

Article

A Multi-Criteria Decision-Making Approach for Assessing the Sustainability of an Innovative Pin-Connected Structural System

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Abstract: Structural design plays a very important role in reducing environmental impacts by reusing resources, recycling materials, and minimizing waste and pollution in the construction sector. Sustainable design becomes more effective than traditional solutions in achieving the transition to sustainability. The decision-making process is not simple due to the different preferences of clients, architects, and engineers. This paper aims to develop a decision framework for assessing sustainability in the early structural design stage. Multi-criteria decision-aiding (MCDA) methods have been implemented to improve the selection of regulations. A technical ranking approach, the Fuzzy Analytic Hierarchy Process (FAHP) method, has been employed to identify the optimal solution. Three alternatives including an innovative and two traditional structural systems have been selected and compared in terms of three criteria—economic, social, and environmental impacts. Nine sub-criteria for ranking the importance level of sustainable design have been determined through a literature review and professional experts. FAHP methods show that the economic impact (58%) is the most important criterion for assessing the sustainability of structural systems, followed by the environment with 31%. The social aspect contributes 11% to this method, and it is ranked as the least important criterion. This research revealed that MCDA methods can be used as a guideline for engineers to improve the selection in the process of sustainable design. The decision model proposed in this study has been verified and, therefore, can be applied for similar projects.

Keywords: structural design; sustainability assessment; Fuzzy Analytic Hierarchy Process (FAHP); multi-criteria decision aiding (MCDA)



Citation: Ma, J.; Siddhpura, M.; Haddad, A.; Evangelista, A.; Siddhpura, A. A Multi-Criteria Decision-Making Approach for Assessing the Sustainability of an Innovative Pin-Connected Structural System. *Buildings* **2024**, *14*, 2221. <https://doi.org/10.3390/buildings14072221>

Academic Editors: Igor Martek and Mehdi Amirkhani

Received: 22 June 2024

Revised: 14 July 2024

Accepted: 16 July 2024

Published: 19 July 2024



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1. Introduction

The construction industry is responsible for 36 percent of global energy demand and 37 percent of energy-related CO₂ emissions in 2020, according to the ‘2022 Global Status Report for Buildings and Construction’ [1]. In order to address climate change, the signing of the Paris Agreement became a crucial moment in global efforts. With rising attributable to materials used in the construction sector (expected to more than double by 2060), the global construction sector shall entirely decarbonize by 2050 to achieve the Paris Agreement. Building sectors play a key role in improving access to decreasing energy, clean fuels, and increasing renewable energy. Architects and allied professionals have advocated sustainable design principles, focusing on frameworks, like the China Green Building Standard, and internationally recognized certification models, such as BREEAM (UK), LEED (US), CASBEE (Japan), NABERS (Australia), and DGNB (Germany). These standards represent benchmarks that many architects and developers aspire to meet, guiding their efforts towards environmentally responsible and resource-efficient building practices [2].

Since building structures make up more than 50% of carbon emissions in terms of the whole construction process, structural engineers become essential players in achieving carbon neutrality. Engineers are inspired to work effectively concerning embodied carbon benchmarks after SE 2050 (The Carbon Leadership Forum's Structural Engineers 2050 Challenge) [3]. Architects and mechanical and electrical engineers are shifting towards embodied carbon with more operationally efficient buildings, while structural engineers are moving much more slowly in this process. To reduce environmental impacts, the most important step for structural engineers is to choose a suitable structural system and use materials efficiently.

However, for structural design, the majority of structural engineers still focus on economic benefits, such as optimizing structural elements and selecting high-strength materials, to meet clients' needs. Other aspects, including social and environmental impacts, have been overlooked entirely. Many countries have launched campaigns and introduced legislation relevant to green building to encourage engineers to control carbon footprints. But, the reality is that one of the important parts of building design, structural design, has been underestimated dramatically by authorities and stakeholders. Additionally, many researchers only emphasize materials selection to reduce environmental effects during the structural design phase. In fact, for some particular buildings, such as long-span industrial buildings, the type of structural system plays a vital role in sustainable structural design [4]. With the increased industrial building development, green industrial buildings have been implemented by more and more professionals; but applicable standards for selecting sustainable building structural systems and materials are notably missing [5]. Therefore, structural engineers are facing unprecedented challenges and difficulties in selecting a sustainable structural system for some specific buildings [6]. There is an urgent need to build a framework or provide some guidelines for selecting feasible building structures [7]. So, structural engineers must act and take responsibility despite the lack of regulatory incentives or guidelines.

This paper gives an extensive review of the process and development of sustainability practices in the construction and structural design area [7,8]. Building a structural system sustainability assessment will help with selecting a reasonable structural system when environmental, social, economic, and other indicators are considered [4]. This study aims to identify the selection criteria to choose, prioritize, and rate different structural systems using a multi-criteria decision-making method. Weightage and pairwise comparison matrixes for the criteria will be developed, and a selection approach will be proposed and recommended. In addition, this study is expected to address the severe shortcomings of current green building assessment in relation to structures and materials. The focus on selecting structural systems will provide deep insight for engineers who hope to perform structural design capturing economic, social, and environmental performance.

2. Literature Reviews

In this section, a comprehensive literature review of the proposed methodologies (Delphi, criteria, MCDA approaches) is provided to introduce the applications in the building literature. The review concentrates on sustainable design or materials selection in building areas, and the review also highlights the use of a multi-criteria decision-making approach in the assessment of building sustainability to support designers in the choice of systems and materials for construction projects. Sustainable assessment should be evaluated and integrated during the preliminary design phases, according to several authors [8–11].

2.1. Structural System Sustainability Assessment

Pin connections are extensively used in the construction of steel structures due to their numerous advantages over other systems, including ease of reuse, retrofitting, and assembly and disassembly [9]. Extensive research on the mechanical properties of pin connections has facilitated their widespread adoption and continuous development in the

steel industry. These connections are pivotal for both structural integrity and architectural aesthetics [10,11]. However, despite the ongoing research on various structural systems, there is a significant lack of focus on sustainability within the context of pin connections. Moreover, existing green building regulations do not adequately assess this new system. Currently, there are many green building rating systems, such as the China Green Building Assessment (GB/T 50378), LEED, BREEAM, CASBEE, GBAS, DGNB, Green Star, and SBTOOL [2]. Nevertheless, none of these systems have been evaluated for life cycle indicators specifically in terms of structural design. Green buildings certified by these systems lack the necessary economic, environmental, and social indicators. Moreover, the multiple certifications implemented to date lack clear sustainability goals, resulting in less efficient processes, especially in the area of structural design. According to the current evaluation criteria, systems in almost all countries only evaluate structural materials, material durability, and building structure types.

This gap is particularly concerning given the increasing importance of sustainable design in the face of climate change and resource depletion. To address this sustainability gap, it is essential to reference existing research on sustainable structural design, which encompasses the use of environmentally friendly materials, energy-efficient construction methods, and principles aimed at minimizing environmental impact. Pin-connected structural systems can contribute to more sustainable building solutions by integrating these sustainable practices, thereby promoting environmental responsibility and long-term ecological balance.

As mentioned above, it is important to conduct sustainable analysis for structural engineers to reduce carbon emissions by selecting suitable structures and materials in the design of building structures. Structural design is very important and can reduce its significant environmental impact if specific structural design choices can opt out appropriately. Unfortunately, to achieve a sustainable built environment, there are still no global standards to obtain a balance between the dimensions of sustainability—economy, environment, and society [12–15]. For structural systems, there are different advantages, such as safety, constructability, workability, and durability, which can be seen as attributes of flexible design in terms of sustainability. Additionally, other design aspects including waste generation, energy use, water consumption, and CO₂ emissions can also be affected by structural engineering decisions significantly [16]. On the other hand, the importance of incorporating sustainable development principles in early phases, like feasibility analysis or preliminary design, is not properly understood by stakeholders. Furthermore, sustainable analysis was rarely considered during the design process, and clients, architects, and engineers paid more attention to costs and deadlines. If the structural systems are well planned and sustainable criteria are considered in the design phase, they can help to improve project sustainability magnificently [17].

In addition to structural design, many policies and specifications related to green buildings have been introduced to improve the construction's environmental performance, and some solutions, such as fabricated structures and steel structures, have been prioritized in this area. Regarding structural design to assess sustainability, the use of eco-efficiency materials was compared, and a selection method was proposed for load-bearing structures [18]. A new modular light-gauge steel framed wallboard (structural system) has been presented in the paper [19], and assessment indexes and guidance are proposed to evaluate the performance of the wallboard. Comparisons of different parameters (cost, technology, and environmental impact) have been made to select structures by implementing methodology combining sustainability criteria, BIM (building information modeling), and multi-criteria decision-aiding methods [20]. In order to deliver sustainable structural designs, a systematic approach and database generation for the EE (embodied energy) of building materials has been developed. Overall, EE reductions of up to 40% can be achieved by comparisons of slab construction techniques through environmental performance measures [21]. In the steel manufacturing industry, a case study was conducted to illustrate the proposed framework to determine the cause-and-effect relationships among

criteria in terms of four prominent sustainability aspects, including engineering, economic, environmental, and social [22].

However, structural engineers typically prioritize mechanical behaviors and costs in enhancing building performance, with most studies focusing predominantly on economic issues. Although some research includes environmental impacts, social sustainability often remains overlooked [17–21]. When social sustainability is considered, it primarily focuses on the construction and architectural design stages [15–21]. A decision model has been developed to evaluate the sustainability of three types of commercial building structures at the early design stage [23]. This model assesses social benefits such as spatial adaptability, safety, comfort, and maintenance within structural design based on integrated design objectives [20]. Despite the recognized importance of sustainability, there is limited research on optimizing structural systems in this context. Consequently, a significant gap exists in the literature regarding the selection of structural systems that comprehensively address economic, environmental, and social sustainability. Addressing this gap is crucial for advancing the field and ensuring that sustainable design principles are integrated from the earliest stages of building development, ultimately leading to more holistic and resilient built environments.

In this study, the systemic approach for sustainability assessment is proposed in the early stage (feasibility or preliminary design). A criteria system, multi-criteria decision-aiding methods, and a decision model for three different alternative structural solutions in the design phase have been developed to assess sustainability.

2.2. Sustainable Criteria for Structural System Selection

Over the last decades, great numbers of articles, books, and consulting reports offered competing positions on the definition of ‘sustainability’ and its implications for action. In general, sustainability rests on three (social, ecological, and economic), four (social, ecological, economic, and technological), or five pillars (ecological, economic, social, political/institutional, and cultural) or more [15]. The interactions among pillars will become very hard to distinguish and portray if more than three pillars are implemented. At the same time, sustainable development pillars or indicators should not be oversimplified to warrant a closer examination and better investigation. At present, different indicators have been proposed and used for diverse purposes by different users in many varied contexts. Most of the sustainability indicator frameworks are based on the three most important pillars: environmental, social, and economic [24]. It is revealed that the criteria for structural system selection have not been established according to a comprehensive review of the literature. Based on three different impact categories, a sustainability assessment framework for sustainable material choice has been applied to some construction projects using the BIM and Fuzzy AHP approach [25]. The criteria established for building construction and material selection are shown in Table 1. A variety of technologies distinguish construction processes and require analyzing the technological aspects as separate and important sustainability categories [15]. Technological aspects or other aspects, such as cultures and policies, are all relevant to social, ecological, and economic factors.

In the next sections, the approach for sustainability assessment will be proposed in the early stage (feasibility or preliminary design). A criteria system, multi-criteria decision-aiding methods, and a decision model for three different alternative structural solutions in the design phase will be developed to assess sustainability. Social, economic, and environmental aspects will be included in these sustainability criteria.

Table 1. Criteria established for building construction.

Indicators	Criteria	Source	Main Contributions
Economic	Construction Maintenance Management Investment cost Maintenance and operation Materials cost Energy cost Risk management Life cycle impacts Design changes Constructability	[14,20,26,27]	Financial advantages of designing flexible spaces that can be easily adapted to future needs, extending the building's useful life. Designing structures with reused components; the use of eco-friendly, recycled, and locally sourced materials to reduce environmental impact; analysis of the cost differences between conventional and sustainable materials and the long-term benefits; life cycle assessment methods; and assessing the sustainability of alternative structural solutions.
Environment	CO ₂ emissions Energy consumption Waste Recycling and reuse Noise Dust and air pollution Resources, consumption, water, land, and materials Production Transportation Waste management	[28–32]	Site selection and materials to energy efficiency and waste management; sustainable material selection with hybrid MCDA; environmental enhancement via building refurbishment; green building indicators; using materials with low environmental impact; engaging all stakeholders early in the design process to identify and implement sustainable solutions; and incorporating new technologies and approaches.
Social	Noise Aesthetic Safety Health Comfort Functions Reliability/maturity Design life Efficiency Primary energy ratio	[17,22,26,33–35]	Promote well-being, equity, and community engagement; project site selection based on health and well-being; social aspect implementation in sustainable construction; social effects by construction methods; ensuring buildings are structurally sound; engaging the community and stakeholders in the planning and design process; and spaces that support community resilience.
Others	Resource Technology Strategic (political) culture Energy Performance Engineering resource Project management Regulatory	[26,36–40]	Novel sustainability framework; sustainable MCDA in civil engineering through technology, culture, and policies; incorporating advanced building management systems; aligning building projects with government policies and initiatives; involving architects, engineers, policymakers, and other stakeholders from the outset; and adopting a mindset of continuous improvement.

2.3. MCDA Approaches

The MCDA method has been adopted widely in the construction industry to generate effective, sustainable solutions in recent decades [41]. There are a majority of technical methods to carry out MCDA, as shown in Table 2. In the building area, it is necessary to consider different aspects of a project, including cost, quality, time, security, ethics, and resources. During the structural design stage of a project, multiple criteria are often involved with a great number of the decisions undertaken and analyzed to ensure a better solution [42]. Many different technical methods for multi-criteria decision making have been developed to address a variety of issues in the building sector [43]. The FAHP approach, combining the Analytic Hierarchy Process (AHP) with fuzzy logic theory, enriches its precedent [44]. The AHP theory is based on the Cartesian and Newtonian way of thinking, which is composed

of making the problem into small parts continually until a precise level is reached. The AHP requires one-to-one comparison judgments among similar criteria to generate the priorities of alternatives using experts [45], while the FAHP employs the fuzzy set theory concepts which use fuzzy numbers instead of real numbers in hierarchical structure analysis [46,47]. In the review of articles regarding the MCDA method (years 2020–2024), the top five most commonly used methods in the construction area are the AHP (878 papers, 24%), Fuzzy AHP (571 papers, 16%), TOPSIS (602 papers, 16.5%), Fuzzy TOPSIS (376 papers, 10%), and ANP (368 papers, 10%). Although the AHP is the most popular method, with 878 papers (24%) from 2021 to 2024, it has several disadvantages, such as subjectivity in judgment, inconsistency in pairwise comparisons, and a lack of handling uncertainty. To address these issues, the use of the Fuzzy AHP (FAHP) is recommended. The FAHP incorporates fuzzy logic to handle the uncertainty and vagueness in human judgment, reducing inconsistencies and improving the overall decision-making quality. Consequently, the FAHP, which accounts for 571 papers (16%) and is a more robust alternative for complex decision-making scenarios in the construction area.

Table 2. MCDA approaches.

Method	Advantage	Limitation	Recommendation
AIRM Aggregated Indices Randomization Method	Ordinal non-numerical information can be translated into a framework.	Time-related biases, especially as sample sizes grow.	Analysis with non-numeric (ordinal), imprecise (interval), and incomplete expert insights.
AHP Analytic Hierarchy Process	Deliberate inclusion of both qualitative and quantitative elements.	This process entails defining the decision problem with precision and crafting accurate pairwise comparison matrices.	Well suited for crafting decisions that encompass a multitude of stakeholders and diverse criteria.
ANP Analytic Network Process	This approach tackles intricate decision challenges involving interconnected criteria and alternatives.	It is more intricate and time intensive compared to the AHP, demanding both expertise and comprehensive data input.	However, it excels in guiding construction decisions where interdependencies among criteria and alternatives are significant.
ARM/ARAS Additive Ratio Assessment Method	Effective for quantitative measurements and allows for flexible adjustment of weights and preference values.	Lacks efficacy in qualitative initial assessments and comparative preference analysis.	It finds extensive use in solving various problems across diverse domains, such as supplier selection and construction issues.
BWM Best Worst Method	Straightforward and user friendly for pinpointing critical factors.	Overlooks interactions between criteria or alternatives.	Conducting pairwise comparisons to ascertain the optimal and least favorable elements within each criterion.
COPRAS Complex Proportional Assessment	Assuming independence between positive and negative ratios.	Subjectivity is involved in assigning weights to criteria.	Particularly useful for structured evaluation processes in construction decisions.
DEMATEL Decision-making Trial and Evaluation Laboratory	Examines the causal connections between criteria and pinpoints pivotal factors.	It prioritizes understanding relationships.	This approach suits decision making in construction, where grasping causal links is vital.
ELECTRE Elimination and Choice Expressing Reality	Tackles the challenge of reconciling diverse criteria through a clear evaluation process.	It takes into account preferences and their respective weights, requiring substantial data.	It is used for construction decisions characterized by conflicting criteria and a requirement for transparency.

Table 2. Cont.

Method	Advantage	Limitation	Recommendation
Fuzzy AHP Fuzzy TOPSIS Fuzzy FMEA and Fuzzy VIKOR	Triangular fuzzy numbers capture the inherent subjectivity of human opinions, while the entropy weighting method efficiently reflects the actual dynamics of decision-making, contingent upon the chosen evaluation criteria.	This method accounts for a decision maker's inclination to allow a single attribute of a candidate or organization to disproportionately influence their overall assessment.	A fuzzy set is well suited for scenarios where precise boundaries or categories are difficult to define, and instead, there exists a degree of ambiguity or uncertainty.
GTA Graph-Theoretic Analysis	Their simplicity and versatility make them applicable across diverse fields.	The permanent function employs qualitative values for different terms.	Widely employed to depict nearly any physical scenario comprising discrete objects and their relationships.
GRA Gray Relational Analysis	This method evaluates the connection between input and output variables.	It is influenced by the choice of reference series and can be challenging to determine input variable weights.	It is valuable for understanding how input variables impact outcomes in construction.
LINMAP Linear Programming Techniques for Multidimensional Analysis of Preference	The LINMAP procedure does not require the decision maker to provide all paired comparison judgments.	However, it is difficult to assess partial orders and obtain reliable weights.	Environmental management, distribution, hydrology, finance, chemistry, logistics, energy management, healthcare, manufacturing, sports, etc.
MAUT Multi-Attribute Utility Theory	MAUT allows decision makers to consider multiple attributes simultaneously.	MAUT can be complex and time consuming.	Involve stakeholders in the decision-making process to ensure that their preferences and concerns are adequately represented.
MIVES Integrated Value Model for Sustainability Assessment	MIVES considers multiple dimensions of sustainability.	Relies on data for various indicators, potentially leading to biases or disagreements.	Transparency and stakeholder engagement.
MOORA Multi-objective Optimization by Ratio Analysis	It can utilize this approach easily to assess different options and choices.	Predicting the weights assigned to different criteria can be challenging.	Performance evaluation in the real estate sector, contractor selection, design selection, and robot selection.
Integrated Methods (Integrated DEMATEL-ANP, Fuzzy FMEA and VIKOR, Gray AHP, Gray TOPSIS, etc.)	It helps alleviate concerns, like human bias and judgment ambiguity.	However, challenges persist in modeling discrete data, particularly when information is lacking, leading to varied outcomes.	In complex projects, it becomes crucial to compare the results generated by diverse methodologies to develop a comprehensive index.
PROMETHEE Preference Ranking Organization Method for Enrichment Evaluations	Ranking alternatives involves comparing them pairwise, taking into account preferences and indifference.	Rankings are more sensitive to normalization methods and weights.	This method is applicable for construction decisions with clearly defined preferences and pairwise comparisons.
SAW/WSM Simple Additive Weightage/Weighted sum method	A proportional linear transformation of raw data.	However, it can be influenced by self-assessment bias.	It is particularly favored for less complex problem environments due to its simplicity.
SWARA Stepwise Weight Assessment Ratio Analysis	This approach establishes priorities based on firms' or nations' set policies and strategies.	Relying on a single ratio might lack comprehensive information and could potentially mislead regarding profits.	It is regarded as the most effective method for evaluating criteria, particularly for determining their relative weights.

Table 2. Cont.

Method	Advantage	Limitation	Recommendation
TOPSIS Technique for Order Preference by Similarity to Ideal Solution	Identifies alternatives that closely approximate the ideal solution and accommodates nonlinear relationships.	Rankings are notably influenced by the weights.	It involves defining criteria, standardizing data, and computing Euclidean distances to gauge the proximity of alternatives to the ideal solution, streamlining the ranking process systematically.
VIKOR VišeKriterijumska Optimizacija I Kompromisno Resenje	Offers a compromise solution when faced with conflicting criteria.	Rankings are affected by the weights assigned to criteria and may not be universally applicable.	Particularly beneficial for construction decisions entailing conflicting criteria and a necessity for compromise.
WASPAS Weighted Aggregated Sum Product Assessment	Addressing single-dimensional issues, adept at balancing multiple criteria, and easily understood.	However, it may not always accurately portray real-world scenarios, leading to illogical outcomes.	To overcome this limitation, complex alternative decisions are ranked, and optimal solutions are sought based on multiple, often conflicting criteria.

3. Materials and Methods

3.1. Evaluation Framework

Multi-criteria analyses have been employed for evaluating different options in this case. Steps involve framing the decision problems, such as identifying all possible alternatives through unbiased experts or members; then, evaluation criteria shall be defined to assess technical, environmental, and social aspects of the alternatives; most importantly, the weights of each evaluation criteria should be attributed based on the assessment of experts. The framework is illustrated in Figure 1.

3.2. Fuzzy AHP Method

The Analytic Hierarchy Process (AHP) and Fuzzy AHP are widely implemented to determine the weights of different criteria and priorities of alternatives in multi-criteria decision-making methods. Based on the pairwise comparison, the Fuzzy AHP is a method that fuzzy sets that will be combined with the AHP values [30]. The scale of the relative important factor (1-9, 1/9-1) will be applied to measure comparison values (as illustrated in Table 3). The AHP typically employs precise numerical values (1–9 scale) to indicate the intensity of preferences between two elements. In contrast, decision makers use fuzzy numbers (e.g., triangular or trapezoidal fuzzy numbers) instead of precise numerical values for pairwise comparisons [27]. The fuzzy AHP values will be used in this study.

To calculate the weight factor, the following steps have been depicted:

Step 1: Comparison of factors

Simple Additive Weighting (SAW) is a simple and reliable approach used to find the sum of the weighting for each alternative when conducting multi-attribute decision making to solve the problem. Normalizing the decision matrix (X) is required when comparing all the ratings of the supposed alternatives [29].

$$r_{ij} = \frac{x_{ij}}{\max(x_{ij})} \quad (1)$$

$$r_{ij} = \frac{\min(x_{ij})}{x_{ij}} \quad (2)$$

$$w = \frac{C1}{C1 + \dots + Cn} \times 100\% \quad (3)$$

$$V_i = \sum_{j=1}^n 1w_j r_{ij} \quad (4)$$

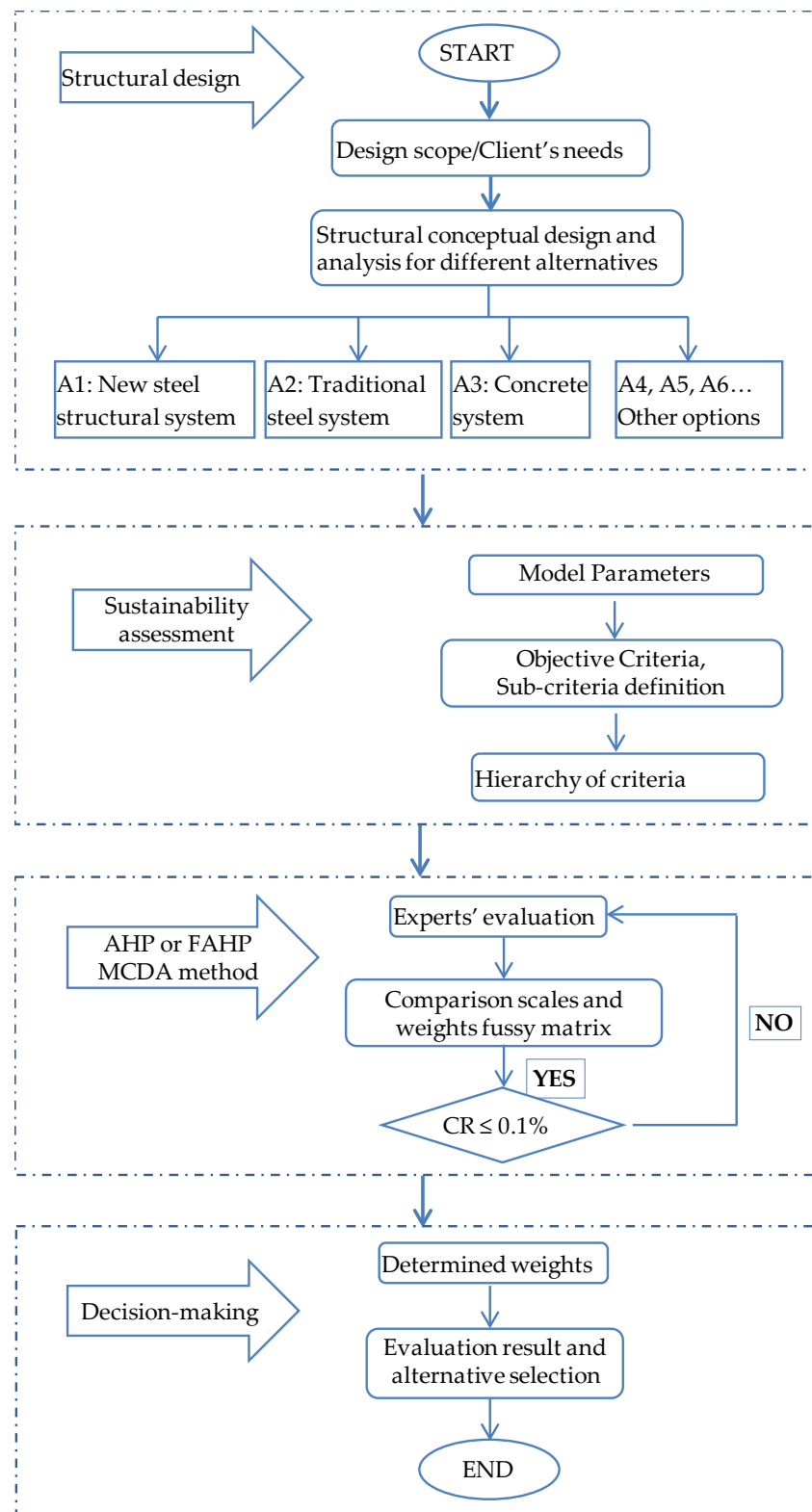


Figure 1. The flowchart of the structural system selection model.

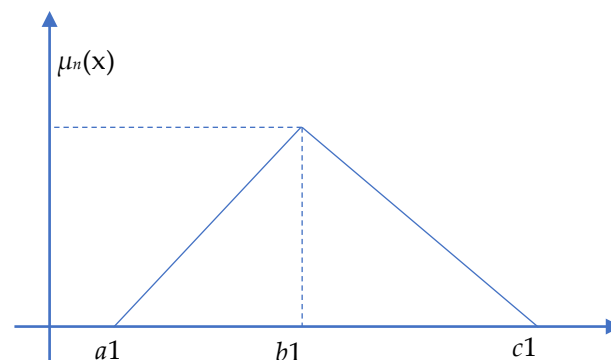
Table 3. Definition of the fuzzy scale.

Importance Assessment	Fuzzy AHP Value	AHP Value
Absolutely strong (AS)	(8,9,9)	9
Very strong (VS)	(6,7,8)	7
Fairly strong (FS)	(4,5,6)	5
Slightly strong (SS)	(2,3,4)	3
Equal (E)	(1,1,1)	1
Slightly weak (SW)	(1/4,1/3,1/2)	1/3
Fairly weak (FW)	(1/6,1/5,1/4)	1/5
Very weak (VW)	(1/8,1/7,1/6)	1/7
Absolutely weak (AW)	(1/9,1/9,1/8)	1/9

The weights of all criteria will be obtained using Formulas (6)–(9). r_{ij} is the normalized performance rating of the alternatives to attribute C_i , A_i ; $i = 1, 2, \dots, n$ and $j = 1, 2, \dots, n$. As shown in Figure 2, $\tilde{n}$ (triangular fuzzy numbers) can be defined by a triplet (a, b, c) with function $\mu_{\tilde{n}}$ as follows:

$$\mu_{\tilde{n}}(x) = \begin{cases} \frac{x-a}{b-a}, & a \leq x \leq b \\ \frac{c-x}{c-b}, & b \leq x \leq c \\ 0, & \text{otherwise} \end{cases} \quad (5)$$

where $a < b < c$. b is the most likely value of the fuzzy number.

**Figure 2.** A triangular fuzzy number $\tilde{n}$.

The distance D between fuzzy numbers can be defined as follows:

$$D(\tilde{n}_1, \tilde{n}_2) = \sqrt{\frac{1}{3}[(a_2 - a_1)^2 + (b_2 - b_1)^2 + (c_2 - c_1)^2]} \quad (6)$$

Step 2: Perform consistency

The factor of consistency shall be calculated to control the consistency of subjective opinions and the accuracy of the following weight factors:

$$CF = (\lambda_{\max} - n) / (n - 1) \quad (7)$$

It is acceptable if the consistency factor is less than 0.1, where $\lambda_{\max}$ is the matrix R maximum eigenvalue and n is the factor number.

The index of consistency for random judgments was defined by Saaty (1980) as the consistency ratio (CR)

$$CR = \frac{CI}{RI} \quad (8)$$

where RI is the average value of CI for random matrices using the given scale (as shown in Table 4), according to Saaty (1980) [48].

Table 4. Values of RI .

Matrix Order	1	2	3	4	5	6	7	8
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41
Matrix Order	9	10	11	12	13	14	15	16
RI	1.45	1.49	1.51	1.48	1.56	1.57	1.59	1.60

Step 3: Converting parameters

Triangular fuzzy numbers follow the conversion rules, and the values of the pairwise comparison matrix shall be converted to these numbers.

$$\tilde{R} = \begin{matrix} A_1 \\ A_2 \\ \vdots \\ A_n \end{matrix} \begin{bmatrix} \tilde{r}_{11} & \tilde{r}_{12} & \cdots & \tilde{r}_{1n} \\ \tilde{r}_{21} & \tilde{r}_{22} & \cdots & \tilde{r}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{r}_{n1} & \tilde{r}_{n2} & \cdots & \tilde{r}_{nn} \end{bmatrix} \quad (9)$$

Step 4: Calculation of the factor dimensions

The fuzzy weight factor dimensions can be obtained as follows:

$$\tilde{u}_i = \left(\tilde{r}_{i1} \odot \tilde{r}_{i2} \odot \cdots \odot \tilde{r}_{in} \right)^{1/n} \quad (10)$$

Step 5: Calculation of the weight factors

The final fuzzy weight factors can be calculated with the following formula:

$$\tilde{w}_i = \tilde{u}_i \odot \left(\tilde{u}_{i1} \oplus \tilde{u}_{i2} \oplus \cdots \oplus \tilde{u}_{in} \right)^{-1} \quad (11)$$

Step 6: Calculation of the true values

The final fuzzy weight factors are as follows:

$$w_i = \left[\left(w_i^u - w_i^l \right) + \left(w_i^m - w_i^l \right) \right] / 3 + w_i^l \quad (12)$$

where $\tilde{w}_i = \left(w_i^l, w_i^m, w_i^u \right)$.

The normalized weight vector is calculated by applying Equation (13) as follows:

$$w_{ni} = \frac{w_i}{\sum_{i=1}^n w_i} \quad (13)$$

4. Sustainability Assessment to Select the Structural System

4.1. Structural Systems (Alternatives) Description

In this paper, based on an industrial building, a novel pin-connection joint (shown in Figure 3) was proposed for all truss–column connections to support the floor system subject to heavy loads in the long-span steel structural system. Typical welded and bolted connections were difficult to meet the requirements of stakeholders (such as cost control by clients, esthetics by architects, and constructability by builders). There will be dramatic disadvantages if implementing traditional solutions (as presented in Figure 3), including too many bolts to control the quality, large truss elements, expensive labor and inspection costs, slow construction speeds, and difficulty in reusing. Meanwhile, the critical issue for applying a conventional structure to this project is the safety risk. Bolted connections are assumed to be ideal pinned connections (a semi-rigid assumption is unlikely because of its complexity and software limitations) when carrying out analysis through structural

software for normal steel structures [10,11]. But, bolted joints behave as semi-rigid connections rather than ideal pinned connections in the real project. For most normal steel structures, there were minor impacts on the safety of the entire structure and connections if ideal pinned conditions were assumed during the design process. However, for long-span, high floor–floor height, and heavy-loading steel structures, if an ideal pinned connection assumption is used for analysis but is designed as a bolted connection it will put huge risks on columns, especially long columns. A bolted semi-rigid connection will resist the moment and transfer to the column, and then the column capacity will be reduced unpredictably; further, it will damage the entire structural system if under extreme hazards (blasts, earthquakes, and strong winds).

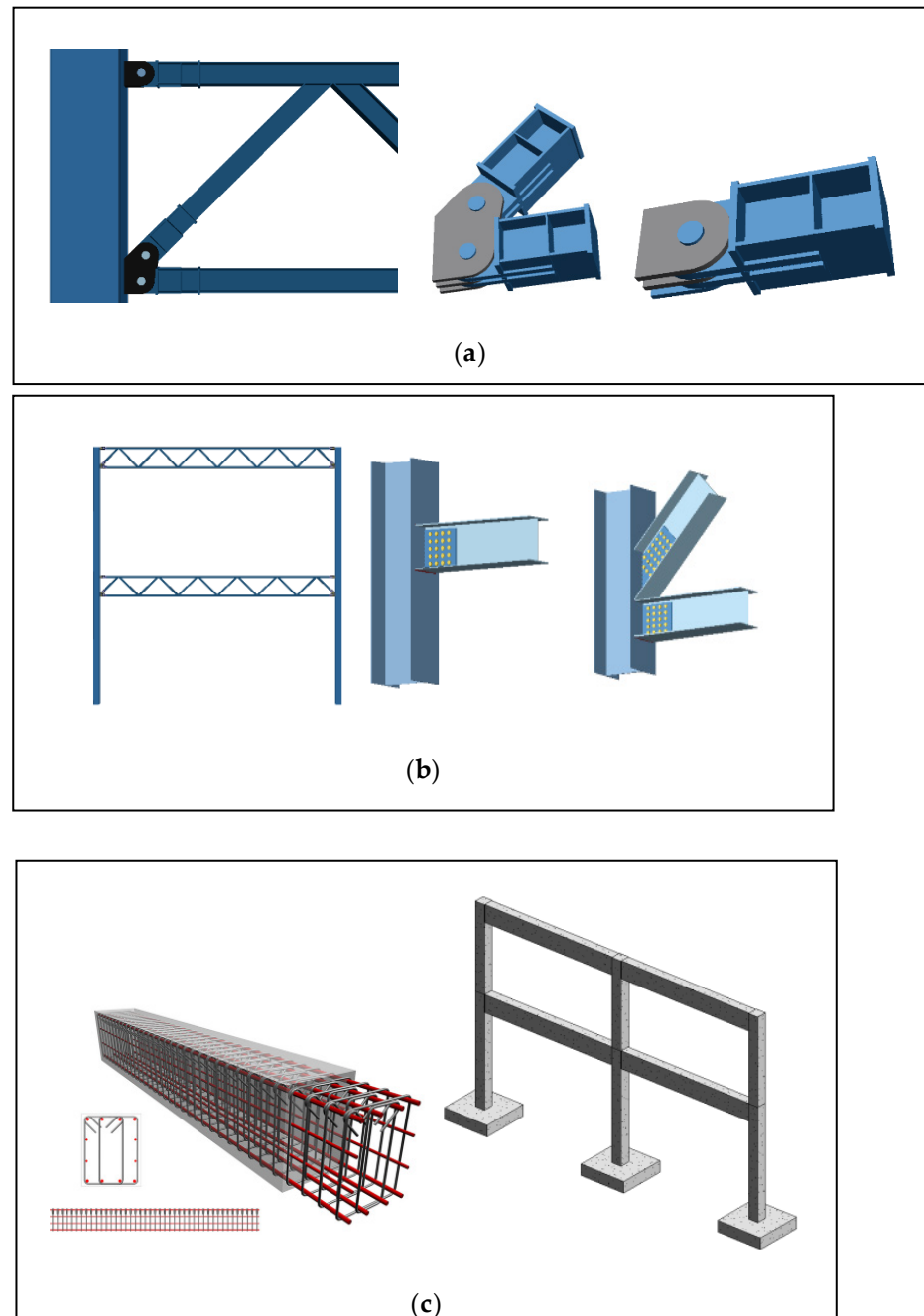


Figure 3. Structural system. (a) Pin connection for a long-span steel structure; (b) traditional connections for a long-span steel structure; (c) a traditional concrete structural system.

4.2. Fuzzy AHP Application

To exemplify the applicability of the proposed sustainable performance evaluation framework to design a structural system, a case study of selecting a suitable structural system is utilized. As detailed in Figure 4, a step-by-step approach to implementing this methodology is developed.

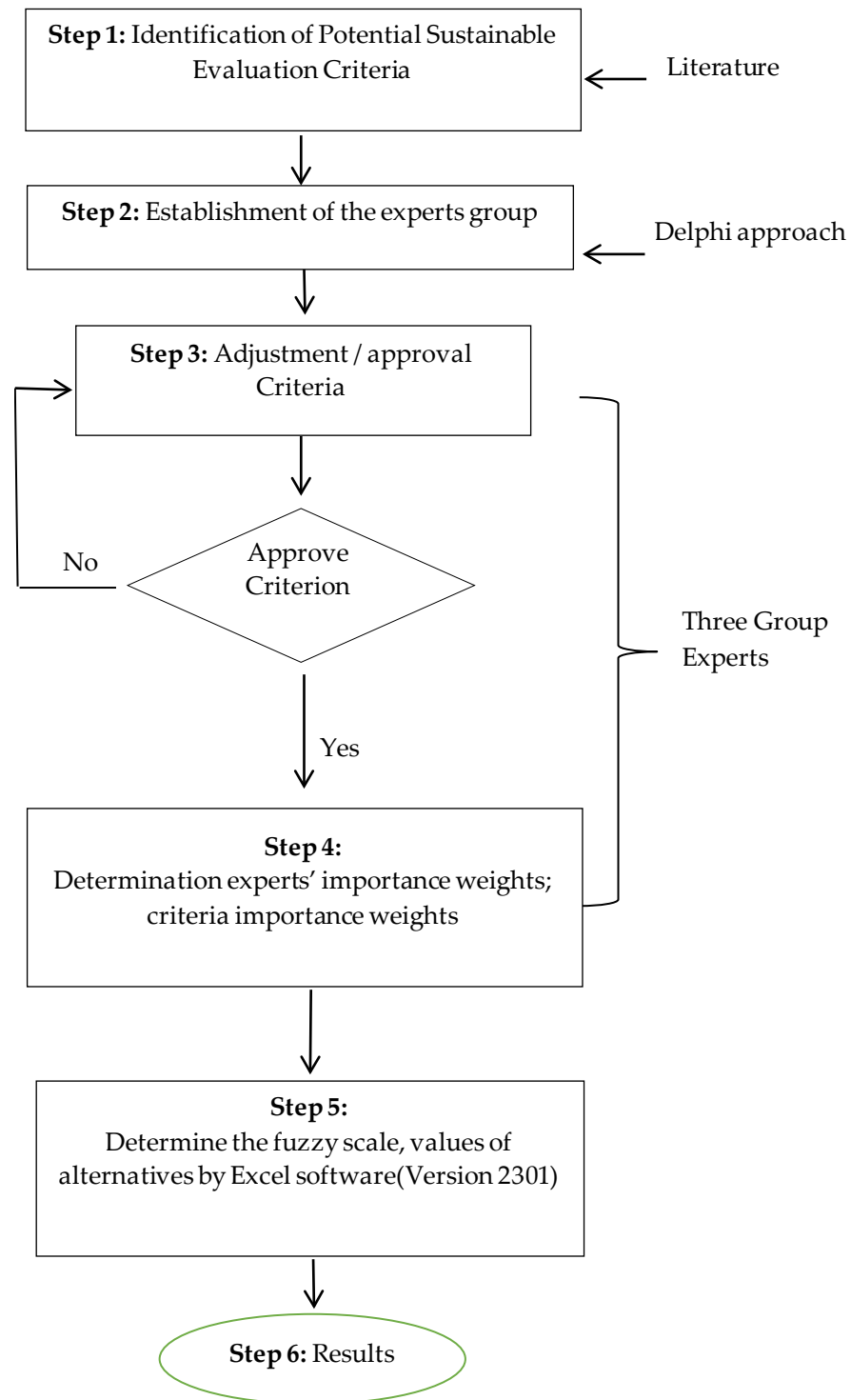


Figure 4. Proposed step-by-step approach.

Step 1. Constructing the hierarchical structure: The main criteria and sub-criteria for the sustainability evaluation of structural systems are identified by considering both the literature review and the expert opinions (Questionnaire refer to Appendix A). to build a framework [27,49,50]. The hierarchical structure is presented in Figure 5.

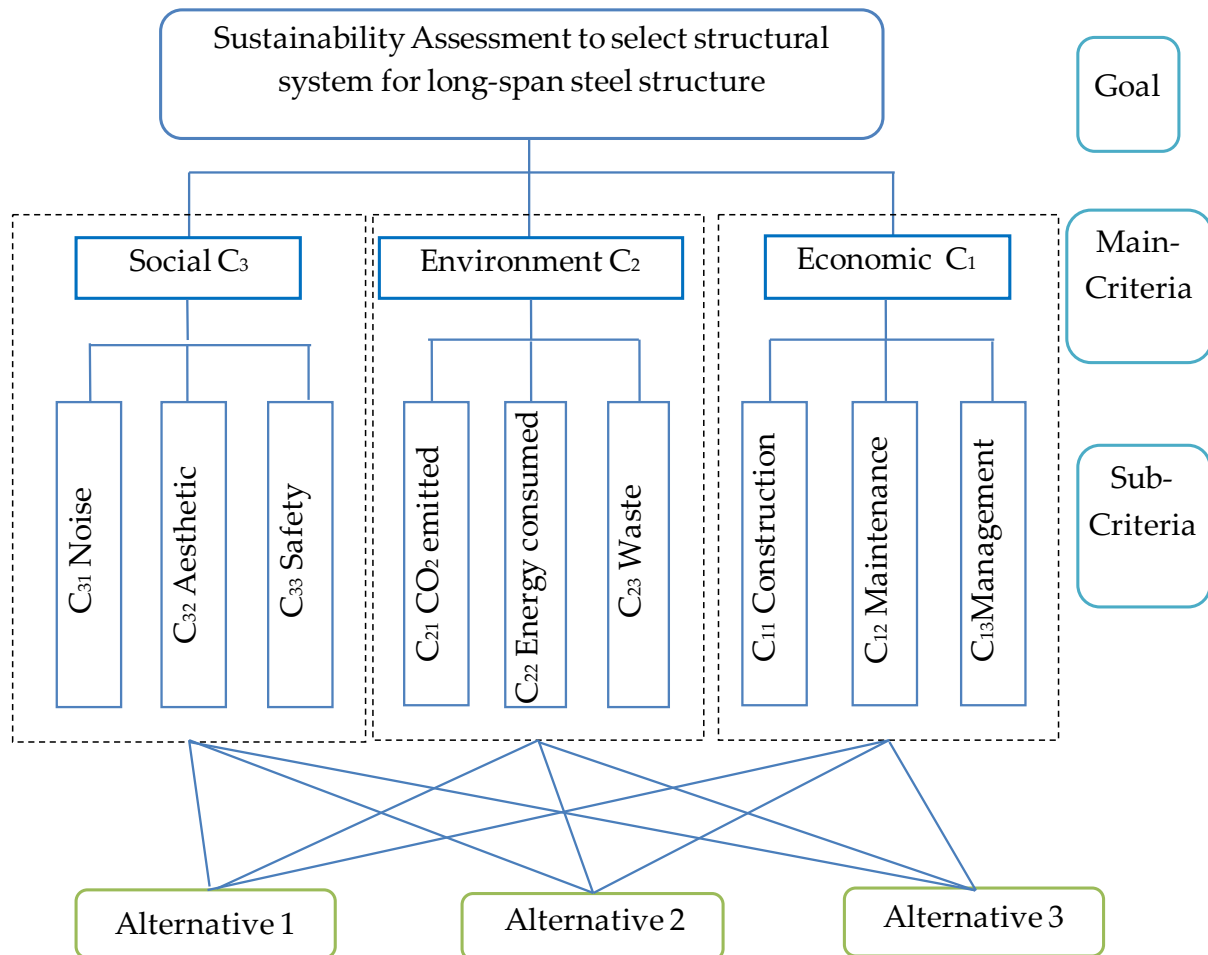


Figure 5. The hierarchical structure of a sustainable design.

Steps 2 and 3. Data collection: In these steps, first, questionnaires are formed as pairwise comparison matrices and evaluated by the 16 experts for the next step (shown in Table 5). In these steps, we outline the criteria used in our FAHP analysis and explain the connection between these criteria and the specific fields of expertise of the professionals interviewed. To ensure the credibility and transparency of the evaluation process, experts are carefully selected based on their qualifications and relevance to this study.

In these steps, the questionnaire (Questionnaire refer to Appendix B). is formed to obtain evaluation data of alternatives. These data are expressed in a matrix format as a fuzzy MCDM problem, with m alternatives and n criteria that are the lowest level criteria of the hierarchy.

Step 4. Determining the weights of the experts and evaluation criteria: Pairwise comparisons are carried out and, thus, fuzzy comparison matrices are obtained, as seen in Table 6. In this scenario, all expert groups are equally important to make decisions. Take the experts in Group 1 as an example; the evaluation matrix built for the evaluation of the sub-criteria with respect to the factors (C₁) is provided in Tables 7–10.

Table 5. Characteristics of the experts.

Expert Groups	Experts	Education	Position	Justification for Expert Selection
Group 1	1	PhD	Lecturer	Expert in structural design and construction, extensive knowledge of evaluating Criterion C1 and C2.
	2	Masters	Structural engineer	Professionals in structural design who provide insights into environmental impact; essential for assessing criterion C1/C2/C3.
	3	Bachelors	Building estimator	Professionals in cost estimation for Criterion C1.
	4	TAFE/ University	Builder or supplier	Professionals in construction management; essential for assessing Criterion C1/C3.
Group 2	5	PhD	Prof.	Background in building design and construction and provides critical insights for Criterion C1/C2/C3.
	6	PhD	Assoc. Prof. Dr.	Background in building design and construction and provides critical insights for Criterion C1/C2/C3.
	7	Masters	Structural engineer	Extensive experience in structural design is essential for evaluating Criterion C1/C2/C3.
	8	TAFE/ University	Builder or supplier	Background in building construction and materials.
Group 3	9	Masters	Structural engineer	Professionals in design. Essential for assessing Criterion C1.
	10	Masters	Manager	Professionals from construction management; essential for assessing Criterion C1/C2/C3.
	11	Bachelors	Architect	Professionals in architectural design and green building experts. Essential for assessing Criterion C1/C2/C3.
	12	Bachelors	Building officer	Background in building construction and policy; provides critical insights for C1/C2/C3.

Table 6. Evaluation of the experts.

Experts	Matrix in expert terms		
	G ₁	G ₂	G ₃
G ₁	-	E	E
G ₂		-	E
G ₃			-
G	Matrix in fuzzy terms		
	G ₁	G ₂	G ₃
G ₁	1	(1, 1, 1)	(1, 1, 1)
G ₂	(1, 1, 1)	1	(1, 1, 1)
G ₃	(1, 1, 1)	(1, 1, 1)	1
Note: The weight vector is calculated as $W_G = (0.333, 0.333, 0.333)$			

Table 7. Evaluation of the main criteria.

Sustainability	Matrix in expert terms		
Assessment	C ₁	C ₂	C ₃
C ₁	-	E/SS	FS
C ₂		-	SS
C ₃			-
	Matrix in fuzzy terms		
	C ₁	C ₂	C ₃
C ₁	1	(1, 2, 3)	(4, 5, 6)
C ₂	(1/3, 1/2, 1)	1	(2, 3, 4)
C ₃	(1/6, 1/5, 1/4)	(1/4, 1/3, 1/2)	1
Note: The weight vector is calculated as $W_C = (0.566, 0.324, 0.110)$			

Table 8. Evaluation of the sub-criteria with respect to C₁.

	Matrix in expert terms		
	C ₁₁	C ₁₂	C ₁₃
C ₁			
C ₁₁	-	SS	FS
C ₁₂		-	SS
C ₁₃			-
	Matrix in fuzzy terms		
	C ₁₁	C ₁₂	C ₁₃
C ₁	1	(2, 3, 4)	(4, 5, 6)
C ₁₁	(1/4, 1/3, 1/2)	1	(2, 3, 4)
C ₁₂	(1/6, 1/5, 1/4)	(1/4, 1/3, 1/2)	1
C ₁₃			
Note: The weight vector is calculated as $W_{C1} = (0.629, 0.264, 0.107)$			

Table 9. Evaluation of the sub-criteria with respect to C₂.

	Matrix in expert terms		
	C ₂₁	C ₂₂	C ₂₃
C ₂			
C ₂₁	-	E/SS	SS
C ₂₂		-	E/SS
C ₂₃			-
	Matrix in fuzzy terms		
	C ₂₁	C ₂₂	C ₂₃
C ₂	1	(1, 1, 2)	(2, 3, 4)
C ₂₁	(1/2, 1, 1)	1	(1, 1, 2)
C ₂₂	(1/4, 1/3, 1/2)	(1/2, 1, 1)	1
C ₂₃			
Note: The weight vector is calculated as $W_{C2} = (0.483, 0.313, 0.203)$			

Step 5: Performance Evaluation in terms of Sustainability Factors

The economic performance criteria values and their importance weights for three alternatives are shown in Table 11, and Table 12 shows the results of all sustainability factors.

Table 10. Evaluation of the sub-criteria with respect to C_3 .

	Matrix in expert terms		
	C_{31}	C_{32}	C_{33}
C_3			
C_{31}	-	SS	E/SS
C_{32}		-	E/SS
C_{33}			-
	Matrix in fuzzy terms		
	C_{31}	C_{32}	C_{33}
C_3			
C_{31}	1	(2, 3, 4)	(1, 1, 2)
C_{32}	(1/4, 1/3, 1/2)	1	(1, 1, 2)
C_{33}	(1/2, 1, 1)	(1/2, 1, 1)	1

Note: The weight vector is calculated as $W_{C_3} = (0.488, 0.241, 0.271)$

Table 11. Evaluation of alternative 1 with respect to C_{11} .

Alternatives	Matrix in expert terms		
	A_1	A_2	A_3
A			
A_1	-	E/SS	E/SS
A_2		-	E/SS
A_3			-
	Matrix in fuzzy terms		
	A_1	A_2	A_3
A			
A_1	1	(1, 2, 2)	(1, 2, 3)
A_2	(1/2, 1/2, 1)	1	(2, 2, 3)
A_3	(1/3, 1/2, 1)	(1/3, 1/2, 1/2)	1

Note: The weight vector is calculated as $W_C = (0.454, 0.351, 0.195)$

Table 12. Criteria performance of alternatives A1–A3.

Expert Groups	Main Criteria	Sub-Criteria	A1	A2	A3
G1 G2 G3	C1: Economic (0.566)	C11	0.454	0.351	0.195
		C12	0.403	0.302	0.295
		C13	0.391	0.322	0.287
	C2: Environment (0.324)	C21	0.401	0.382	0.217
		C22	0.522	0.302	0.196
		C23	0.446	0.287	0.267
	C3: Social (0.110)	C31	0.359	0.311	0.330
		C32	0.397	0.301	0.302
		C33	0.356	0.335	0.309

5. Results

In this section, the results obtained from the FAHP method will be presented and discussed. The MCDA approach and framework model have been explained in Section 3.

The results of the criteria weights for the evaluation matrices, including local and global weights, are presented in Table 13 (expert groups 1–3). In this study, all expert groups are assumed to give the same weights for the weights.

Table 13. Evaluation criteria weights with respect to G1.

	Experts	Main Criteria	Sub-Criteria	Local Weight	Global Weight	Rank
Multi-criteria analysis results	G1 G2 G3	C1: Economic (0.566)	C11	0.629	0.356	1
			C12	0.264	0.149	3
			C13	0.107	0.061	6
		C2: Environment (0.324)	C21	0.483	0.156	2
			C22	0.313	0.101	4
			C23	0.203	0.066	5
		C3: Social (0.110)	C31	0.488	0.054	7
			C32	0.241	0.027	9
			C33	0.271	0.030	8

The fuzzy decision-making matrix, utilizing the global weights of all sub-criteria obtained through the FAHP, is designed to evaluate and rank alternatives. This matrix, shown in Table 14, systematically integrates these weights to provide a comprehensive assessment and prioritization of each alternative.

Table 14. Final ranking results.

Sub-Criteria	Global Weight	A1	A2	A3
C11	0.356	0.162	0.125	0.069
C12	0.149	0.060	0.045	0.044
C13	0.061	0.024	0.020	0.018
C1 Total	0.566	0.246	0.190	0.131
C21	0.156	0.063	0.060	0.034
C22	0.101	0.053	0.031	0.020
C23	0.066	0.029	0.019	0.018
C2 Total	0.323	0.145	0.109	0.071
C31	0.054	0.019	0.017	0.018
C32	0.027	0.011	0.008	0.008
C33	0.030	0.011	0.010	0.009
C3 Total	0.111	0.041	0.035	0.035
Total	1.000	0.431	0.333	0.236
Ranking	N/A	1	2	3

In Table 14, it can be seen that the weights within all criteria levels and importance ranking for the three alternatives have been exhibited. The results show that the most salient one of the main criteria levels is the economic indicators (0.566), followed by the environmental indicators (0.323). In the sub-criteria level, C11—construction (0.356) is the best performance within this level. This criterion is trailed by C21—CO₂ emissions (0.156) and C12—maintenance (0.149). Therefore, for sustainable structural design, economic (construction cost) is considered the most important factor, whereas social (aesthetic) is viewed as the least important decision-making factor. Figure 6 clearly shows that in terms of sustainability indicators, priority is given to the economic factor for all three alternatives, and the environmental factor is placed in the second spot. That means the economic dimension is the most influential dimension among the three sustainability indicators. Consequently, structural engineers shall put in more resources to improve the contributions of top-ranked criteria during the early design stage.

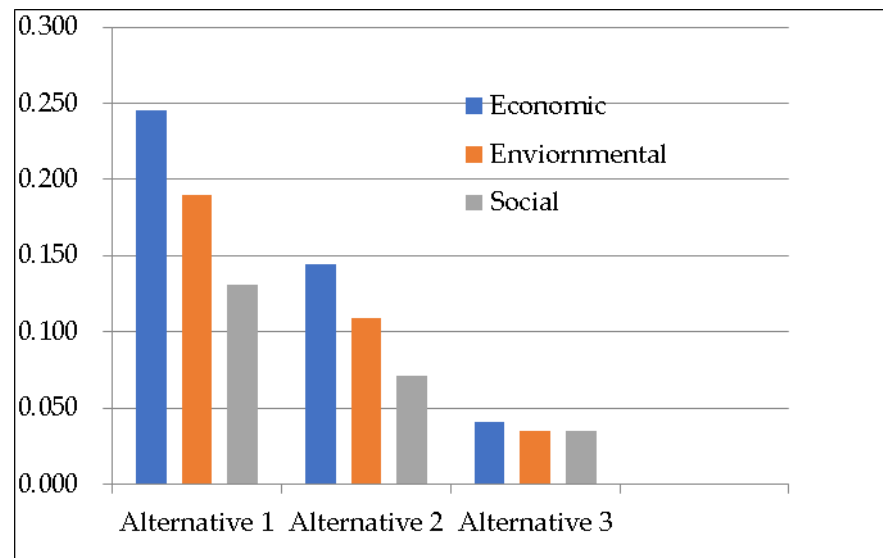


Figure 6. Final ranking.

In this case, economic considerations by experts continue to dominate the selection criteria for pin-connected new building structural systems, overshadowing sustainability assessments. The pin connection new structural system offers several advantages that align well with low-cost considerations, lower maintenance costs, and enhanced building lifespans, especially in terms of reuse, retrofitting, and ease of assembly and disassembly.

A critical discussion point is the tendency of structural engineers and project stakeholders to emphasize immediate cost savings over sustainable practices. Despite the availability of green building codes and sustainable design principles, the higher upfront costs associated with environmentally friendly materials and energy-efficient construction methods often deter their adoption. This cost-centric approach overlooks the potential long-term benefits and savings that sustainable practices can offer, such as reduced energy consumption, lower maintenance costs, and enhanced building lifespans.

Moreover, it is crucial to explore whether the proposed sustainable approach can effectively influence the opinions of owners and designers if it is perceived as financially burdensome. Even if sustainable methods are proven to be beneficial, their adoption hinges on demonstrating economic viability. Therefore, further discussion and strategies are recommended to align economic incentives with sustainability goals. This could include presenting case studies where sustainable practices have led to cost savings, advocating for regulatory incentives, or proposing financial models that highlight the long-term economic benefits of sustainable building practices.

Sensitivity Analysis

Sensitivity analysis is a crucial step in multi-criteria decision-making (MCDM) methods, as it examines how variations in input data or criteria weights affect the final ranking of alternatives. It helps test the robustness of our results, ensuring that conclusions are not overly sensitive to specific weightings. Through sensitivity analysis, we can identify which criteria have the most significant impact on the final decision. This is particularly useful for policymakers and practitioners in the building industry, as it highlights where efforts and resources should be focused to achieve substantial sustainability improvements. The traditional AHP is valued for its straightforward implementation, ease of understanding, and widespread acceptance. However, it can sometimes struggle with handling the inherent uncertainties and vagueness present in real-world decision making, especially in complex fields, like building sustainability. The Fuzzy AHP extends the traditional AHP by incorporating fuzzy logic to address these uncertainties. In this study, we explore the Fuzzy AHP to further refine the decision-making process in building sustainability evaluations.

Conducting sensitivity analysis for MCDA methods involves selecting the best option that meets the following requirements and conditions: (a) maintaining priorities in most scenarios despite changes in weight coefficients, (b) preserving the rankings of alternatives when the measurement scale changes, and (c) keeping the ranking of alternatives consistent when modifying the criteria formulation. The three typical approaches to perform sensitivity analysis include:

- (1) Changes to the weight of the criteria.

The results of the MCDA methods mostly depend on attributed weights on the criteria. The ranks of the alternatives vary with changes in the weight assigned to the criteria.

- (2) Changes to the measurement scale.

Measure the qualitative attributes on the 1, 2, 3, 4, and 5 scale or the 1, 3, 5, 7, and 9 scale. The final ranking list of alternatives should not change or should have a minor change based on the sensitivity analysis results.

- (3) Different criteria formulations are identified.

Some criteria are shown in two normatively equivalent ways (benefit type and cost type or income and expenditure), which will generate magnificent impacts on the outcome by decision makers.

In this research, to investigate and verify the results' stability over a range of input variable values, the sensitivity analysis is performed by employing the method suggested by Shankha [51]. Three factors and nine subfactors have been involved by changing the weight of the criteria. The first step is to evaluate the most sensitive factor for the three criteria without changing the weight. A sensitivity analysis has been conducted to determine the impacts of global weights for each criterion or sub-criteria. The effects of the final results can be reflected by a sensitivity analysis if the input data are not modified or if there are no changes in the main criteria, sub-criteria, weight, and alternatives. Criteria and sub-criteria were carried out for this sensitivity analysis, and the analysis was performed by the local and global weights of each criterion.

As depicted in Figure 7, the FAHP method shows that the economic impact (58%) is the most important criterion for assessing the sustainability of the structural system, followed by the environment with 31%. The social aspect contributes 11% to this method, and it is ranked as the least important criterion. The evaluation of technology encompasses a comprehensive analysis of various sub-criteria, each contributing differently to the overall assessment.

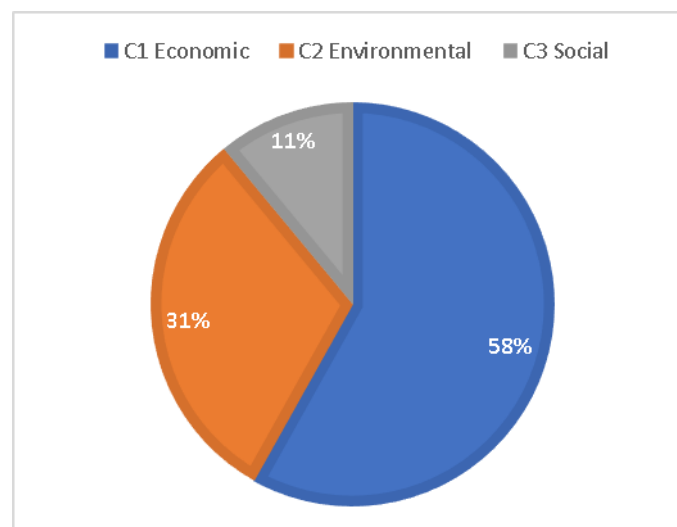


Figure 7. Criteria priority by the FAHP (%).

Figure 8 provides insights into the relevance of nine such sub-criteria, shedding light on their respective importance in decision-making processes. Construction emerges as the most pivotal factor, commanding a weightage of 36%. Its significance lies in its direct contribution to and support of economic criteria, making it a focal point for evaluation. Following closely are management and maintenance, with contributions of 15% and 10%, respectively, to the cost aspect. Notably, social indicators C31, C32, and C33 demonstrate low sensitivity to decision making, as depicted in Figure 8. Environmental considerations are dominated by CO₂ emissions and are given weights of 15%. Waste management follows suit, with weights of 10%, while energy consumption garners comparatively lesser emphasis, with 7%. This underscores the experts' prioritization of mitigating CO₂ emissions and managing waste, indicative of heightened environmental consciousness. In contrast, the social aspect assumes a lesser role in decision-making processes. Safety, aesthetics, and noise, collectively accounting for around 10%, are considered less critical compared to economic and environmental factors. This suggests a prevailing sentiment among experts that social impacts, while not disregarded, hold less weightage in technology evaluations. The evaluation of technology involves a nuanced consideration of various sub-criteria, with construction and CO₂ emissions standing out as paramount concerns. While economic and environmental factors carry significant weight, social considerations are comparatively less influential.

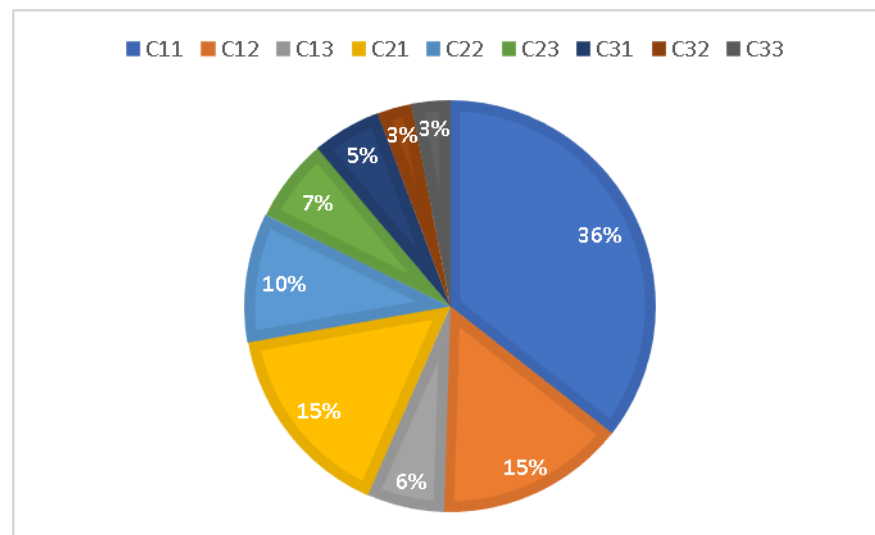


Figure 8. Sub-criteria priority by the FAHP (%).

A sensitivity analysis has been conducted to determine the impacts of global weights for each criterion or sub-criteria (as depicted in Table 15 and Figures 7 and 8). The effects of the final results can be reflected by a sensitivity analysis if the input data are modified, including changes in the main criteria, sub-criteria, weight, and alternatives. Nine sub-criteria were carried out for this sensitivity analysis, and the analysis was performed by local and global weights of each criterion. Table 15 and Figure 7 show that social indicators C31, C32, and C33 are generally not sensitive to decision making.

Table 15. The results of the sensitivity analysis.

Indicator	Criteria	Global Weights			Ranking
		A1	A2	A3	
1	Economic	0.246	0.190	0.131	A1 > A2 > A3
2	Environment	0.145	0.109	0.071	A1 > A2 > A3
3	Social	0.041	0.035	0.035	A1 > A2 = A3

The experts were international and Chinese engineers and academics who compared the criteria and sub-criteria of MCDA methods in pairs to understand their performance. Figures 9 and 10 provide the experts' comparisons between the selected alternatives in terms of criteria and the individual sub-criteria. Most stakeholders and experts emphasized the economic indicator, which has the highest acceptance. In contrast to social criteria, environmental aspects have more capacity, which is more preferred by the public. Social is the one with less impact on sustainability development, so it was ranked the lowest level for all the three alternatives.

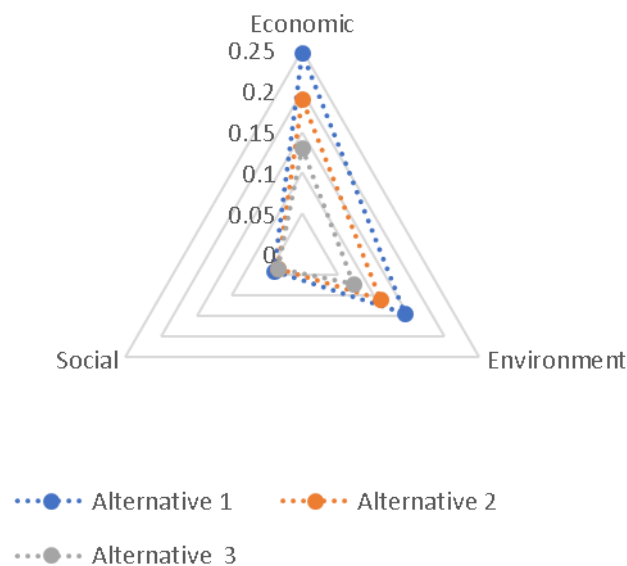


Figure 9. Alternative sensitivity analysis.

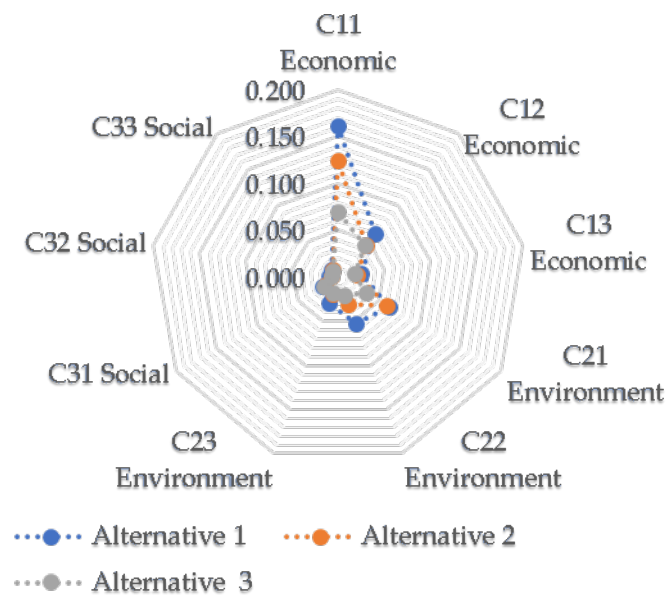


Figure 10. Criteria sensitivity analysis.

Construction, maintenance, and management were ranked the most important aspects by the majority of the experts for all of the alternatives. Economics has a prominent place in the process of structural sustainable design. Similar to economic indicators, such as CO₂ emissions, waste, and energy, the experts assigned high rankings to all three alternatives. However, for the sub-criteria related to social aspects (aesthetics, noise, and safety), the three alternatives showed some slight differences but received the lowest rankings.

6. Conclusions

This research proposes a sustainable design process for building structural systems and assessing environmental, social, and economic impacts using a multi-criteria decision-making (MCDA) method. Additionally, it presents a decision-making and computational model for evaluating and ranking different structural systems. A thorough literature review and expert consultations identified nine structural design perspectives, which were consolidated into three main criteria: environment, society, and the economy. To assess sustainability during the design phase, three alternative structural solutions were developed: one innovative new structural system and two traditional systems.

The key conclusions derived from this research are as follows:

- The framework empowers structural engineers to evaluate and select the most efficient system by considering various decision-making factors.
- The MCDA approach's validity was confirmed through practical applications, demonstrating its effectiveness as a tool for developing new structural systems.
- The proposed model (the hierarchical tree) is flexible, allowing users to modify it without restricting alternatives.
- This research offers significant benefits for engineers and society by enhancing the potential of structural design to minimize its negative impacts.

Future research directions include expanding the framework to incorporate additional criteria and more detailed substances. The theoretical framework should be tested on a broader range of building structures than those covered in this study to identify crucial assessment factors. Moreover, adopting different MCDA approaches will ensure a comprehensive measurement of all relevant factors through a comparative analysis of the results. Lastly, economic considerations still dominate the selection criteria for building structural systems and need further elaboration. It is crucial to note that structural engineers often prioritize cost considerations over strict adherence to green building codes when circumstances require it. This prioritization arises from the industry's focus on short-term financial gains rather than long-term sustainability goals.

In conclusion, this research makes a substantial contribution to sustainable structural design by introducing a systematic method for evaluating multiple criteria. The adaptability of the proposed model and the validation of the MCDA approach underscore its potential as a valuable tool for engineers. Further development and testing of the framework on diverse building structures will enhance its robustness and applicability, ultimately contributing to the creation of more sustainable built environments. Future studies can refine this framework, ensuring precise and comprehensive assessments by incorporating additional criteria and employing various MCDA methods. This research shows that MCDA methods are effective in guiding engineers in improving sustainable design selection processes. The validated decision model proposed in this study can be applied to similar projects and evaluating different structural systems, providing a robust framework for enhancing sustainability in engineering practices. This research thus provides a foundation for advancing sustainable practices in structural engineering, benefiting both the profession and society at large.

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

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

Acknowledgments: The authors deeply acknowledge the technical and financial support from the Engineering Institute of Technology.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Questionnaire 1: Validating the selection of the sustainability indicators

From your perspective, how important are the following indicators to the sustainability performance assessment of alternatives? Please indicate whether you Strongly agree (SA), Agree (A), Neutral (N), Disagree (D), or Strongly disagree (SD) that each performance indicator is essential.

Expert's Opinion	Strongly Disagree SD	Disagree D	Neutral N	Agree A	Strongly Agree SA
A.1 CO ₂ emission	☐	☐	☐	☐	☐
A.2 Energy efficiency	☐	☐	☐	☐	☐
A.3 Land use	☐	☐	☐	☐	☐
A.4 Abiotic depletion potential	☐	☐	☐	☐	☐
A.5 Acidification potential	☐	☐	☐	☐	☐
A.6 Eutrophication potential	☐	☐	☐	☐	☐
B.1 Revenue generation	☐	☐	☐	☐	☐
B.2 Total cost	☐	☐	☐	☐	☐
B.3 Landfill-cost savings	☐	☐	☐	☐	☐
C.1 Job creation	☐	☐	☐	☐	☐
C.2 Noise emission	☐	☐	☐	☐	☐
C.3 Human toxicity	☐	☐	☐	☐	☐
C.4 Health and Safety	☐	☐	☐	☐	☐
C.5 Social Commitment	☐	☐	☐	☐	☐
C.6 Information Disclosure	☐	☐	☐	☐	☐

Appendix B

Sample of the Questionnaire

Dear respondent,

The following questionnaire is crafted to explore the selection criteria for contractors. Your input will aid us in determining the significance of various factors such as “good records,” “financial capabilities,” “planning and project control abilities,” and “technical expertise” in

the contractor selection process. Additionally, your insights will help establish the relative weights of relevant sub-criteria associated with these main criteria. Your participation is invaluable to this research, and your time and contribution are greatly appreciated.

In this study, the comparative values of criteria and sub-criteria are denoted by options A to E for relative assessment.

A: Very more important

B: More important

C: Equally important

D: Less important

E: Very less important

The following questions assess the comparative importance of specific criteria in the selection of contractors.: “environmental”, “social”, and “economic”.

Please indicate the relative importance of each criterion by checking the appropriate boxes:

1. How important is the criterion of “environmental” as compared with the criterion of “social”?

A ☐ B ☐ C ☐ D ☐ E ☐

2. How important is the criterion of “environmental” as compared with the criterion of “economic”?

A ☐ B ☐ C ☐ D ☐ E ☐

3. How important is the criterion of “economic” as compared with the criterion of “social”?

A ☐ B ☐ C ☐ D ☐ E ☐

The following questions compare with each other the importance of the following sub-criteria relating to the criterion of “Construction, Maintenance, Management, CO₂ emission, Energy consumption, Waste, Noise, Aesthetic, Safety”.

Please indicate the relative importance of sub-criteria by checking the appropriate boxes.

4. How important is the criterion of “Construction” as compared with the criterion of “Maintenance”?

A ☐ B ☐ C ☐ D ☐ E ☐

5. How important is the criterion of “Maintenance” as compared with the criterion of “Management”?

A ☐ B ☐ C ☐ D ☐ E ☐

6. How important is the criterion of “Construction” as compared with the criterion of “Management”?

A ☐ B ☐ C ☐ D ☐ E ☐

7. How important is the criterion of “CO₂ emission” as compared with the criterion of “Energy consumption”?

A ☐ B ☐ C ☐ D ☐ E ☐

8. How important is the criterion of “CO₂ emission” as compared with the criterion of “Waste”?

A ☐ B ☐ C ☐ D ☐ E ☐

9. How important is the criterion of “Energy consumption” as compared with the criterion of “Waste”?

A ☐ B ☐ C ☐ D ☐ E ☐

10. How important is the criterion of “Noise” as compared with the criterion of “Aesthetic”?

A ☐ B ☐ C ☐ D ☐ E ☐

11. How important is the criterion of “Safety” as compared with the criterion of “Aesthetic”?

A ☐ B ☐ C ☐ D ☐ E ☐

12. How important is the criterion of “Safety” as compared with the criterion of “Noise”?

A ☐ B ☐ C ☐ D ☐ E ☐

Perhaps the questions in this questionnaire are limiting your ability to fully express your thoughts on the selection criteria for contractors. If that’s the situation, please feel free to share your views in the provided space below.

Personal data:

Name: Surname:

Place of service: Organizational position:

Work record:

Date when the questionnaire was filled out:

Your highest educational degree:

High school diploma ☐ Associate’s degree ☐

Bachelor’s degree ☐ Master’s or a higher degree ☐

Lower ☐

In which one of the following fields do you have experiences?

Technical and commercial committee ☐ Contract affairs ☐

Project execution ☐ Practices of contractors ☐

How long did you work in the above fields?

Less than a year ☐ One to three years ☐

More than three years ☐

Thank you for your honest cooperation. Please review the questionnaire again to ensure that no questions were overlooked, and then kindly return

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