Multi-Criteria Decision-Making approach for assessing the sustainability of the innovative pin-connected structural system

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Abstract

Structural design is essential for minimizing environmental impacts by encouraging the reuse of resources, recycling materials, and reducing waste and pollution in construction projects. Compared to traditional approaches, sustainable design more effectively supports sustainability objectives. Nonetheless, the decision-making process can be complicated due to differing preferences among clients, architects, and engineers. This research aims to develop a decision-making framework to assess sustainability in the initial phases of structural design. Multi-Criteria Decision-Aiding (MCDA) techniques are utilized to facilitate regulatory choices, with the Fuzzy Analytic Hierarchy Process (FAHP) employed to identify the best solution. Three structural system alternatives—one innovative and two conventional—are evaluated based on economic, social, and environmental criteria. A literature review and expert feedback reveal nine sub-criteria for prioritizing sustainability factors. The FAHP findings indicate that the economic impact is the most significant criterion for assessing the sustainability of structural systems, followed by environmental concerns, while social aspects are the least important. This research emphasizes the potential of MCDA methods to assist engineers in enhancing the selection process for sustainable design, with the proposed framework validated for application in similar future projects.

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

1. INTRODUCTION

The construction industry was responsible for 36% of global energy demand and 37% of energy-related CO_2 emissions in 2020, according to the '2022 Global Status Report for Buildings and Construction.' The Paris Agreement emphasizes the urgent need for the global construction sector to achieve decarbonization by 2050. With emissions from construction materials projected to more than double by 2060, building sectors must improve access to clean fuels, reduce energy consumption, and increase renewable energy use. Sustainable design frameworks, such as BREEAM (UK), LEED (US), and others, set benchmarks for environmentally responsible practices (Rebelatto, B.G 2024). Structural engineers, whose work influences over 50% of carbon emissions in construction, are crucial for achieving carbon neutrality. Inspired by the SE 2050 Challenge, engineers are urged to address embodied carbon benchmarks. However, the focus in structural design often remains on economic benefits, neglecting social and environmental impacts. Many green building initiatives emphasize material selection, overlooking the importance of structural system choices, especially for buildings like long-span industrial structures. The lack of standards for sustainable structural systems presents a challenge.

This paper reviews sustainability practices in construction and structural design, aiming to develop a framework for selecting sustainable structural systems. The study seeks to enhance current green building assessments, providing engineers with comprehensive guidelines for sustainable design, by identifying and prioritizing criteria through a multi-criteria decision-making method.

2. LITERATURE REVIEWS

This section presents a comprehensive literature review of the proposed methodologies, focusing on their applications in the field of building design. The review emphasizes sustainable design and system selection in construction, while also highlighting the use of multi-criteria decision-making approaches to assess building sustainability. These approaches aim to assist designers in selecting systems and materials for construction projects.

2.1. Structural system Sustainability Assessment

Pin connections are extensively used in steel construction due to their advantages, including ease of reuse, retrofitting, and assembly. Research on their mechanical properties has facilitated widespread adoption in the steel industry, emphasizing their structural integrity and architectural aesthetics. However, sustainability considerations for pin connections are often overlooked, and existing green building regulations inadequately assess this system. Current green building rating systems, such as LEED, BREEAM, and others, do not evaluate life cycle indicators specifically for structural design (Jianwei Ma, 2024). As a result, buildings certified by these systems often lack comprehensive economic, environmental, and social indicators. Addressing this gap is crucial. Sustainable structural design can significantly reduce carbon emissions and environmental impact by selecting suitable structures and materials. Integrating sustainability principles, such as the use of eco-friendly materials and energy-efficient construction methods, from the early design phases can enhance project sustainability. This approach promotes environmental responsibility and long-term ecological balance. A systematic approach to incorporating sustainable criteria in the design phase is essential to advance the field and ensure more holistic and resilient built environments.

2.2. Sustainable Criteria for structural system Selection

In recent decades, various articles, books, and consulting reports have introduced a wide range of definitions for "sustainability" and its practical implications. Typically, sustainability is measured using three key indicators: social, ecological, and economic. Different frameworks have been developed for specific purposes and contexts, though most focus on these three pillars (Mahak Sharma, 2023). According to the literature, a comprehensive set of criteria for selecting structural systems is still lacking. A sustainability assessment framework for material selection in construction has been implemented through the BIM and Fuzzy AHP approach, targeting three impact categories (Alam Bhuiyan, 2023). Moreover, technological, cultural, and policy factors are increasingly relevant to social, ecological, and economic aspects (Anjamrooz, T., 2024; Ma Jw, 2024).

The MCDA method has been extensively applied in the construction industry to develop effective and sustainable solutions. The FAHP enhances the traditional AHP by integrating fuzzy set theory, which utilizes fuzzy numbers instead of precise values in the analysis of hierarchical structures. The FAHP, by incorporating fuzzy logic, addresses uncertainties and ambiguities in human judgment, making it a more reliable option for complex decision-making situations.

3. MATERIALS AND METHODS

This study adopted an exploratory sequential design for the collection and analysis of both quantitative and qualitative data. As illustrated in Figure 1, the research unfolded in two distinct phases: a qualitative phase and a subsequent quantitative phase. According to Lutangu Munga (2024), an initial qualitative phase was employed at the onset of this design for data collection and analysis, succeeded by a quantitative phase for the same purpose. Following these phases, there ensued a final phase where data from both qualitative and quantitative phases were integrated. Figure1 describes the three phase of data analysis and shows the process of research design.

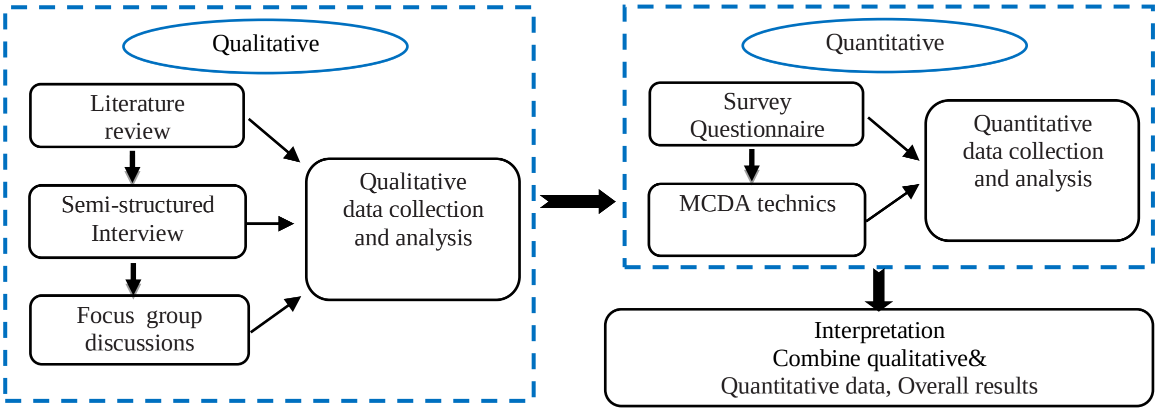

Figure 1. The process of research design

4. SUSTAINABILITY ASSESSMENT TO SELECT THE STRUCTURAL SYSTEM

4.1. Structural systems(alternatives) description

In this paper, Jw. Ma (2024) proposed a novel pin-connection joint (illustrated in Figure 2) for truss-column connections in an industrial building, designed to support the floor system under heavy loads in a long-span steel structural system (alternative a). Traditional welded and bolted connections (alternative b) were deemed inadequate in meeting stakeholder requirements. Additionally, a conventional concrete structural system (alternative c) was considered as another potential solution for this type of project.

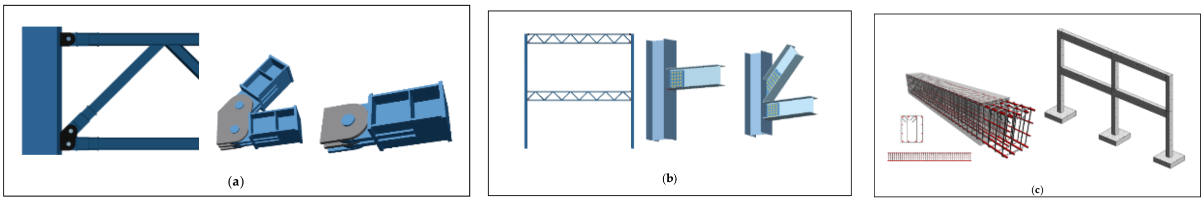

Figure 2. Structural system. (a) Pin connection for a long-span steel structure; (b) traditional connections for a long-span steel structure; (c) traditional concrete structural system

4.2. Fuzzy AHP application

The AHP and Fuzzy-AHP are commonly used to assign weights to various criteria and rank alternatives in multi-criteria decision-making methods. Fuzzy-AHP extends AHP by integrating fuzzy sets into the pairwise comparison process, enhancing the handling of uncertainties in decision-making (Ming-Yang Xu, 2023). A relative importance scale (ranging from 1-9 and 1/9-1), as shown in Table 1, is applied to assess comparison values. In this study, Fuzzy-AHP values will be used for the analysis.

Table 1. Definition of the fuzzy scale

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

To demonstrate the applicability of the proposed sustainable performance evaluation framework for designing a structural system, a case study is presented to select an appropriate structural system. Figure 3 outlines the step-by-step process for implementing this methodology.

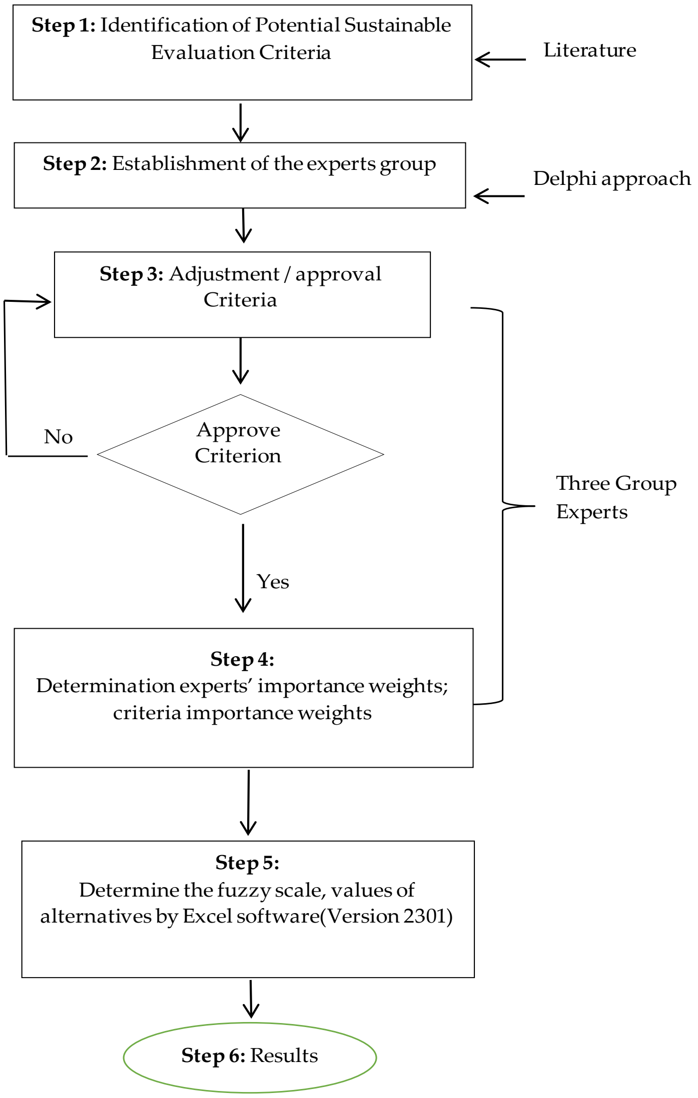

Figure 3. Proposed Step-by-Step Approach

Step 1. Constructing the hierarchical structure: main- criteria and sub-criteria for sustainability evaluation of structural systems are identified by considering both the literature review and the expert opinions to build a framework. The hierarchical structure is presented in Figure 4.

Steps 2 & 3: Data Collection: In this phase, questionnaires are created as pairwise comparison matrices and assessed by three experts for the subsequent step. The questionnaires are designed to gather evaluation data for the alternatives, which is then represented in matrix format as a MCDM problem, encompassing m alternatives and n criteria at the lowest level of the hierarchy.

Step 4: Determining the Weights of Experts and Evaluation Criteria: Pairwise comparisons are conducted to generate fuzzy comparison matrices. In this context, all expert groups are considered equally important in the decision-making process.

Step 5 &6. Calculating the results and analysis by using equations as shown below:
The pairwise comparison matrix (r_{ij} is the normalized performance rating of alternatives on attribute C_i, A_i; i = 1,2, ..., n and j = 1,2, ..., n):

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

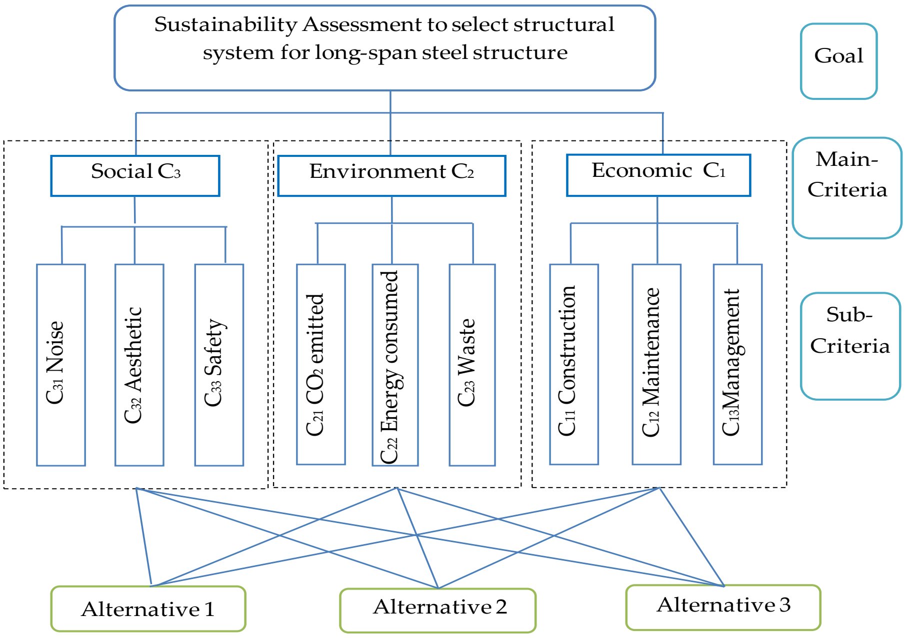

Figure 4. **The hierarchical structure of a sustainable design**

Fuzzy weight factor dimensions can be obtained: : $\tilde{u}_i = (\tilde{r}_{i1} \odot \tilde{r}_{i2} \odot \ldots \odot \tilde{r}_{in})^{1/n}$ (2)
The final fuzzy weight factors can be determined using the following formula:

$$\widetilde{w}_i = \tilde{u}_i \odot (\tilde{u}_{i1} \oplus \tilde{u}_{i2} \oplus \ldots \oplus \tilde{u}_{in})^{-1} \quad (3)$$

Final fuzzy weight factors: $w_i = \left[\left(w_i^u - w_i^l\right) + \left(w_i^m - w_i^l\right)\right]/3 + w_i^l$

(Where $\widetilde{w_i} = (w_i^l, w_i^m, w_i^u)$). (4)

And the normalized weight vector by applying equation: $w_{ni} = \frac{w_i}{\sum_{i=1}^{n} w_i}$ (5)

5. RESULTS AND SENSITIVITY ANALYSIS

5.1 Results

In this section, we will present and discuss the results obtained from the FAHP method, as outlined in section 4.2. The MCDA approach and framework model were explained in section 4. The criteria weights for the evaluation matrices, including both local and global weights, are shown in Table 2. In this study, it is assumed that all Expert Groups assign equal weights. The fuzzy decision-making matrix, which includes the global weights of all sub-criteria derived from the FAHP, is constructed to evaluate and rank the alternatives (as illustrated in Table 2).

Table 2. Final ranking results

Sub – criteria	Global weigh	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

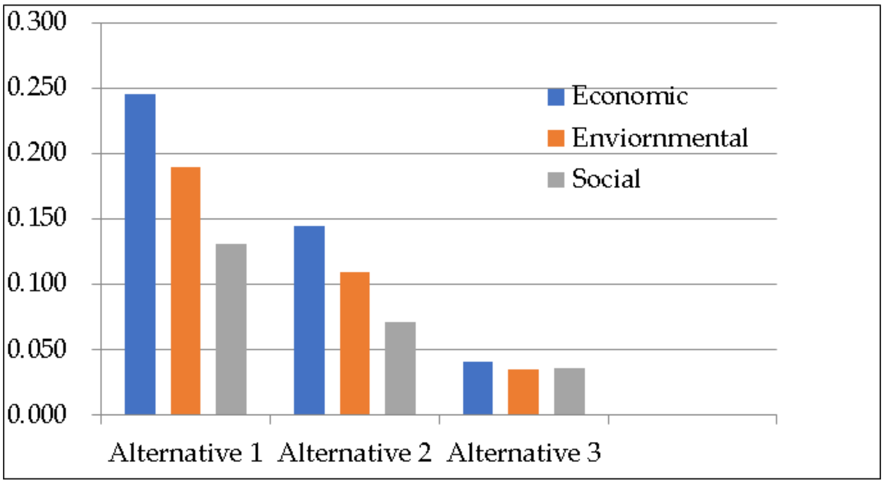

Figure 5. Final ranking

From Table 2 it can be seen, weights within all criteria levels and importance ranking for three alternatives have been exhibited. 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 - CO_2 Emission (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 5 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. In consequence, structural engineers shall put in more resources to improve the contributions of top-ranked criteria during the early design stage.

The overall totals for each alternative (A1, A2, A3) reflect their combined weights across all sub-criteria, with A1 having the highest total weight of 0.432, followed by A2 with 0.333, and A3 with 0. 236.Based on these rankings and weights, the alternatives are ranked accordingly, with A1 being the most preferred, followed by A2 and then A3.

5.2 Sensitivity Analysis

Sensitivity analysis has been conducted to determine the impacts of global weights for each criterion or sub-criteria vary (as depicted in Table 3, Figure 6). The effects of the final results can be reflected by sensitivity analysis if the input data are modified, including changes in 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. Most stakeholders and experts emphasized 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 impacts on the sustainability development, so it was ranked the lowest levels for all the three alternatives (as illustrated in Figure 6). Construction, maintenance and management was ranked the most important aspect by the majority of the experts for all of the alternatives. Economic has a prominent place in the process of structural sustainable design. Similar to economic indicator, CO2 emission, waste and energy, the experts gave a high ranking for all three alternatives. Sub criteria (aesthetics, noise and safety) for social aspects, three alternatives have some slight differences, but lowest rankings.

Table 3. 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

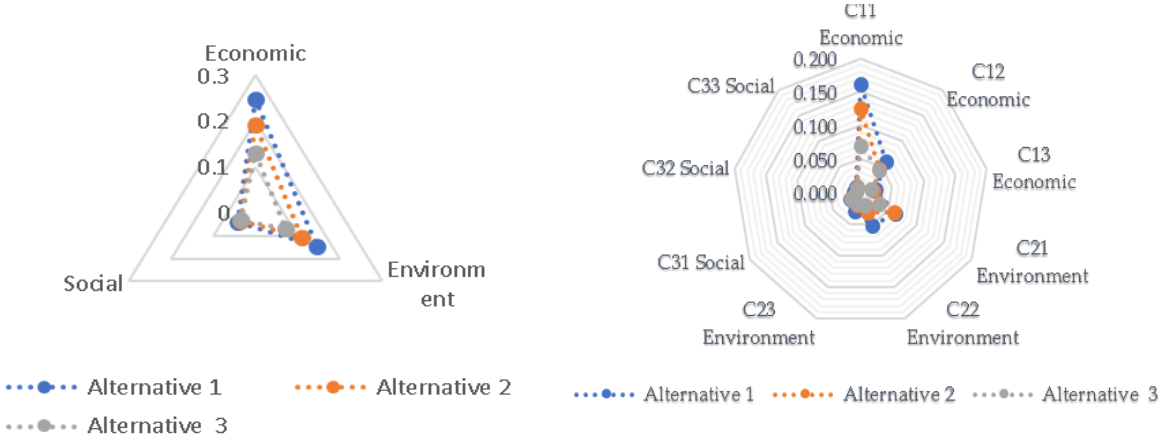

Figure 6. Alternative and Criteria sensitivity analysis

6. CONCLUSIONS

This research presents a sustainable design process for building structural systems by assessing their environmental, social, and economic impacts through multi-criteria decision-making (MCDA). Nine perspectives on structural design are organized into three main criteria: environmental, social, and economic. Sustainability assessments are conducted on three alternative structural solutions, comprising one innovative system and two traditional options. The conclusions emphasize:

- The framework aids engineers in selecting the most efficient system by considering diverse factors.
- The validity of the MCDA approach is affirmed, supporting new structural system development.
- The hierarchical model is flexible, enabling users to adjust it without limiting the alternatives.

This research provides valuable insights for engineers and society by improving the capacity of structural design to reduce negative impacts. Future efforts should focus on broadening the framework by incorporating additional criteria and applying it to different building types, while utilizing various MCDA methods to enhance accuracy.

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