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ORIGINAL CONTRIBUTION

Assessment of Qualitative Performances of Structures in Architecture, Case Studies: Space Frame Structures in Tehran, Iran

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Abstract The main goal of this research is to create an advanced framework for evaluating the performance of architectural structures. Structures have various functions beyond just providing support, stability, and cost-efficiency. This study suggests using state-of-the-art numerical analysis to assess the quality of structures in architecture. It focuses on evaluating the qualitative performance of space frame structures in Tehran, using five prominent case studies. The assessment encompasses mechanical performance, environmental performance, aesthetics and meaning performance, spatial considerations, and economic factors, utilizing a multi-criteria decision-making method. In this research, the Delphi method is used to determine the primary criteria. Then, the Analytic Hierarchy Process (AHP) is employed to assign weights to each criterion and rate each case study accordingly. The scores are then used to rank the case studies. The analysis showed that Milad Tower received the highest overall score, followed by Imam Khomeini International Airport. The Tehran International Exhibition Center and Tehran Book Garden also demonstrated strong performances in specific areas. However, Azadi Stadium had the lowest overall score. Milad Tower showed the most balanced performance across various criteria. These results emphasize the importance of considering multiple factors when evaluating architectural structures.

Keywords Structural performances · Quantitative assessment · Qualitative performances · Space frame structures · Tehran architecture

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Introduction

Throughout history, humans have strived to build durable and secure homes. In architecture, a structure has roles beyond bearing load and resisting forces [10]. Efficiency and elegance are important factors in engineering a structure. The final shape of a structure is a compromise between these factors and aesthetics. Santiago Calatrava integrates engineering and architectural expression to prioritize aesthetics [15]. According to leading thinkers, a building's structure is an integral part of architecture with functions including environmental effects, aesthetics, usefulness, style, social effects, sustainability, and resistance [2].

Space frame structures are widely used in modern architecture due to their effectiveness and appealing aesthetics. In Tehran, several significant space frame structures showcase these characteristics. This paper aims to analyze and compare these structures based on qualitative performance criteria. The study seeks to both evaluate the performance of space frame structures and identify the strengths and weaknesses of each structure's performance.

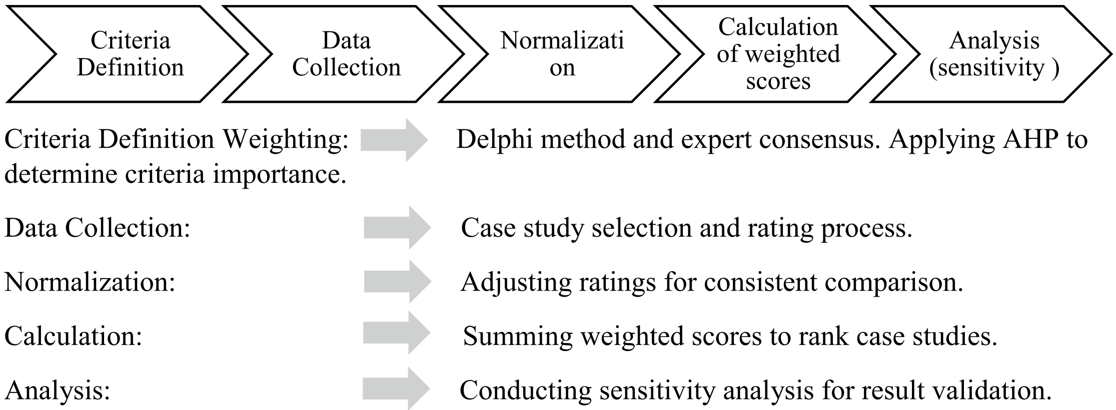


Fig. 1 Research Method Process from Authors

Literature Review

Research on space frame structures has provided valuable insights into their structural efficiency, environmental impact, aesthetic value, and economic performance. However, much of the literature focuses on specific aspects, often neglecting the need for a holistic evaluation that incorporates multiple criteria. This literature review critically evaluates key studies and identifies areas where further research is required.

Structural Efficiency and Performance

Space frame structures are widely recognized for their load-bearing capacity and structural efficiency. [14] demonstrated that space frames are effective in spanning large distances while minimizing material usage, making them particularly suitable for large-scale buildings. These findings are supported by [3], who emphasized the adaptability of space frames in seismic zones, highlighting the importance of designing for safety and durability in earthquake-prone regions. While these studies underscore the strength of space frame structures in handling large loads and seismic stresses, they primarily focus on mechanical performance.

Environmental Impact

[6] Provided a comprehensive analysis of the environmental benefits of space frame structures, noting their efficient use of materials and potential to reduce the carbon footprint of buildings. They argue that space frames can optimize natural lighting and ventilation, contributing to both energy efficiency and user comfort. [5] Extended this analysis, demonstrating that space frames can result in significant energy savings. Few studies have considered how environmental factors interact with other performance criteria.

Aesthetic and Spatial Qualities

The geometric flexibility of space frames has been praised for enabling innovative architectural designs. [7] Highlighted their ability to create iconic architectural landmarks, while Wang and [16] focused on how space frames support open, adaptable spaces, particularly beneficial in public buildings. Existing studies tend to treat aesthetics as a secondary consideration, with little attention paid to how architectural form can simultaneously serve functional, environmental needs.

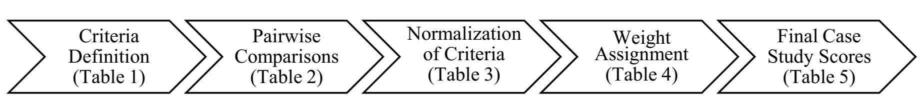
Economic Considerations

From an economic perspective, [11] found that while space frames often have higher initial costs, the long-term savings in maintenance and operational costs frequently outweigh the upfront investment. Similarly, [1] performed a cost–benefit analysis of space frame structures, emphasizing their economic advantages Although these findings underscore the economic efficiency of space frames over time, they often fail to account for context-specific challenges.

Research Gaps

While previous studies offer valuable insights into individual performance metrics of space frame structures, several research gaps remain:

Fig. 2 Methodological flow from Delphi results to final scores



Most studies overlook the importance of user experience and how spatial flexibility impacts the overall functionality of space frames in public and commercial buildings. The economic analysis of space frames largely focuses on developed countries, leaving a gap in understanding how these structures perform in regions with budget constraints and socioeconomic challenges Figs. 1 and 2.

The research aims to answer the following questions:

How can space frame structures be evaluated across multiple qualitative performance criteria?
How does the integration of environmental, mechanical, and spatial considerations affect the holistic performance of space frame structures?

Research Method

This research employs the Delphi method and the Multi-Criteria Decision-Making (MCDM) approach to assess and compare the qualitative performances of space frame structures. The methodology consists of several critical steps, detailed below:

Defining and Weighing Criteria

The Delphi method was used to refine the selected variables, resulting in five key performance criteria. These criteria were assigned weights through expert consultations. A panel of 27 civil and architectural engineers participated in the rating process using a Likert scale. Finally, weights for each criterion were assigned based on their relative importance using Saaty's Analytic Hierarchy Process (AHP). The criteria with the highest significance were given larger weights, reflecting their influence on the overall performance assessment.

Collecting Data

Data was collected through case studies of five prominent space frame structures in Tehran: Milad Tower, Tehran International Exhibition Center, Tehran Book Garden, Imam Khomeini International Airport, and Azadi Stadium. Expert ratings on a scale of 1 to 10 were gathered for each criterion across these case studies.

Normalizing Ratings

To ensure consistency across all case studies, the ratings for each criterion were normalized. This process adjusted for differences in rating scales and units of measurement. The formula used for normalization was: $\text{Normalized Score} = \frac{\text{Raw Score}}{\text{Sum of All Scores for the Criterion}}$

This method ensured that each case study's score was proportionally weighted, allowing for fair comparisons between structures.

Applying Weights and Calculating Scores

The normalized scores for each criterion were then multiplied by their assigned weights to obtain weighted scores. The total score for each case study was calculated by summing the weighted scores across all criteria. This step allowed for the integration of the expert panel's evaluations into a comprehensive ranking system, reflecting the relative performance of each structure. The weighted score formula is as follows: $\text{Weighted Score} = \text{Normalized Score} \times \text{Weight of Criterion}$.

For example, if the normalized score for "Mechanical Performance" was 0.20 and its weight was 0.423, the weighted score would be: $0.20 \times 0.423 = 0.0846$.

Analyzing Results

After calculating the total scores, the case studies were ranked based on their overall performance. A sensitivity analysis was conducted to assess how changes in criterion weights impacted the rankings, ensuring the robustness of the results. This analysis helped provide a clearer understanding of the influence of each criterion on the overall rankings, allowing the identification of key factors that contributed most to the structures' performances.

Defining and Weighing Criteria

The Delphi process can be iterated continuously until an agreement is reached. However, according to a study by Custer [8], it is typically possible to collect the necessary data and reach an agreement within three iterations. In this research, twenty-seven experienced civil and architectural engineers, holding advanced degrees and with over twenty years of practical experience, rated each factor using a Likert scale. Among these experts, 15 are university professors. Following a comprehensive literature review and research background, the factors affecting the structural performance of architecture were identified and categorized into 4 primary criteria and 51 sub-criteria. Experts were asked to evaluate each factor based on a Likert rating scale.

This process was repeated three times, with experts adding or removing criteria and sub-criteria. Finally, five primary criteria and 30 sub-criteria were identified. The mean scores of each factor were then calculated. Any factor with a mean score lower than 3 was eliminated from the final list. It is also noteworthy to state that the number of Delphi

Table 1 Delphi result, main criteria detection from Authors

No	Dimension	Index	Number of responses	Minimum Score	Maximum Score	Mean	Standard Deviation
1	Environmental Performance	Amount of energy consumed	27	2	5	4.14	1.21
2		Amount of carbon dioxide production	27	1	5	3.43	1.72
3		Amount of waste production	27	2	5	3.14	1.07
4		Amount of water consumption	27	2	3	2.43	0.53
5		Possibility of using daylight	27	1	4	1.86	1.46
6	Mechanical Performance	Geometrical stability	27	6	8	7.43	0.98
7		Structural efficiency	27	5	8	6.29	1.25
8		Resistance of materials	27	4	8	6.14	1.35
9		Physical aspects (resistance to fire, corrosion, rust and durability)	27	1	6	4.14	1.68
10		formability	27	1	7	3.57	2.30
11		Hardness	27	3	6	3.86	1.07
12		Repairability	27	1	6	2.71	1.70
13		Computability	27	1	3	1.71	0.76
14	Beauty and Meaning Performances	Beauty	27	4	5	4.71	0.49
15		Proportions	27	2	5	3.71	0.95
16		Architectural style	27	1	4	2.29	1.11
17		Community acceptability	27	1	5	2.43	1.51
18		Signs	27	1	3	1.86	0.69
19	Functional and Spatial Performances	Development ability	27	4	6	5.29	0.76
20		Geometric order	27	1	6	3.86	2.19
21		Optimal space	27	1	6	3.57	1.81
22		Spatial organization	27	1	6	3.86	1.46
23		Sense of safety	27	1	4	2.43	0.98
24		Flexibility	27	1	3	2.00	0.82
25	Economic Performance	Indigenous technology	27	2	6	5.00	1.53
26		Ease of construction	27	4	6	4.86	0.69
27		Level of assembly technology	27	1	6	3.57	1.51
28		Possibility of mass production	27	2	5	3.14	1.07
29		Prefabricated construction	27	1	6	2.43	1.72
30		Transportation	27	1	5	2.00	1.53

iterations is mostly dependent on the level of consensus pursued by the researchers being in the range of 3–5 [9, 4]. It is this research, after third iteration for stable results, the authors decided to discontinue the iterations and make final decision after third round.

The reliability of the questionnaire was assessed using Cronbach's alpha in SPSS software, which is a widely used measure of internal consistency. This method was chosen to ensure that the items in the questionnaire were consistently measuring the intended criteria. A Cronbach's alpha value above 0.7 was considered acceptable, indicating good internal consistency across the expert responses.

The dimensions and indexes in Table 1 were identified through a systematic process that combined insights from the existing body of knowledge with the practical expertise of professionals in the field. The Delphi method allowed for the refinement and validation of these dimensions. This approach provided a robust framework for assessing multiple aspects of structural performance.

Step 1: Comprehensive Literature Review:

The first step in identifying the dimensions and indexes was conducting a thorough review of the existing literature on the performance of space frame structures and architectural evaluation frameworks. The literature review helped to compile an initial list of factors or dimensions that were repeatedly highlighted as significant in evaluating structural performance.

Step 2: Expert Consultation:

After the literature review, the Delphi method was applied, relying on the expertise to validate and refine the dimensions identified from the literature. The experts were asked to evaluate and modify the dimensions and indexes,

Table 2 pairwise comparison matrix for the criteria from research experts

Criterion	Mechanical Performance	Environmental Performance	Beauty and Meaning Performance	Functional and Spatial Performance	Economic Perfor-mance
Mechanical Performance	1	4	3	3	2
Environmental Performance	0.25	1	0.5	1	0.5
Beauty and Meaning Performance	0.33	2	1	1	0.5
Functional and Spatial Performance	0.33	1	1	1	0.5
Economic Performance	0.5	2	2	2	1

Next, each element was divided by the sum of its column to normalize the matrix [13]

Table 3 normalize matrix of the criteria from Authors

Criterion	Mechanical Performance	Environmental Performance	Beauty and Meaning Performance	Functional and Spatial Performance	Economic Performance
Mechanical Performance	0.4	0.4	0.6	0.6	0.4
Environmental Performance	0.1	0.1	0.2	0.2	0.1
Beauty and Meaning Performance	0.13	0.2	0.1	0.2	0.1
Functional and Spatial Performance	0.13	0.1	0.1	0.2	0.1
Economic Performance	0.2	0.1	0.2	0.4	0.2

adding any missing factors or removing those they deemed irrelevant or redundant. The experts also helped prioritize the most significant factors.

Explanation on Dimensions and Indexes

1. Environmental Performance

Environmental performance plays a critical role in sustainable architecture and measures how a structure impacts the environment. The five sub-criteria in this dimension reflect key environmental factors.

2. Mechanical Performance

Mechanical performance ensures the structural integrity and physical durability of a building. The sub-criteria focus on how the building withstands forces and environmental conditions.

3. Beauty and Meaning Performances

Table 4 the average for the rows from Authors

Criterion	Weight
Mechanical Performance	0.423
Environmental Performance	0.089
Beauty and Meaning Performance	0.110
Functional and Spatial Performance	0.110
Economic Performance	0.078

This dimension emphasizes the aesthetic and cultural aspects of architecture, focusing on how a structure is perceived by its users and society.

4. Functional and Spatial Performances

This dimension assesses the practical usability and spatial efficiency of the building. It focuses on how well the structure fulfills its intended function while providing flexibility and safety for its occupants.

5. Economic Performance

It evaluates the cost-effectiveness of the structure, considering both initial construction costs and long-term operational expenses. The criteria here emphasize practicality and efficiency.

The mean reflects the central tendency or the average rating given by experts for each criterion.

The standard deviation indicates the variability or dispersion of expert ratings from the mean. A lower standard deviation suggests a higher consensus among experts, while a higher standard deviation implies greater disagreement or variability.

Next, the following steps were taken:

The Table 1 (Delphi results) forms the basis for all subsequent tables. The criteria detected via Delphi are compared and weighted through pairwise comparisons (Table 2), normalized (Table 3), assigned weights (Table 4), and ultimately used to calculate the final case study scores in Tables 5, 6, 7, 8 and 9.

Table 5 ratings for the case studies done by the research experts from Authors

Case Study	Mechanical Performance	Environmental Performance	Beauty and Meaning Performance	Functional and Spatial Performance	Economic Performance
Milad Tower	9	6	9	8	7
Exhibition Center	8	5	6	9	8
Book Garden	7	8	9	9	7
Airport	8	4	8	7	9
Azadi Stadium	7	6	6	8	8

To comparisons. The experts rated the following pairwise comparison matrix based on importance. [12]

In addition, calculations to determine the average for each row were performed, which allowed to obtain the respective weights.

Normalization of Scores: To make the scores comparable across all criteria, the ratings need to be normalized. The formula for normalizing the score for each criterion *i* is:

Normalized Score $_{i=}\frac{\text{Raw Scorei}}{\sum \text{Raw Scores}}$

For example, the normalized score for the "Amount of energy consumed" in Environmental Performance (mean = 4.14) would be:

Normalized Score for Energy $= \frac{414}{\sum \text{Raw Scores for Environmental Performance}}$

The sum of all raw scores for the Environmental Performance criteria is:

$4.14 + 3.43 + 3.14 + 2.43 + 1.86 = 14.00.$

Therefore, the normalized score for "Amount of energy consumed" would be: $\frac{4.14}{14.00}$=0.296.

Weight Calculation Using AHP: Once the normalized scores are calculated, AHP assigns weights to each criterion. Experts compare the importance of criteria in pairwise comparisons, resulting in a comparison matrix. The experts rated the importance of the Environmental Performance dimension relative to Mechanical Performance. The comparison results in weights:

$W_{\text{Mechanical Performance}} = 0.50$ $W_{\text{Environmental Performance}} = 0.25.$

The final weight for each criterion ("Geometrical stability" under Mechanical Performance) is calculated by multiplying the normalized score by the overall weight of the dimension:

$W_{\text{Geometrical Stability}}$ = Normalized Score for Geometrical Stability $\times W_{\text{Mechanical Performance}}$.

For Geometrical Stability, with a mean of 7.43 and assuming a total sum of raw scores for Mechanical Performance is: $7.43 + 6.29 = 13.72.$

The normalized score for "Geometrical Stability" would be: $\frac{7.43}{13.72}$=0.541.

Mechanical Performance was assigned a weight of 0.423 through the AHP process, the final weight for "Geometrical Stability" would be: $0.541 \times 0.423 = 0.229.$

This means "Geometrical Stability" contributes approximately 22.9% to the total weight of Mechanical Performance.

Combining Weights Across Criteria: The final score for each case study is calculated by multiplying the normalized scores by the weights assigned to each criterion and summing them across all criteria.

For any criterion *i*: $W_{\text{Criterion}} = \left(\frac{MeanofCriterion}{\sum MeanScoresofDimension}\right).$

Research experts have assigned ratings on a scale of 1–10 for each case study. A 1–10 scale provides sufficient granularity, enabling experts to distinguish between closely related performance levels.

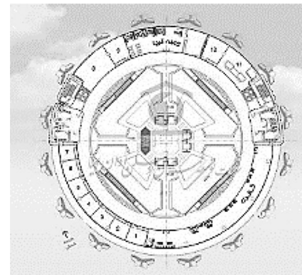
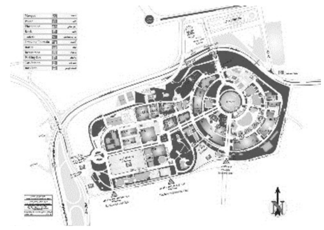
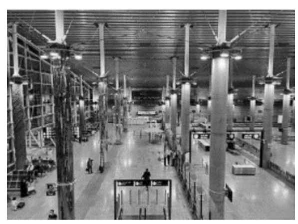
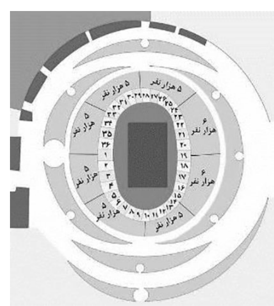
Collecting Data

The selected case studies offer a comprehensive view of space frame structures in Tehran, encompassing functional, aesthetic, and economic aspects. They provide valuable insights into the performance of space frames in different applications and their contributions to the architectural and urban landscape of the city.

The five case studies—Milad Tower, Tehran International Exhibition Center, Tehran Book Garden, Imam Khomeini International Airport, and Azadi Stadium—have been chosen for several reasons. While using a single building type might have provided more consistency in some aspects, the diversity of building types used in this research enriches the study by exploring the full potential of space frame structures in different architectural contexts. It provides a more comprehensive understanding of the performance of space frame structures across varied applications, scales, and design challenges.

Furthermore, each case study offers unique insights into various performance criteria. For example, structures like Milad Tower and Azadi Stadium exemplify high-load and seismic considerations for mechanical performance, while the Tehran Book Garden and Exhibition Center demonstrate how space frames contribute to environmental efficiency and sustainability.

Table 6 Introduction of case studies

Case Study	Description	Pic	Plan
Milad Tower	Milad Tower is the sixth tallest telecommunications tower in the world, standing at 435 m. Its space frame structure efficiently distributes loads, offering **stability** and **resilience** to seismic forces, a critical consideration in Tehran's earthquake-prone region. (caoi, 2024)		
Tehran International Exhibition Center	The Exhibition Center consists of several halls that utilize **space frame structures** to cover large areas without the need for internal supports. This design creates flexible, **unobstructed interior spaces**, ideal for hosting exhibitions and large events. (caoi, 2024)		
Tehran Book Garden	The **Tehran Book Garden** features a unique **space frame roof** that spans the atrium, allowing for a **large, open space** filled with natural light. This design enhances both the aesthetic and functional quality of the structure. (caoi, 2024)		
Imam Khomeini International Airport	The terminal at **Imam Khomeini International Airport** extensively utilizes **space frame structures** in its roof design. This structural system enables a **spacious, column-free environment**. (caoi, 2024)		
Azadi Stadium	**Azadi Stadium** employs **space frame structures** in its roof and seating areas to cover vast spans without the need for many internal columns, ensuring clear sightlines for spectators. This design demonstrates how space frames can provide **structural stability** (Zaker & Eghtesad, 2018)		

The selection of different building serves several key purposes:

Broader Scope of Application

By examining a variety of building types, the research demonstrates the versatility and adaptability of space frame structures across different architectural forms and functional uses. This diversity ensures that the findings can be generalized across a wide range of architectural contexts, enhancing the practical applicability of the research.

Understanding Performance Across Scales and Functions:

Different types of buildings provide insight into how space frame structures perform under various functional requirements and environmental conditions.

Table 7 The normalized rating for case studies on performance from Authors

Case Study	Mechanical Performance	Environmental Performance	Beauty and Meaning Performance	Functional and Spatial Performance	Economic Performance
Milad Tower	9 / 39 = 0.231	6 / 29 = 0.207	9 / 38 = 0.237	8 / 41 = 0.195	7 / 39 = 0.179
Exhibition Center	8 / 39 = 0.205	5 / 29 = 0.172	6 / 38 = 0.158	9 / 41 = 0.220	8 / 39 = 0.205
Book Garden	7 / 39 = 0.179	8 / 29 = 0.276	9 / 38 = 0.237	9 / 41 = 0.220	7 / 39 = 0.179
Airport	8 / 39 = 0.205	4 /2 9 = 0.138	8 / 38 = 0.211	7 / 41 = 0.171	9 / 39 = 0.231
Azadi Stadium	7 / 39 = 0.179	6 / 29 = 0.207	6 / 38 = 0.158	8 / 41 = 0.195	8 / 39 = 0.205

Table 8 the calculations for each performance criterion and the total score for each case study

Case Study	Mechanical Performance	Environmental Performance	Beauty and Meaning Performance	Functional and Spatial Performance	Economic Performance	Total Score
Milad Tower	0.231 × 0.423 = 0.098	0.207 × 0.089 = 0.018	0.237 × 0.110 = 0.026	0.195 × 0.110 = 0.021	0.179 × 0.078 = 0.014	**0.241**
Exhibition Center	0.205 × 0.423 = 0.087	0.172 × 0.089 = 0.015	0.158 × 0.110 = 0.017	0.220 × 0.110 = 0.024	0.205 × 0.078 = 0.016	**0.241**
Book Garden	0.179 × 0.423 = 0.076	0.276 × 0.089 = 0.025	0.237 × 0.110 = 0.026	0.220 × 0.110 = 0.024	0.179 × 0.078 = 0.014	**0.212**
Imam Khomeini Airport	0.216 × 0.423 = 0.091	0.138 × 0.089 = 0.012	0.211 × 0.110 = 0.023	0.171 × 0.110 = 0.019	0.231 × 0.078 = 0.018	**0.226**
Azadi Stadium	0.179 × 0.423 = 0.076	0.207 × 0.089 = 0.018	0.158 × 0.110 = 0.017	0.195 × 0.110 = 0.021	0.205 × 0.078 = 0.016	**0.195**

Table 9 The case studies ranking based on total score from Authors

Rank	Case Study	Normalized Rating
1	Milad Tower	0.241
2	Imam Khomeini Airport	0.226
3	Exhibition Center	0.214
4	Book Garden	0.212
5	Azadi Stadium	0.195

Evaluation of Multiple Performance Criteria:

Each building type allows for a nuanced assessment of various performance criteria such as mechanical performance, spatial and functional performance, environmental efficiency, and aesthetic value.

Diverse Challenges and Solutions:

By selecting buildings with distinct structural challenges, the research demonstrates how space frame structures can be adapted to solve different architectural problems. This allows the study to offer solutions to various challenges in architectural design and construction.

Influence on Urban Development:

The case studies chosen have significantly influenced Tehran's urban landscape, contributing to the architectural identity of the city. Their varied functions—from public landmarks like Milad Tower to functional spaces like the Airport and Exhibition Center—offer insights into how space frame structures can impact both aesthetics and functionality in urban environments.

Normalizing Ratings

Normalize the ratings by dividing each value by the sum of ratings for that criterion.

Sum of ratings for each criterion:

- Mechanical Performance: 9 + 8 + 7 + 8 + 7 = 39.
- Environmental Performance: 6 + 5 + 8 + 4 + 6 = 29.
- Beauty and Meaning Performance: 9 + 6 + 9 + 8 + 6 = 38.
- Spatial and Functional Performance: 8 + 9 + 9 + 7 + 8 = 41.
- Economic Performance: 7 + 8 + 7 + 9 + 8 = 39.

Applying Weights and Calculating Scores

Multiply normalized ratings by the criterion weights and sum for each case study:

Analyzing Results

The Case Studies based on the total scores were ranked as below:

Discussion and Results

The results indicate that Milad Tower ranks highest among the case studies due to its outstanding mechanical performance and economic viability. This is attributed to the tower's advanced engineering, which provides structural stability, resilience against seismic forces, and efficient load distribution. These mechanical advantages are further supported by the economic benefits, such as the tower's ability to demonstrate a balance between initial construction costs and long-term economic returns.

Imam Khomeini Airport also exhibits strong mechanical performance, particularly in its capacity to support span large areas without compromising structural integrity. This underscores the importance of considering mechanical factors, especially in high-traffic public buildings where safety and functionality are paramount.

The International Exhibition Center and Tehran Book Garden performed exceptionally in terms of environmental and spatial performance. Both structures highlight the role of space frame systems in creating large, flexible interior spaces that optimize natural light, contributing to environmental sustainability. These buildings demonstrate how space frames can enhance user experience through flexible design, making them suitable for multi-functional use while reducing energy consumption.

Finally, Azadi Stadium, while functional and mechanically sound, received lower scores in aesthetic and economic performance. This suggests that while space frames provide structural benefits, they may need additional considerations in terms of visual appeal and long-term cost efficiency for large public facilities.

Conclusion

Milad Tower stands out as the top-performing space frame structure in this study, owing to its superior mechanical integrity, load-bearing capacity, and economic sustainability. This research highlights the necessity of a multi-criteria approach to evaluating architectural structures, emphasizing that factors such as environmental impact, user experience, and aesthetic appeal are equally important alongside mechanical performance. The findings underscore the importance of balancing structural efficiency with aesthetic and spatial considerations to achieve optimal performance. Space frame structures, by their nature, offer flexibility and efficiency, but their overall effectiveness depends on their integration with environmental and user-centered design principles.

Implications

The study's findings have important implications for both architectural practice and policy. While mechanical performance remains a critical consideration, the spatial and aesthetic aspects of design significantly influence the overall success of a building. **Practitioners** should adopt a holistic evaluation approach when designing structures, ensuring that mechanical efficiency does not overshadow other performance criteria. This can lead to more sustainable, user-friendly, and economically viable designs that meet a broader range of needs.

For **architects and engineers**, this research suggests that incorporating environmental considerations (such as natural light and energy efficiency) and user experience factors into the design process can enhance both the functionality and attractiveness of structures. Policy makers can use these insights to inform future building regulations and guidelines, ensuring that all new constructions meet balanced performance standards.

Future Study

Future research should address gaps in the current understanding of space frame structures. While this study provided valuable insights, there are several areas where further investigation is necessary:

Long-term performance and durability: More research is needed to evaluate how space frame structures hold up over time, particularly in varying environmental conditions.

User experience and functionality: More work is needed to understand how different users interact with these spaces and how architectural design can improve user satisfaction, safety, and flexibility.

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Data Availability The authors declare that all data, models, codes, and Individual interview transcripts are available from the corresponding author upon request.

Declarations

Conflict of interest The authors declare no known financial or personal relationships that could have influenced this paper.

References

1. M. Ali, S. Hsu, Cost-benefit analysis of space frame structures. J. Build. Perform. **11**(4), 195–210 (2020)

2. L. Beghini, N. Katz, W.F. Baker, G.H. Paulino, Connecting architecture and engineering through structural topology optimization. Elsevier J. **59**, 716–726 (2013)
3. X. Chen, L. Zhang, T. Wang, Performance of space frame structures under seismic loading. Eng. Struct.Struct. **206**, 110319 (2020)
4. A.L. Delbecq, A.H. Van de Ven, D.H. Gustafson, Group Techniques for Program Planning: A Guide to Nominal Group and Delphi Processes, Scott Foresman (1975)
5. R. Garcia, J. Martinez, Energy performance of space frame buildings. J. Build. Perform. **12**(3), 123–135 (2021)
6. A. Khan, J. Lee, Environmental benefits of space frame structures. J. Build. Environ. **146**, 63–72 (2019)
7. S. Lee, J. Kim, H. Park, Aesthetic and design flexibility of space frame structures. Struct. Des. Tall Spec. Build. **26**(5), 1245–1258 (2017)
8. B. Ludwig, Predicting the future: have you considered using the Delphi methodology. J. Ext. **35**(5), 1–4 (1997)
9. B.G. Ludwig, Internationalizing Extension: an Exploration of the Characteristics Evident in a State University Extension System that Achieves Internationalization, The Ohio State University (1994)
10. A.J. Macdonald, *Structural design for architecture* (Architectural Press, Woburn, 1997)
11. R. Miller, P. Roberts, Economic performance of space frame systems. Eng. Struct. **173**, 619–628 (2018)

12 Saaty, T.L. (2008) Decision making with the analytic hierarchy process. Int. J. Serv. Sci. **1**, 83. https://doi.org/10.1504/IJSSCI.2008.017590

13. T. L. Saaty, L. G. Vargas, Models, Methods, Concepts & Applications of the Analytic Hierarchy Process. Int. Ser. Op. Res. Manag. Sci. 130 (2012)

14 J. Smith, R. Jones, Structural efficiency of space frame systems. Struct. Eng. Rev.. Eng. Rev. **25**(2), 45–58 (2018)

15. C. J. Thoume, “A Critical Analysis of Santiago Calatrava’s Bachde Roda Bridge”, Barcelona. Proceedings of Bridge Engineering 2 Conference. University of Bath. UK 2009
16. X. Xu, J. You, Y. Wang, Y. Luo, Analysis and assessment of life-cycle carbon emissions of space frame structures. J. Cleaner Product. **385**, 135521 (2023). https://doi.org/10.1016/j.jclepro.2022.135521