similarity to one another than to those in other clusters. Four distinct clusters were highlighted in different colors, with each revealing the underlying semantic themes within the textual data and showcasing emerging research patterns [19]. Cluster #1 concentrated on sustainable development, environmental impact, energy utilization, and sustainable construction. Cluster #2 addressed sustainability, life cycle assessment, and life cycle analysis. Cluster #3 focused on recycling, carbon dioxide, and performance assessment. Cluster #4 examined global warming, GHG, and carbon footprint. Figure 1 visually represents the key research themes and their interrelationships.

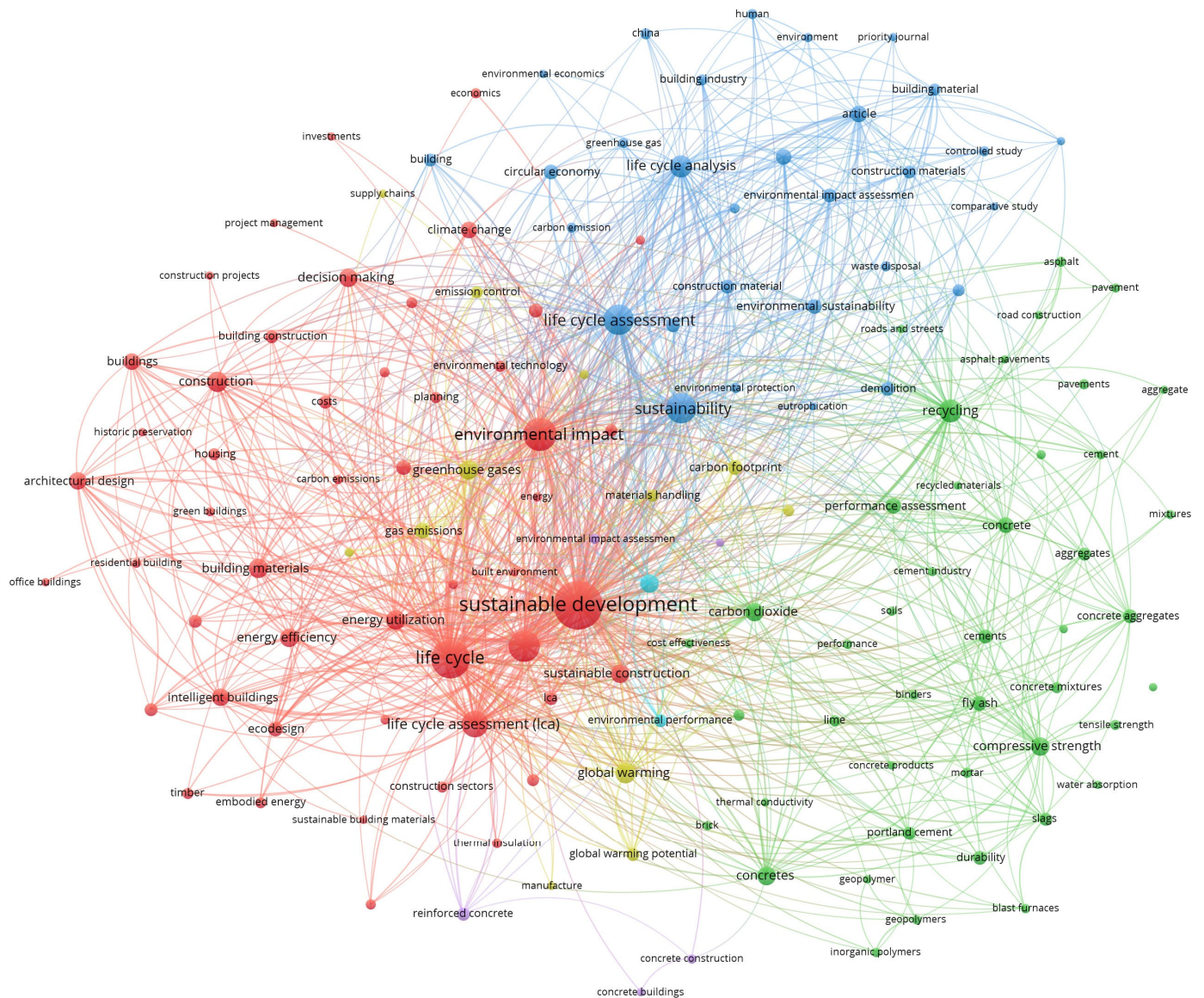


Figure 1. Sustainable construction material related topics addressed in previous studies.

Figure 2 illustrates that China leads in publications on sustainable construction material assessment, followed by the USA, Italy, and India. Notably, New Zealand has relatively few publications on this topic and limited associations with high-volume countries, except for India. This suggests a lack of tailored research for the New Zealand market. Additionally, there has been a notable increase in publications post-2010, which correlates with heightened global awareness of sustainability issues.



Figure 2. Global distribution of publications on sustainable construction materials.

The literature review process comprised four stages, illustrated in Figure 3, commonly used in various research studies. For instance, Yi and Chan Albert [20] employed a similar process in their study on construction labor productivity, as did Xue, et al. [21] in their review of collaborative working in construction, and Ke, et al. [22] in their research on Public–Private Partnerships.

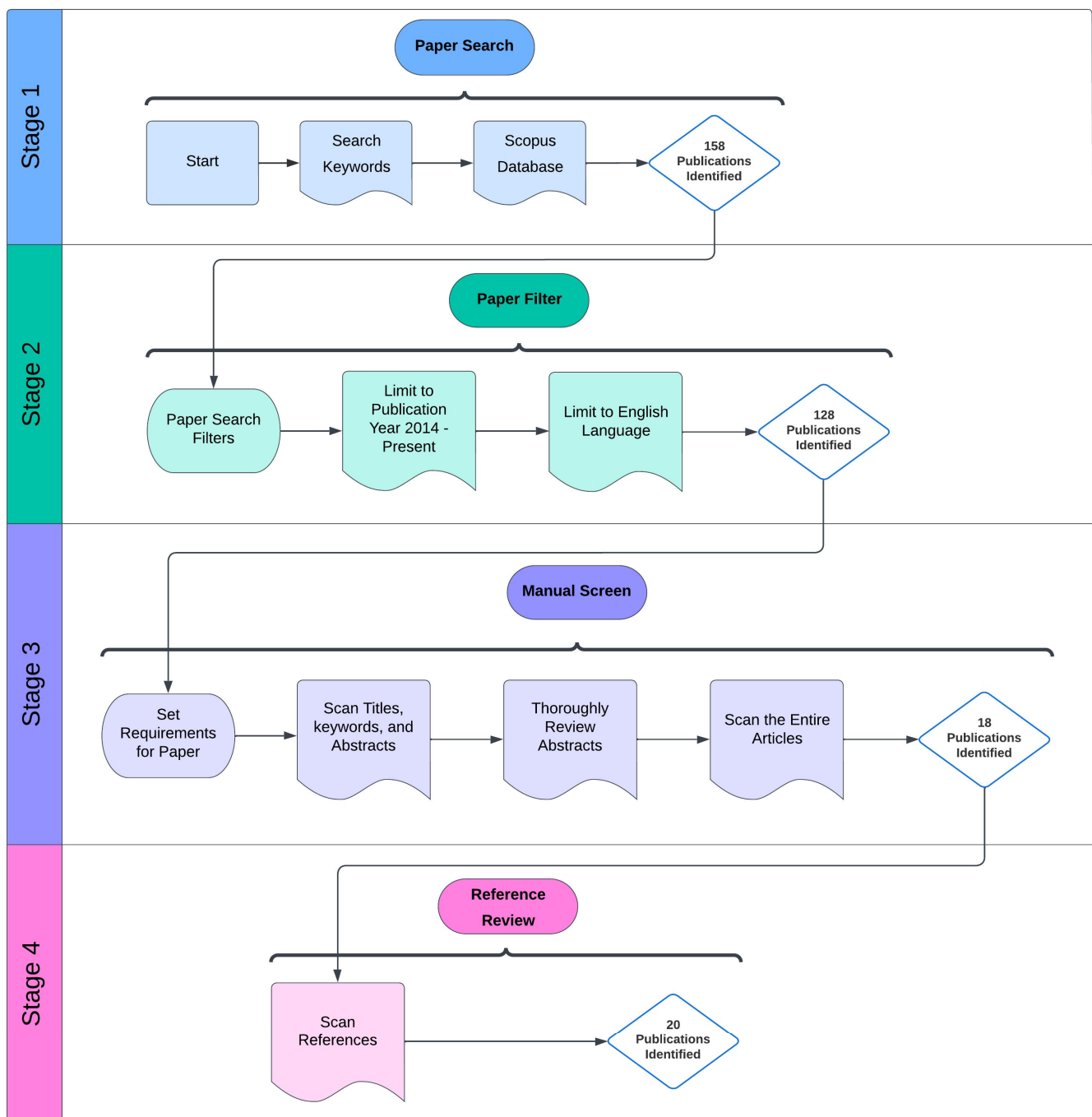


Figure 3. Literature review process.

2.1. Sustainable Construction Materials

Sustainable construction materials are fundamental to advancing sustainability in the construction industry. The definitions of sustainable construction materials vary, but they generally include materials that reduce resource consumption, limit waste, and offer durability and recyclability [23]. A critical examination of various sustainable construction materials reveals diverse approaches to achieving sustainability. Advanced and sustainable materials in the construction industry can significantly enhance sustainability by reducing the reliance on scarce resources, lowering GHG emissions, improving safety, and supporting the resilience of structures, all while promoting modern construction practices [24]. For example, recycled aggregates provide substantial environmental benefits by minimizing waste and conserving resources [25,26]. Similarly, high-performance con-

cretes contribute to sustainability by improving energy efficiency and reducing carbon footprints [9]. Maraveas [27] suggested that agro-waste materials have the potential to replace conventional construction materials. Other materials, such as polymer composites [28], advanced concrete products [29,30], and glulam [31], have also been explored for their potential. Additionally, post-tensioned timber, which is a combination of timber's aesthetic and environmentally friendly properties with the strength and ductility of steel, is said to offer improved strength and flexibility in construction [32].

However, the use of these materials often requires specialized knowledge and skilled labor [33]. Moreover, challenges related to lead times and the supply chain for procuring and transporting these materials to construction sites could pose additional barriers, particularly in New Zealand. Furthermore, the difficulty of evaluating the future benefits of new materials can make it challenging to justify their use, given their increased cost [24]. As a result, material selection should be approached with a holistic view, considering not just material performance, but also the broader logistical and contextual factors. This underscores the importance of identifying critical criteria for material selection from multiple perspectives.

2.2. Life Cycle Sustainability Assessment

The concept of life cycle sustainability assessment (LCSA), aligning with ISO 14040 [34] guidelines, has become prevalent in evaluating sustainability by considering environmental, social, and economic aspects throughout a product's life cycle [35–37]. It aims to assess both the negative impacts and the benefits across these dimensions, offering valuable insights for decision-making processes [38]. Initially proposed by Kloeppfer [39] and further developed by Capitano, et al. [40], LCSA combines three primary techniques, as follows: life cycle assessment (LCA) for environmental analysis [41], social life cycle assessment (S-LCA) for social evaluation [42], and life cycle costing (LCC) for economic considerations [43].

However, traditionally, construction material selection has focused on meeting technical requirements, such as material strength [44,45]. Although the technical aspect is a critical component of sustainability assessment, few studies have systematically integrated technical, economic, social, and environmental aspects to analyze overall sustainability [46]. Encouragingly, more researchers now recognize that an ideal classification of sustainability involves a commitment to environmental, social, and economic impacts alongside technical impacts [47–49].

This study will assess the selection of sustainable construction materials from the perspectives of technical, economic, social, and environmental sustainability. In particular, innovative and advanced sustainable materials will be given greater emphasis on their technical impacts, which will increase their likelihood of being selected as preferred materials for sustainable construction in this study. There is a potential for academia to gain from systematically integrating the technical aspects with the commonly employed three pillars [46]. All identified criteria will be organized within these four categories.

2.3. Identifying the Assessment Criteria of Sustainable Construction Material Selection

Effective sustainable construction material selection involves assessing various criteria that impact cost, quality, and sustainability [50–52]. The existing literature provides valuable insights into establishing material selection assessments [13,53–55], as delineated in Table 1. In most of the selected research studies, AHP serves as the primary methodology or is integrated into the methodology. MCDA methods are commonly used to prioritize these criteria by breaking down complex decisions into manageable components [56]. AHP involves decomposing the problem into smaller components iteratively until achieving a precise and scalable level [57].

Table 1. Quick summary of the literature review.

Abbr.	Authors	Methodologies	Goals
L1	Abeyesundara, et al. [58]	-	Sustainable material selection for buildings in Sri Lanka
L2	Aghazadeh, et al. [13]	Kendall Coefficient Calculation Method	Material selection in construction projects from the perspective of different stakeholders
L3	Aghazadeh and Yildirim [52]	Hybrid MCDM Method	Sustainable material selection in mass housing projects
L4	Akadiri, et al. [47]	-	Sustainable assessment criteria for building material selection
L5	Akadiri and Olomolaiye [3]	Fuzzy AHP	Multi-criteria evaluation model for sustainable material selection
L6	AlKheder, et al. [59]	Fuzzy AHP	Sustainable assessment criteria for airport runway material selection
L7	Balali and Valipour [60]	AHP	Identification and selection of building façade's smart materials
L8	Alam Bhuiyan and Hammad [46]	Hybrid MCDM Method	Sustainable structural material selection for multistorey building construction
L9	Do and Kim [61]	AHP	Selection process of patching materials for concrete repair
L10	Figueiredo, et al. [57]	Fuzzy AHP	A life cycle sustainability assessment framework
L11	Govindan, et al. [1]	Hybrid MCDM Method	Sustainable material selection for the construction industry
L12	Khosnava, et al. [50]	Hybrid MCDM Method	Rank of green building material criteria
L13	Mathiyazhagan, et al. [62]	Hybrid MCDM Method	A sustainable assessment model for material selection in construction industries
L14	Mayhoub, et al. [63]	AHP	Assessment of green building materials' attributes
L15	Moussavi Nadoushani, et al. [45]	AHP	Multi-criteria selection of façade systems
L16	Sahlol, et al. [8]	AHP	Sustainable building material assessment and selection using system dynamics
L17	Streimikiene, et al. [64]	TOPSIS	Multi-criteria sustainability assessment of green building insulation materials
L18	Uğur and Baykan [65]	AHP	A model proposal for wall material selection decisions
L19	Yüksek [66]	-	Evaluation of building materials in terms of energy efficiency
L20	Zhao, et al. [67]	Hybrid MCDM Method	Material selection in sustainable design

These studies were selected based on the diversity of cases examined, geographical, project types, and methodologies employed. They have tackled the selection problem of sustainable construction materials through various approaches. Table 2 illustrates the different criteria of the sustainable materials examined in these studies. The table presents assessment criteria for selecting sustainable construction materials based on different purposes and scenarios. By considering the comprehensive review of the research literature, the critical criteria influencing this field can be categorized into the following four categories: (1) environmental, (2) economic, (3) social, and (4) technical. Furthermore, after merging

and removing duplicate and identical parameters sourced from different references, the critical criteria identified in each category have been compiled.

Table 2. Criteria identified from the literature review.

Assessment Criteria	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15	L16	L17	L18	L19	L20
Environmental Impacts																				
Reusability		✓	✓	✓	✓	✓		✓			✓	✓	✓	✓						✓
Embodied Energy	✓	✓		✓	✓	✓	✓								✓	✓	✓			
Environmental impacts		✓	✓	✓				✓					✓	✓					✓	✓
Renewability		✓	✓				✓					✓		✓		✓		✓	✓	✓
Energy consumption		✓		✓	✓		✓				✓	✓		✓						
Potential for increasing global warming	✓	✓								✓	✓		✓	✓						
Source material extraction		✓		✓	✓	✓					✓		✓							
Pollution		✓	✓	✓	✓	✓	✓													
Disposal		✓	✓	✓	✓	✓														
Impact on air quality				✓	✓	✓						✓		✓						
Zero/low toxicity				✓	✓	✓	✓							✓		✓				
Ozone depletion potential			✓	✓	✓	✓														
Amount of likely wastage in use				✓	✓	✓								✓		✓				
Water savings		✓									✓	✓	✓							
Impact during harvest				✓	✓	✓														
Environmental statutory compliance			✓		✓	✓														
Potential for acidification	✓									✓										
GHG emission								✓								✓				
Landfill waste											✓		✓							
Reducing the use of fossil fuels and conserving energy			✓								✓									
Production and transportation activities											✓		✓							
Land acquisition											✓		✓							
Potential for nutrient enrichment	✓																			
Acoustic resistance		✓																		
Eutrophication potential										✓										
Low-emitting materials (low VOC emissions)														✓						
Resistance to high temperatures			✓																	
Healthy interior environment													✓							
Soil consumption											✓									
Economic Impacts																				
Initial cost	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓		✓	✓		✓		
Repair and maintenance cost	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓		✓	✓				
Recycle/disposal cost		✓	✓	✓	✓	✓		✓			✓	✓				✓				
Life cycle cost	✓	✓	✓				✓			✓				✓					✓	✓
Operation cost		✓								✓		✓				✓				
Construction cost							✓	✓							✓					
Fabrication cost	✓	✓																		
Energy efficiency cost			✓										✓							
Meeting user needs											✓		✓							
Tax contribution											✓		✓							

2.4. Research Gap

Despite substantial research in this field, the identified gaps underscore the need for further exploration into the criteria influencing decision making for sustainable material selection, while also emphasizing the ongoing imperative for construction practices to align with zero-carbon objectives [68]. The existing literature predominantly addresses frameworks for sustainable process design [69,70], individual sustainable materials [5,68,71,72], and sustainability assessment methods applicable to diverse geographic contexts [73].

The prominent avenues for future investigation outlined in these studies include the development of a decision support system for sustainable material selection [74], the evaluation of the economic benefits and implications associated with the adoption of sustainable practices [75], and the facilitation of the practical implementation of research findings in material selection processes [6].

In addition, New Zealand faces unique challenges due to its geographical location. Despite being a developed nation, New Zealand has a relatively small economy with high expectations for industrial performance. Its geographic remoteness from major economic centers worldwide contributes to higher costs of construction materials compared to other countries. Furthermore, statistics from the New Zealand Department of Labor indicate that less than two percent of building-related trade workers hold degrees, resulting in a labor force with lower levels of education and skill than their counterparts in other countries [76]. Additionally, the construction industry in New Zealand tends to lag behind in embracing innovative philosophies and introducing new concepts compared to global standards [17]. Jaques [77] emphasized the importance of selecting materials in New Zealand that minimize waste and utilize modular components and prefabricated building elements. However, Darlow, et al. [78] highlighted that technological limitations have slowed the adoption of certain construction materials. According to Xia and Xu [79], a significant challenge in New Zealand is the shortage of materials, which has been exacerbated by supply chain pressures. Samarasinghe [80] pointed out that the processes of purchasing, transporting, storing, and handling materials must be carefully managed when selecting materials for construction projects in New Zealand. Muthuveerappan, et al. [81] further supported this, noting that New Zealand's remote geographical location results in the limited availability and production of building materials. The recent pandemic has worsened this situation, making it even more difficult for designers to find alternatives. Identifying the reliance on local materials is another key challenge in selecting construction materials in New Zealand [81]. Consequently, when selecting sustainable construction materials in New Zealand, designers must give special consideration to criteria such as logistics, purchasing capacity, material lead times, and labor availability. This necessitates a unique set of assessment criteria and priorities compared to other research studies.

Moreover, there is a notable dearth of published research on zero-carbon buildings within New Zealand [82]. The Ministry for the Environment [4] advocates for more research in this area, recognizing that environmentally sustainable procurement is crucial for New Zealand's transition to a net-zero emissions economy. Thus, there exists a clear research gap concerning the selection assessment of sustainable construction materials specific to the New Zealand market and building environment.

3. Methods

The research methodology employed in this study unfolds in five key stages. Initially, an extensive literature review was undertaken to identify the existing assessment criteria for selecting sustainable construction materials. Furthermore, three interviews were conducted with experts to gain insights into the identified criteria and to supplement them with any additional criteria not previously mentioned. In the third stage, questionnaire surveys were used to gather industry opinions and prioritize the categories and criteria. Following this, in stage four, the criteria were evaluated using the AHP, with a focus on the following four distinct categories: environmental, economic, social, and technical. Prioritization and ranking were established for each criterion within these categories based on a 5-point

relevance scale derived from the survey data. Finally, the research findings underwent validation through interviews with industry experts.

3.1. Data Collection Methods

3.1.1. Expert Interviews

The use of expert interviews in research denotes a qualitative approach to data collection, wherein researchers engage in structured or semi-structured interviews with individuals possessing specialized knowledge, experience, or expertise pertinent to the subject area under investigation [83,84]. In this study, experts were consulted to review and expand upon the sustainability criteria compiled from previous research (Table 2). These experts were asked to validate the existing criteria and suggest any additional ones that might impact the selection of sustainable materials. Three interviews were conducted with two project managers and a sustainability expert, each possessing over 20 years of experience in the New Zealand construction industry. The results of these interviews helped to establish the decision rules for excluding criteria, as follows:

1. Criteria that appeared in 2 or fewer of the selected 20 papers (see Table 2) were excluded.
2. Duplicate criteria were removed.
3. Very similar or closely related criteria were combined.

Based on these rules, an initial list of criteria was developed, as presented in Figure 4.

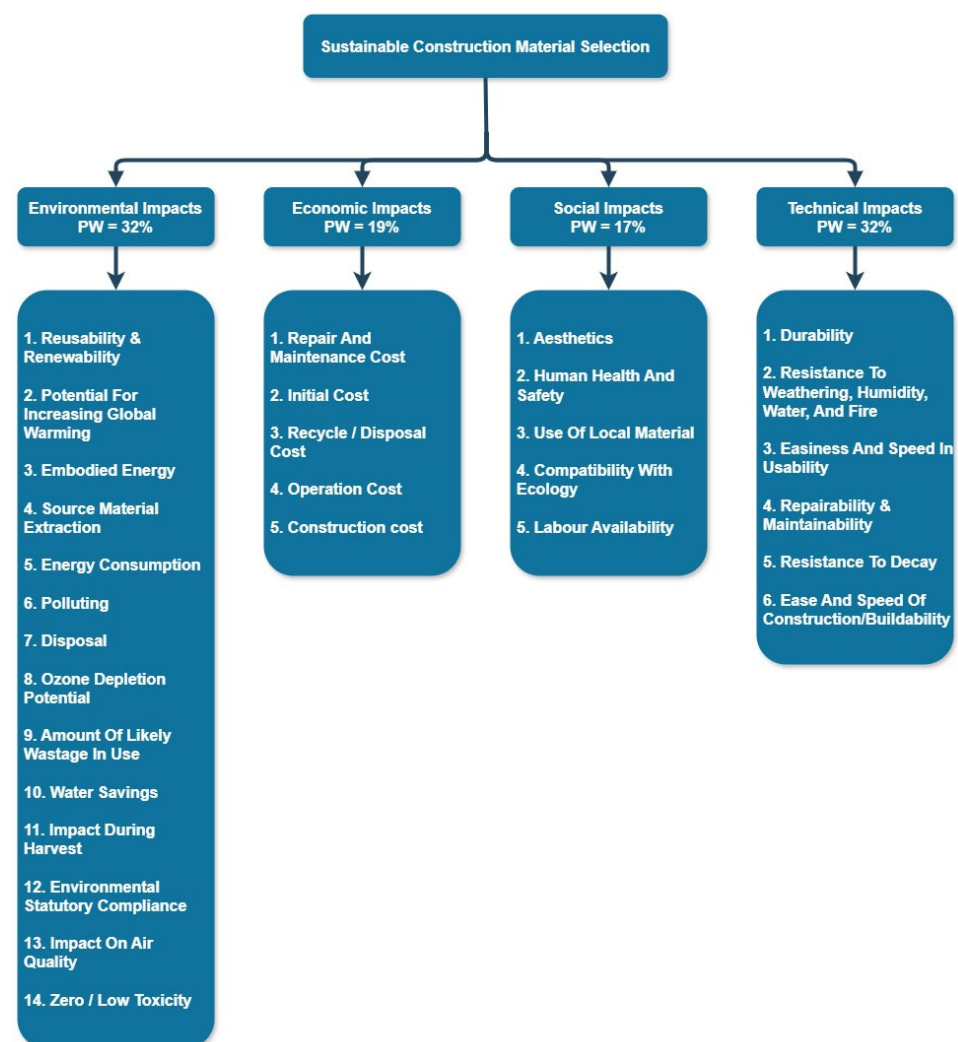


Figure 4. Initial criteria compilation for sustainable construction material assessment.

3.1.2. Questionnaire Surveys

This study delves into the perspectives of three distinct groups of professionals in New Zealand engaged in the selection of building materials, as follows: project managers, quantity surveyors, and consultants, including architects, engineers, and sustainability experts.

Two types of surveys were conducted for this research.

The first survey focused on critical criteria, adopting a questionnaire approach similar to that employed by Akadiri and Olomolaiye [3] in their development of sustainable assessment criteria for building material selection. It entailed an industry questionnaire designed to gauge the industry participants' viewpoints regarding the significance of these selection criteria. The survey commenced with gathering background information about the participants' years of experience, working background, and qualifications. Subsequently, the respondents were prompted to rate the importance level of the criteria using a scale ranging from 1 to 5, with 1 denoting "not at all important", 2 "slightly important", 3 "important", 4 "fairly important", and 5 "very important". A similar 5-point importance index was also used in previous studies for construction material selection [8,13,50,60,85,86]. The questionnaire provided clear definitions for each criterion and guidance for completion, as exemplified in Table 3. Additionally, respondents were encouraged to propose supplementary criteria influencing material selection that might not have been included in the questionnaire provided.

Table 3. Description of the identified criteria.

Criteria	Definitions
Environmental Impacts	
Reusability and renewability	The material's potential to be renewed and reused at the end of a building's life cycle without compromising quality or performance.
Potential for increasing global warming	The material's contribution to global warming, taking into account criteria such as the use and release of CFCs, emission of CO ₂ , and other GHGs during its lifecycle.
Embodied energy	The energy consumed during the extraction and processing of raw materials, the manufacturing of construction materials, transportation and distribution, as well as during assembly and construction.
Source material extraction	Whether from renewable or finite sources, which can significantly contribute to ecological damage.
Energy consumption	The energy demand for its operation.
Pollution	The material's potential to release pollutants, including waste and emissions, into the environment during its life cycle.
Disposal	Availability of environmentally sound disposal options at the end of the material's life cycle.
Ozone depletion potential	The material's contribution to ozone layer depletion, accounting for substances that may harm the ozone layer.
Amount of likely wastage in use	The quantity of material likely to be wasted and sent to landfill or incineration during its use.
Water savings	The material's impact on water conservation and use efficiency.
Impact during harvest	The material's environmental impact during the extraction or harvesting of its source materials.
Environmental statutory compliance	Compliance with relevant environmental regulations and standards.
Impact on air quality	The material's impact on air quality during its life cycle.
Zero/low toxicity	Whether this material has low or non-toxic content to ensure human health.

Table 3. Cont.

Criteria	Definitions
Economic Impacts	
Repair and maintenance cost	The cost required for repairing and maintaining the material over its lifespan.
Initial cost	The cost required for purchasing or manufacturing the material.
Recycle/disposal cost	The cost required for the end-of-life disposal of the material, including transportation costs to landfill.
Operation cost	The cost of operating structures built with the material, including criteria such as energy consumption.
Construction cost	The cost required for construction, labor, and transportation.
Economic Impacts	
Aesthetics	The material's aesthetic qualities, which may vary from person to person and depend on the designer's preferences.
Human health and safety	The material's impact on the well-being of workers, including exposure to toxic and harmful chemicals, ergonomic considerations, and occupational safety measures.
Use of local material	Whether the material is locally sourced, which can contribute to the local economy and reduce transportation-related environmental impacts.
Compatibility with ecology	How well the material aligns with the architectural design and ecological priorities of a particular region or community.
Labor availability	The availability of skilled labor for working with the material.
Technical Impacts	
Durability	The material's ability to maintain its structural integrity and performance over time, meeting or exceeding behavioral requirements.
Resistance to weathering, humidity, water, and fire	The material's ability to withstand various climatic conditions, including resistance to weathering, humidity, water, and fire.
Ease and speed of construction/buildability	The ease of handling and speed of construction with the material.
Repairability and maintainability	How easily the material can be repaired and maintained.
Resistance to decay	The material's ability to resist decay, such as erosion and corrosion.
Ease and speed of usability	The ease of using the material during its operation.

To assess the clarity, comprehensiveness, and feasibility of the questionnaire, as well as to pre-empt any unforeseen issues before the main research commenced, three pilot surveys were carried out. The pilot study carried out with the above three experts served to evaluate and refine the questionnaire, ensuring its suitability for the larger-scale research endeavor. As a result of the analysis of the pilot survey, the questionnaire underwent revisions aimed at enhancing its suitability. These revisions included adjusting the sequence of questions to improve logical coherence and refining the descriptions of the criteria to enhance clarity and ease of understanding.

The survey sample was drawn from the researcher's and research supervisors' contacts and industry organizations within New Zealand's construction industry. The participants were also urged to distribute the survey to their colleagues and other industry peers for broader participation. Ensuring the reliability and adequacy of the collected data necessitated sampling from a comprehensive population, as advocated by Alreck and Settle [87].

A total of 78 questionnaires were distributed via email over three rounds or face-to-face interaction, accompanied by a cover letter and study objectives to encourage participation. In total, 47 responses were received. However, responses that scored fewer than 25 out of 30 on the criteria scale were considered to reflect insufficient knowledge or experience

with sustainable material selection and were, therefore, excluded. After excluding 5 incomplete responses, 42 valid responses remained, resulting in a 54% valid response rate. Malhotra and Grover [88] suggested that a response rate above 20% is generally sufficient for a positive assessment of a survey. Similar surveys by Mathiyazhagan, et al. [62] and Figueiredo, et al. [57] achieved response rates of 43% and 58%, respectively.

While the sample size is relatively small, efforts were made to ensure diversity by inviting participants from different locations across New Zealand and across various types of projects, which helps to enhance the generalizability of the findings. The survey's primary aim is to verify the criteria for selecting sustainable construction materials, therefore, while the smaller sample size may affect the precision of the results, it does not undermine the overall value of the study. Comparable studies by Aghazadeh and Yildirim [52] and Abeysundara, et al. [58] received 66 and 40 responses, respectively. Despite this limitation, the study's significance remains clear, as these factors highlight areas for further investigation rather than diminishing the reliability of the results.

Additionally, outreach was conducted with non-respondents to understand the reasons for their non-participation. Eight individuals responded, as follows: six cited a lack of time, and two felt they lacked sufficient knowledge about sustainability. This suggests that the survey participants likely possess strong expertise and experience in sustainability, which may have led them to place greater emphasis on environmental and social impacts in their responses. Moreover, the reliance on voluntary participation may introduce selection bias, as those who chose to participate might have different perspectives and experiences than those who decided not to participate [89].

The second survey facilitated the determination of the relative weight of the following four categories of selection criteria: environmental, economic, social, and technical. A questionnaire was crafted and distributed among construction experts to gather their perspectives. Each expert was tasked with providing a rating of importance for each category relative to the others through pairwise comparisons. This scale uses numerical values to represent varying degrees of importance, as follows: 1 signifies "Equally important", 3 denotes "Slightly more important", 5 indicates "Strongly more important", 7 reflects "Very strongly more important", and 9 represents "Extremely more important." To illustrate the relative dominance of one alternative over another, reciprocals of these values are used [90].

The target population for this study comprised a 10-member team of senior project managers, senior quantity surveyors, and senior consultants specializing in construction materials and sustainable development within the construction industry. Similar expert surveys for AHP conducted by Aghazadeh, et al. [13], Akadiri, et al. [47], AlKheder, et al. [59], Figueiredo, et al. [57], Moussavi Nadoushani, et al. [45], and Sahlol, et al. [8] included 12, 5, 15, 7, 8, and 10 experts, respectively. The experts were chosen using the snowball sampling method, leveraging the researcher's network. Aghazadeh, et al. [13] employed a similar sampling method in their study on Optimal Structural System Selection. This sampling approach is typically employed when access to all members of the population is challenging or when the population size is limited.

The selection of these experts was based on three main criteria, as follows:

1. Knowledge and experience in the relevant field, either possessing a bachelor's degree or higher, with a minimum of 10 years of experience or having at least 25 years of experience.
2. Willingness to actively participate in the discussions.
3. Availability of sufficient time to engage in the survey.

It is acknowledged that the survey method employed in this study has limitations. Snowball sampling can result in a sample that is not fully representative of the broader population. Since the participants were recruited through existing social or professional networks, individuals with similar characteristics, experiences, or viewpoints are more likely to refer others from the same circle [91]. To minimize this bias, deliberate efforts were made to recruit participants from a variety of backgrounds and social circles to enhance the diversity of the sample [92]. However, it is important to note that most participants are

from government sectors or large contracting companies due to their extensive experience, which may skew the results, particularly in terms of the emphasis on environmental and social impacts, as these factors tend to be more prioritized in these sectors. Additionally, the sample comprised project managers, quantity surveyors, and consultants, potentially overlooking other stakeholders, such as clients, who also influence material selection. Expanding the sample size to encompass a broader range of stakeholders could help mitigate sampling errors. Nonetheless, this study's significance remains intact, with these limitations serving as avenues for future research rather than detractors.

3.2. Data Analysis Methods

3.2.1. Criteria Ranking

In this study, the importance index (II) analysis method was chosen to rank criteria based on their relative importance. The majority of responses were assessed using a Likert scale. Relative importance index analysis is well suited for analyzing such data, as it employs non-parametric statistics [93], a method previously employed by Akadiri and Olomolaiye [3] in their research.

Initially, to ensure the consistency of the rating scale in assessing the criteria across different instances, a reliability analysis called Cronbach's alpha was conducted using the internal consistency method [94]. This approach has also been used in AHP studies by Aghazadeh and Yildirim [52], Aghazadeh, et al. [13], Balali and Valipour [60], and Khoshnava, et al. [50]. Cronbach's alpha values typically range between 0 and 1. The closer it is to 1, the higher the internal consistency reliability of the criteria within the scale. Values exceeding 0.7 are generally considered acceptable, indicating excellent internal consistency among the criteria incorporated into the scale [95]. This coefficient can be calculated manually according to the following formula [96]:

$$\alpha = \frac{j}{j-1} \left(1 - \frac{S_j^2}{S^2} \right) \quad (1)$$

where the number of items, variance of the j -th criteria score, and variance of the total score are shown by j , S_j^2 , and S^2 , respectively.

Then, the importance index is utilized to specify the degree of importance for each parameter. Five levels of importance are defined for II values by Rooshdi, et al. [97], as follows: High "H" ($0.8 \leq II \leq 1$), High-Medium "H-M" ($0.6 \leq II < 0.8$), Medium "M" ($0.4 \leq II < 0.6$), Medium-Low "M-L" ($0.2 \leq II < 0.4$), and Low "L" ($0 \leq II < 0.2$). These categories mirror typical condition rating schemes, with a 20% span [98] used for the classification of the results. II is calculated using Equation (1) [99,100], as follows:

$$II = \frac{\sum_{i=1}^N w_i x_i}{A \times N} \quad (2)$$

where, w_i represents the 5-point priority scaling ranging from 1 to 5, x_i denotes the frequency of the priority scale, A stands for the highest priority value (i.e., 5), and N represents the number of respondents.

Criteria categorized as "M-L" and "L" are eliminated, and only criteria with other ratings are considered [101]. The remaining criteria are then ranked under each category based on their ratings. Sahlol, et al. [8] also employed a similar analysis method in their research to rank parameters for sustainable building material assessment.

In addition, the statistical analysis of the questionnaire data is achieved by calculating the arithmetic mean, the standard deviation, and the error margin according to the following formula [102], which was also used in a similar study by Falih and Rasheed [103].

$$M = \frac{\sum_{i=1}^N w_i \times x_i}{N} \quad (3)$$

$$SD = \sqrt{\sum_{i=1}^N (wi - M)^2 \times \frac{1}{N-1}} \quad (4)$$

$$Adjusted\ error\ margin = \frac{Z \times \frac{SD}{\sqrt{N}}}{A} \quad (5)$$

A confidence level of 95% is assumed in this study, and $Z = 1.96$ [104].

3.2.2. Relevant Weight of Four Categories

Decision makers often face challenges when planning or executing projects, particularly when dealing with the complexities inherent in multi-attribute problems, which are common in Multiple-Criteria Decision Making (MCDM). Most MCDM methods can be classified into two main categories: non-compensatory and compensatory methods. Non-compensatory methods do not allow trade-offs between attributes and are often criticized for their simplicity [105,106]. In contrast, compensatory methods do permit trade-offs between attributes [107]. Scoring methods, which transform attribute values into a common preference scale, enable comparisons across different attributes. Examples of scoring methods include the Simple Additive Weighting (SAW) method and the AHP [61]. Additionally, there are compromising methods, such as the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [64], as well as concordance-based methods like the Linear Assignment Method. Among the various techniques used for MCDM, the AHP method, introduced by Saaty [108], stands out prominently. AHP allows for the quantification of inconsistent judgments and facilitates the mathematical assessment of preferences [59]. Its effectiveness relies heavily on the decision maker's preferences regarding attributes and is widely employed for weighting determination [109]. Furthermore, AHP addresses inconsistencies in human perspectives while quantitatively evaluating them to the minimum degree permissible. The method presents problems in a hierarchical structure, facilitating group decision making by calculating their geometric mean concerning each attribute and alternative through assessments [110]. Typically, AHP utilizes data derived from questionnaires, converting these inputs into scores to evaluate the existing alternatives based on selection criteria [60]. This effective technique has demonstrated its accuracy and has been utilized in numerous studies. Balali and Valipour [60] applied AHP to select smart materials for façades, while Do and Kim [61] used AHP for selecting patching materials. Mayhoub, et al. [63] employed AHP to choose façade materials, Sahlol, et al. [8] used AHP to identify sustainable building materials, and Uğur and Baykan [65] applied AHP to select building materials. In this study, AHP was chosen, as it is a common and preferable applied method to solve problems related to prioritizing criteria [111] and it is a simple way of making judgments according to several criteria and minimizing inconsistencies in opinions [112]. It was used in this study to make paired comparisons between material selection criteria categories based on a fundamental scale within a hierarchy in order to identify the preferences in making a decision [113].

Despite its proven accuracy and widespread usage in numerous studies, AHP does have limitations. Notably, this approach may limit flexibility in dynamic or large-scale applications where the weighting of criteria could vary depending on the project or context. Additionally, the method requires an increasing number of pair-wise comparisons as the number of criteria in the study grows [114]. Thus, this study focused solely on four categories of criteria in the AHP analysis and used an alternative method for ranking these criteria.

The AHP Excel Template with Multiple Inputs developed by Goepel [115] was used in this study to calculate the priority weights and error margins using the eigenvector method.

3.2.3. Validation Interview

Four validation interviews were conducted with professionals holding over 15 years of experience, including a construction project manager, a quantity surveyor, a sustainability director, and an environmental expert advisor. Each participant has substantial expertise in

sustainable material selection and has led at least 10 construction projects in New Zealand with sustainability requirements. The goal of these interviews was to obtain feedback, insights, and additional information to ensure the accuracy, relevance, and reliability of the research findings.

4. Results

4.1. Sample Characteristics

The basic factual data collected regarding the respondents' professional positions and years of experience for both surveys are presented in Table 4. Overall, these findings underscore the significant roles the respondents play within their organizations, supported by strong educational backgrounds and extensive experience. Their insights on material selection criteria, as reflected in the survey results, are thus deemed crucial and reliable.

Table 4. Summary of respondents for surveys.

Respondents for the Criteria Survey				
	0–4 years	5–10 years	11–19 years	>20 years
Project Manager	8	5	3	2
Quantity Surveyor	3	3	5	1
Consultant	2	4	3	3
Total	42			
Respondents for the Expert Survey				
	11–24 years with a degree		>25 years	
Senior Project Manager	3		2	
Senior Quantity Surveyor	1		1	
Senior Consultant			3	
Total	10			

4.2. Criteria Importance Ranking

In order to maintain consistency in the measurement results over time, we conducted a reliability analysis using the internal consistency method to assess the rating scale for various criteria. Cronbach's alpha was employed to gauge the internal consistency reliability of the scale. After calculating the variance of each criterion, the number of items, the variance of the 30th criteria score, and the variance of the total score were 30, 22.794, and 111.292, respectively. The computed Cronbach's alpha value for all criteria was 0.823, surpassing the minimum threshold of 0.7. This signifies acceptable reliability and excellent internal consistency among the criteria incorporated into the scale.

To determine the relative importance of the assessment criteria for materials based on survey data, a ranking analysis was conducted. Employing relative importance index analysis, the criteria were ranked according to their importance. Table 5 illustrates the ranking outcomes for each criterion derived from this analysis and their adjusted error margins. From these results, it was evident that 13 criteria were notably classified as possessing a "high" level of importance in the evaluation of sustainable construction materials, with II values ranging from 0.80 to 0.93.

A noteworthy observation emerged, as follows: none of the criteria were categorized under "M-L" or "L" importance levels. This underscores the considerable importance attributed to sustainability criteria by decision makers when assessing building materials. Consequently, no criteria were excluded from the list, affirming that each criterion significantly impacts the selection of sustainable construction materials, albeit to varying degrees of importance.

Table 5. Rank of assessment criteria.

Sustainable Material Selection Criteria	Importance Index	Rank by Category	Overall Rank	Importance Level	Error Margin
Environmental Impacts					
Pollution	0.86	1	4	H	0.057
Zero/low toxicity	0.83	2	7	H	0.069
Disposal	0.80	3	9	H	0.067
Environmental statutory compliance	0.80	3	9	H	0.052
Impact on air quality	0.80	3	9	H	0.058
Energy consumption	0.78	6	14	M-H	0.047
Water savings	0.76	7	17	M-H	0.060
Potential for increasing global warming	0.74	8	18	M-H	0.056
Reusability and renewability	0.74	8	18	M-H	0.051
Amount of likely wastage in use	0.74	8	18	M-H	0.060
Ozone depletion potential	0.70	11	22	M-H	0.061
Source material extraction	0.67	12	24	M-H	0.053
Embodied energy	0.58	13	29	M	0.058
Impact during harvest	0.56	14	30	M	0.054
Economic Impacts					
Repair and maintenance cost	0.84	1	6	H	0.053
Operation cost	0.83	2	7	H	0.046
Construction cost	0.77	3	15	M-H	0.051
Initial Cost	0.77	3	15	M-H	0.038
Recycle/disposal cost	0.65	5	28	M-H	0.052
Social Impacts					
Human health and safety	0.93	1	1	H	0.052
Labor availability	0.80	2	9	H	0.037
Compatibility with ecology	0.68	3	23	M-H	0.051
Aesthetics	0.67	4	24	M-H	0.053
Use of local material	0.67	4	24	M-H	0.046
Technical Impacts					
Resistance to weathering, humidity, water, and fire	0.91	1	2	H	0.038
Durability	0.91	1	2	H	0.036
Repairability and maintainability	0.85	3	5	H	0.057
Resistance to decay	0.80	4	9	H	0.042
Ease and speed of usability	0.71	5	21	M-H	0.054
Ease and speed of construction/buildability	0.66	6	27	M-H	0.054

4.3. Deciding Priority Weight of Four Categories

To ascertain the weights of four categories in assessing material selection criteria, the AHP method was employed using Microsoft Excel. The pairwise comparison matrix was constructed by computing the geometric average of respondents' responses. Subsequently,

upon the formation of the pairwise comparison matrix, the priority weights for evaluation parameters were calculated through a two-step process. Initially, the pairwise comparison matrix was normalized, followed by the derivation of weights, as presented in Table 6.

Table 6. Pairwise and normalized comparison matrix with categories' priority weights.

Pairwise Comparison Matrix				
	Environmental Impacts	Economic Impacts	Social Impacts	Technical Impacts
Environmental Impact	1.00	1.81	1.62	1.08
Economic Impacts	0.55	1.00	1.25	0.52
Social Impacts	0.62	0.80	1.00	0.54
Technical Impacts	0.93	1.92	1.85	1.00
Normalized Comparison Matrix				
	Environmental Impacts	Economic Impacts	Social Impacts	Technical Impacts
Environmental Impacts	0.32	0.33	0.28	0.34
Economic Impacts	0.18	0.18	0.22	0.17
Social Impacts	0.20	0.15	0.18	0.17
Technical Impacts	0.30	0.35	0.32	0.32
Categories' Priority Weights				
Category	Preference Vector		Priority Weight	
Environmental Impacts	0.32		32%	
Economic Impacts	0.19		19%	
Social Impacts	0.17		17%	
Technical Impacts	0.32		32%	

Ensuring the consistency of pairwise comparisons is crucial. To achieve this, the $\lambda_{\max}$ value was computed, resulting in 4.0148. Subsequently, this $\lambda_{\max}$ value was utilized to determine the CI, yielding a result of 0.0049. The CR was then calculated by dividing the CI by the RI, where the RI was determined by the number of evaluating criteria, equating to 0.9 for four criteria. Consequently, the CR was found to be 0.0055, which falls below the threshold of 0.1, indicating acceptable consistency in judgments. Finally, the priority weights, illustrated in Table 6, are now available for utilization in the selection process of sustainable construction materials. Figure 5 shows that the error margins calculated by the AHP Excel Template with Multiple Inputs [115] for environmental impacts, economic impacts, social impacts, and technical impacts are 2.3%, 2.5%, 2.1%, and 3%, respectively.

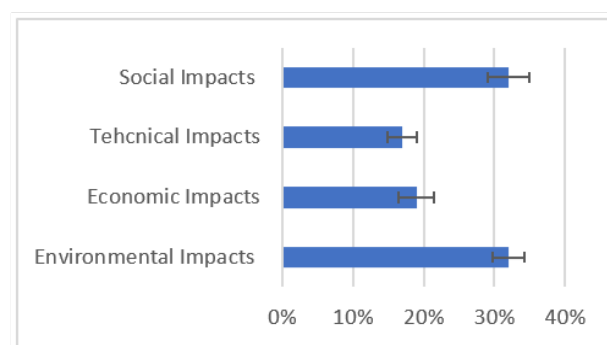


Figure 5. Error margins of priority weights.

4.4. Validation

During the validation phase of our research, we conducted in-depth discussions with four industry experts, as including a construction manager, a quantity surveyor, a sustainability director, and an environmental expert advisor. The feedback from the participants affirmed the relevance of our approach in prioritizing various categories and criteria for selecting sustainable construction materials. They emphasized the necessity of continued research in this area, aligning with New Zealand's sustainability goals.

The environmental advisor confirmed agreement with the priority weights and ranking of criteria, particularly noting the significance of New Zealand's targets, including zero landfill by 2040 and net-zero carbon emissions by 2050. The sustainability director added that there is an increasing focus on modern slavery and its social impacts, suggesting that criteria such as human satisfaction and fair wages, while not included in this study, should be incorporated in future research.

The quantity surveyor emphasized that client preferences should be considered when determining priority weights, especially for large projects. Although the study provides valuable insights into sustainable material selection for general construction projects, it was agreed that priority weights should be customized to reflect the specific preferences of clients in large scale developments.

Additionally, the construction manager recommended consolidating the rankings into a clear, accessible table to aid decision makers in efficiently interpreting and applying the information. Taking this valuable feedback into account, Figure 6 presents a well-organized overview of the priority weights for the four main categories, along with the rankings for the criteria within each category.

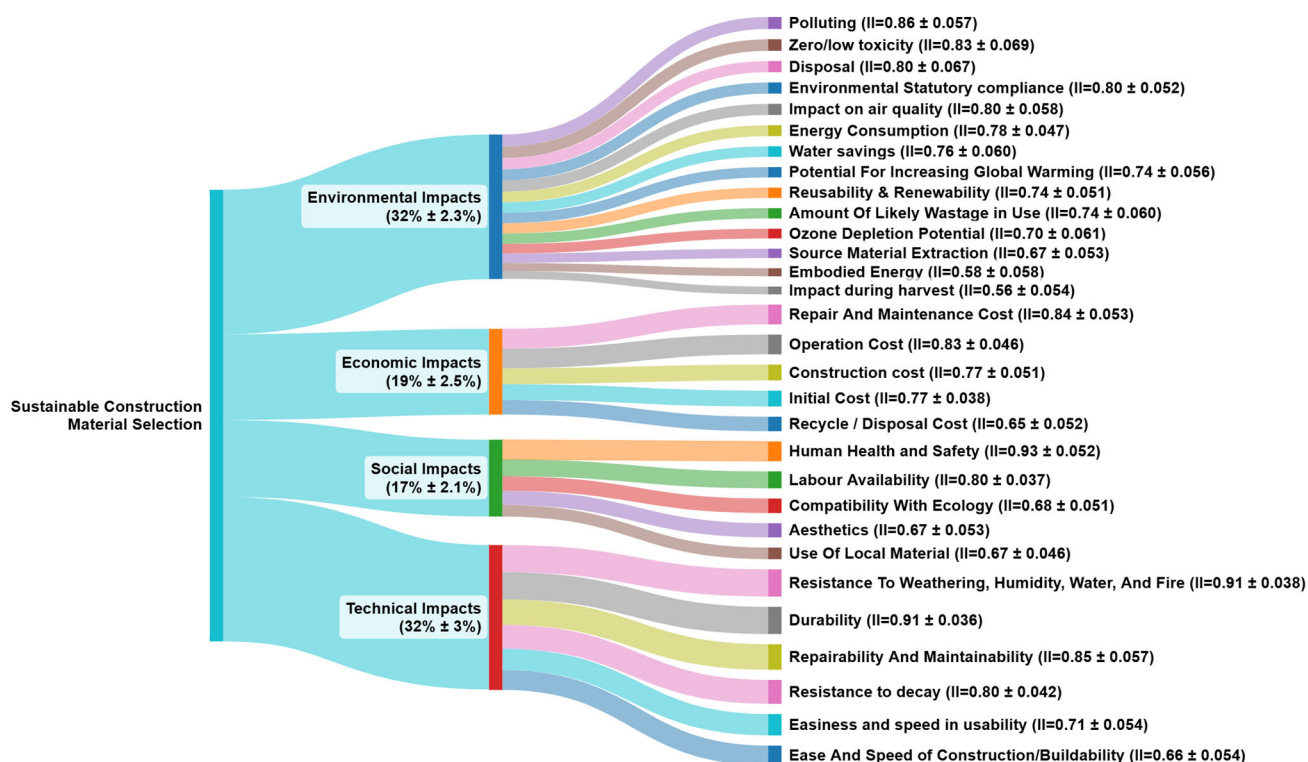


Figure 6. Priority weights and criteria rankings for sustainable construction material assessment.

The sustainability director also suggested developing a tool to further commercialize this research with two primary objectives. First, the tool could serve to educate staff on the broader scope of sustainability, highlighting that it extends beyond environmental factors. By presenting a comprehensive list of criteria and their explanations, the tool would enhance staff awareness and decision making in material selection. Second, the tool

could offer a simple, user-friendly interface for comparing materials based on sustainability criteria. In just five minutes, users would be able to assess and select the most sustainable material options for their projects in general.

The insights gained from these expert validations provide valuable guidance for industry stakeholders, empowering them to align their material selection practices with New Zealand's sustainability objectives.

5. Discussion

Regarding the priority weights for material selection, a similar study conducted by Mathiyazhagan, et al. [62] in India found that the priority weights for environmental impacts, economic impacts, and social impacts were 69%, 23%, and 8%, respectively. In India, there is a strong emphasis on environmental impacts, with environmental factors receiving a significantly higher weight compared to that of New Zealand. The economic factor is also prioritized more than social impacts, reflecting India's focus on addressing environmental challenges. This contrasts with New Zealand, where social impacts are given greater consideration, as highlighted by Malcolm, et al. [116], who noted the importance of supplier diversity and social benefits in the New Zealand construction industry.

In a study conducted in Kuwait, the priority weights for technical, social-economic, and environmental factors were 64%, 23%, and 13%, respectively [59]. The lower priority given to environmental factors in Kuwait may be attributed to the region's specific climate and resource conditions, where technological innovations in construction are seen as more immediately beneficial. In contrast, New Zealand's construction sector places equal emphasis on environmental and technical impacts, both at 32%. This balance highlights the significant role that environmental considerations play in New Zealand's material selection, particularly given the country's environmental values and need for resilience in construction practices.

A global study showed that the priority weights of environmental impacts, economic impacts, social impacts, and technical impacts were 30%, 31%, 4%, and 35%, respectively [3]. In this study, environmental, economic, and technical impacts were assigned relatively similar weights, which mirrors the results of the New Zealand study (32%, 19%, and 32%, respectively), though New Zealand places slightly less importance on economic factors. This could reflect the high performance expectations placed on New Zealand's construction industry, where technical and environmental concerns are prioritized over cost.

A study conducted in Australia showed that the priority weights of environmental impacts, economic impacts, technical impacts, and social impacts, are 39%, 39%, 15%, and 7%, respectively [45]. The lower emphasis on technical and social impacts compared to New Zealand suggests regional differences in priorities. The higher weight assigned to technical impacts in New Zealand could be attributed to the country's challenging logistics conditions due to its geographic isolation. Additionally, the greater emphasis on social impacts in New Zealand, relative to global trends, further underscores the unique priorities of the country's construction sector. This focus on social factors is consistent with New Zealand's societal values, which prioritize community welfare, cultural sensitivity, and sustainable development.

Moreover, in comparison to similar studies conducted by Akadiri, et al. [47], AlKheder, et al. [59], and Sahlol, et al. [8], the critical criteria regarding importance ranking exhibit notable similarities. Specifically, pollution levels, toxicity levels, impact on air quality, and adherence to environmental regulations consistently emerge as the most significant criteria under environmental impact. Conversely, criteria with indirect effects on individuals, such as impacts during harvest and embodied energy, are considerably less emphasized.

Nevertheless, a deviation is observed in the prioritization of aesthetics. While Akadiri, et al. [47] emphasize aesthetics as the foremost criterion, AlKheder, et al. [59] rate it as moderately important. Interestingly, this study indicates that aesthetics holds relatively less significance in the New Zealand market. Conversely, health and safety emerge as particularly crucial in New Zealand compared to the aforementioned studies. This finding

is unsurprising, given New Zealand's renowned high standards of industrial performance, especially in health and safety practices, surpassing global benchmarks.

Another noteworthy observation is the heightened importance of labor availability in the New Zealand context, contrasting with findings from other studies. This discrepancy is likely attributable to New Zealand's unique geographical challenges, which pose difficulties in sourcing suitable labor for material installation. Additionally, the elevated cost of labor underscores the criticality of material durability in New Zealand, as maintenance expenses during building operation are expected to be higher compared to global averages.

The substantial parallels between this study and existing research underscore the reliability of the findings. Conversely, the disparities, stemming from the distinct characteristics of New Zealand, highlight the significance of this study in delineating critical criteria, especially tailored to the construction sector in New Zealand.

6. Conclusions

The aim of this research was to identify the critical criteria in the selection of sustainable materials specifically suited for construction projects in New Zealand. By evaluating material selection through four key pillars—environmental, economic, social, and technical impacts—this study diverged from traditional approaches that often prioritize only the first three factors. The inclusion of technical factors highlights their significant role in assessing construction materials. Through expert surveys involving 10 senior industry professionals, the priority weighting for each category was determined by AHP analysis. The findings indicate that the environmental impact and technical impact hold greater significance than the economic impact and social impact, with respective weights of 32%, 32%, 19%, and 17%.

Furthermore, a total of 30 critical criteria were identified across these four categories, derived from an extensive literature review and expert interviews. A questionnaire survey conducted in New Zealand garnered 42 valid responses, allowing for a ranking analysis that categorized all criteria as “high”, “high-medium”, or “medium” importance in material selection. Notably, 13 criteria were classified as having “high” importance, with “health and safety”, “resistance to weathering, humidity, water, and fire”, and “durability” ranking as the top three factors.

The main findings of the study include the following:

1. The key concerns are pollution levels, toxicity, air quality, and compliance with environmental regulations.
2. Criteria with indirect effects, such as impacts during material harvest and embodied energy, have less emphasis.
3. Aesthetics hold relatively low significance in the New Zealand market.
4. Health and safety emerge as particularly crucial in New Zealand
5. The importance of local labor availability is highlighted.
6. Given the high anticipated maintenance costs, material durability is critical.

Based on these findings, we propose the following recommendations for stakeholders within New Zealand's construction industry:

1. **Construction Firms:** Integrate the identified criteria into procurement policies to ensure that material selection aligns with sustainability goals. For smaller firms, these criteria can help staff and owners to gain a deeper understanding of sustainable material selection, emphasizing that there are multiple factors to consider for enhancing sustainability in their projects. Additionally, starting with pilot projects focused on sustainable material selection, along with leveraging government incentives, can provide firms with valuable opportunities to improve their material selection practices.
2. **Material Suppliers:** Invest in research and development of sustainable materials that meet the high-ranking criteria, particularly those that are durable and have a low environmental impact. Additionally, providing education and support to smaller construction firms can help to promote the adoption of sustainable materials, as these firms may lack the resources and knowledge needed to implement advanced sustainable options.

3. Industry Associations: Facilitate training and workshops that educate stakeholders, particularly in smaller construction firms, on the importance of these criteria, ensuring that all parties understand the parameters of sustainable construction materials.
4. Academic Institutions: Collaborate with industry partners to develop case studies that illustrate the benefits of sustainable material choices.

The insights gained from this study offer significant guidance for industry stakeholders, facilitating improved material selection practices in alignment with New Zealand's sustainability objectives. Implementing these recommendations will require a collaborative effort across all sectors, encouraging innovation and enhancing environmental outcomes and public health. By prioritizing the identified critical criteria, the New Zealand construction industry can advance towards a more sustainable future.

7. Limitations of Research Findings

While the criteria are broad, their comprehensive coverage of economic, environmental, social, and technical impacts warrants further investigation. Additionally, individual decision maker preferences should be considered in priority weighting, as the current weightings are based on survey results from general scenarios. While the paper provides general recommendations, it would benefit from more specific future research directions, such as exploring how these criteria impact different types of construction projects (e.g., residential versus commercial) or their applicability in urban versus rural contexts. Given the reliance on human judgments from a limited respondent pool, statistical validation across diverse groups is necessary to ensure more accurate insights. Furthermore, alternative MCDM methods could be explored to enhance the accuracy and flexibility of the weighting system, allowing for adjustments based on project type or context. This would provide a more robust approach to criteria weighting in material selection.

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