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Evaluation of alternative construction methods for architectural additive manufacturing applications

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Abstract
The development of various construction robots has transformed the architectural landscape, facilitating the design and construction of more unique structures through the implementation of diverse designs. This study explores 13 architectural building applications constructed using the additive construction method, comparing them with traditional construction methods as alternatives. Initial steps involved establishing critical criteria for the construction process through extensive literature review and expert consultations. The significance of these criteria was determined using fuzzy Shannon's Entropy Based on Alpha Level, identifying considerations paramount during the construction phase. Subsequently, the importance degrees of these criteria were instrumental in evaluating potential construction methods for each architectural application using the Fuzzy TOPSIS method, renowned for its efficacy. Findings prioritize building size, construction time, and cost for the architectural applications under review. The comparative analysis revealed that 6 out of the 13 applications constructed with the additive method would benefit more from alternative methods, with the Wood Skeleton method emerging as the superior alternative, closely followed by Concrete Pouring with Mold. Incorporating Fuzzy Shannon's Entropy and the Fuzzy TOPSIS method, it offers a more nuanced and comprehensive assessment of various construction techniques. Furthermore, the study's focus on key criteria such as building size, construction time, and cost aligns closely with the industry's evolving priorities, emphasizing efficiency and sustainability. The findings underscore the need for a more adaptive and selective application of construction technologies and setting a new benchmark for future studies in construction method optimization that blend traditional techniques with cutting-edge decision-making tools.

Keywords
Additive manufacturing, Fuzzy Shannon's entropy based alpha level, Fuzzy TOPSIS, Robotic architecture, Traditional construction methods.

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1. Introduction

In the race toward modernity, the artistry and wisdom of traditional construction methods are often overshadowed. These centuries-old techniques are shaped by a profound understanding of the local environment and available resources, so they also are great examples in terms of sustainable and resilient architecture. However, also advancements in technology have brought about significant changes in the field of architectural building applications, with construction robots playing a pivotal role in shaping the future of the industry. These robots offer numerous advantages, such as precise form fabrication and improved safety, cost-effectiveness, and reduced construction time. However, despite their undeniable benefits, the literature suggests that construction robots have not yet reached their full potential in size, investment, building safety, and other factors (Tay et al., 2017). Although this technology offers many structural, economic, and environmental benefits, its use is still limited due to certain limitations that are still being studied (Al-Tamimi et al, 2023).

The evolution of construction methods as seen in Figure 1 over centuries is a testament to human ingenuity and technological progress. From the use of natural materials like wood and stone in ancient structures such as Stonehenge, to the sophisticated brickwork and masonry of the Bronze and Iron Ages epitomized by the Egyptian pyramids, each era has contributed significantly to architectural practices. The Romans introduced revolutionary techniques with the use of concrete, arches, and domes, leading to remarkable structures that have withstood the test of time.

The Gothic period marked a new chapter with the rise of magnificent cathedrals, characterized by flying buttresses and intricate designs. The Industrial Revolution further transformed construction, introducing iron and steel as core materials, which laid the foundation for modern skyscrapers. In contemporary times, the field of construction has embraced sustainable practices, digital design innovations like Building Information Modeling (BIM), and cutting-edge technologies such as 3D printing and robotics. These advancements have not only enhanced efficiency but have also elevated environmental responsibility within the construction industry.

However, amidst the quest for modernity, the inherent artistic flair and pragmatic wisdom embodied within traditional construction methods, intricately woven with local environments and resources, frequently remain overlooked. These methods, perfected over centuries, exemplify sustainable and resilient architecture. Conversely, technological advancements have significantly transformed architectural building applications. Construction robots, in particular, have emerged as a pivotal force in the industry, offering precise form fabrication, improved safety, cost-effectiveness, and reduced construction time. Yet, despite these benefits, literature indicates that the full potential of construction robots, particularly in terms of size, investment, and building safety, remains untapped (Tay et al., 2017; Al-Tamimi et al, 2023).

Despite this rich history, the full potential of modern construction methods, particularly robotics and 3D printing, remains underexplored. This study aims to bridge this gap by examining the integration of construction robots and various traditional construction methods in architectural applications, focusing on structures built using additive construction methods. The objective is to identify the advantages and challenges associated with these technologies and methods, and to evaluate their performance based on specific criteria crucial to architectural construction projects. Insights and recommendations for the construction industry and architecture practitioners will be provided in the manuscript, grounded in a comprehensive analysis of 13 architectural buildings constructed using additive manufacturing techniques.

Specific architectural buildings all built by additive manufacturing technique being studied include Radiolaria, Lewis Grand Hotel, Floatsam and Jetsam Pavilions, Dubai Future Foundation Headquarters, Huashang Teng-

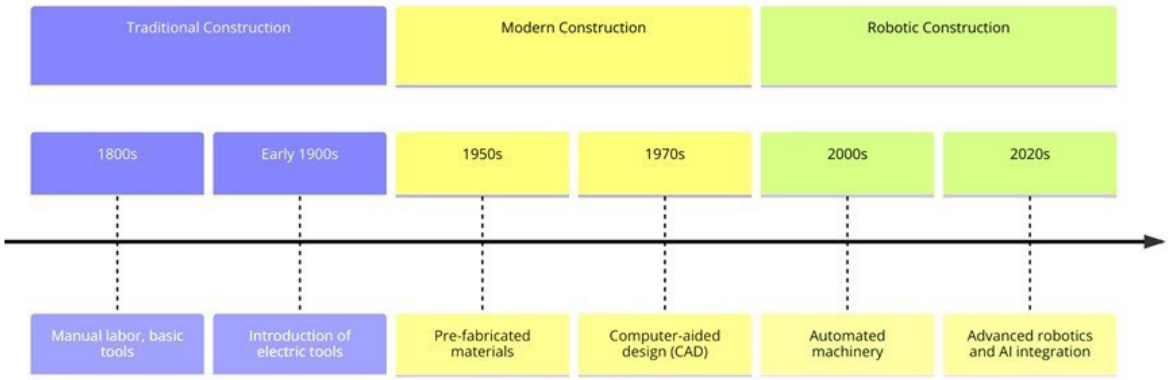

Figure 1. *Construction methods over time.*

da Mansion, ApisCor Concrete House, 3D Housing 05, Pedestrian Bridge MX3D, Trabeculae Pavilion, Gaia House, Dubai Municipality Building, Boashan Pedestrian Bridge, and TECLA. Through this analysis, the article aims to present a comprehensive understanding of the strengths and weaknesses of each construction method in relation to architectural applications.

Radiolaria is an organic, open-cell design created by Andrea Morgante of Shiro Studio in London. Its construction aims to demonstrate the possibility of producing complex structures with innovative technologies and simple materials, without the need for self-supporting, temporary, or single-use molds. This structure, fabricated using extrusion techniques and powdered materials, draws inspiration from marine microorganisms known as Radiolaria. In addition to emulating the physical design criteria of Radiolaria, the concept also incorporates the principle of gradual accumulation of mineral and siliceous skeletons found in underwater formations, aligning with the working principles of the D-Shape company's 3D printing technology, which operates through layer-by-layer deposition. The Lewis Grand Hotel is situated on Don Juico Boulevard in Angeles City, Philippines, and stands out as an appealing destination for international guests. Owned by Lewis Yakich, who holds a degree in materials science from the University of California, the hotel embarked on a renovation project in collaboration with his associate, Audrey Rudenko. The primary objective of this project was to incorporate a party house into this luxurious hotel. In 2016, SHoP Architects designed and Branch Technologies produced two pavilions named "Flotsam & Jetsam" for the 2016 Design Miami forum held in Miami. These structures, resembling jellyfish, received the 2016 Design Visionary Award. With a combined volume of 85 cubic meters, these pavilions are composed of two units, one measuring 55 cubic meters and the other 30 cubic meters. The longest dimension of these pavilions was designed and constructed to be 14.75 meters. The office complex designed as the headquarters for the Dubai Future Foundation aims to be a pioneer in the construction industry in terms of technological advancement, innovation, and creativity. According to Richard Hammond, the Managing Director of Gensler, this endeavor opens the path to a future where 3D printing can assist in addressing environmental and urbanization challenges, while also enabling the provision of customized spaces for clients in a significantly shorter timeframe. In 2016, a 250-square-meter office complex, designed by Gensler, with structural engineering by Thornton Tomasetti and mechanical engineering by Syska Hennessy, was successfully constructed as part of this initiative. The HuaShang Tengda Residence, located in the Tongzhou region near Beijing, is a two-story structure covering an area of 400 square meters, constructed in just 45 days using 3D printing technology, layer by layer, at the construction site. It distinguishes itself from other 3D-printed structures in two significant ways. Firstly, this residence was created through the 3D printing of traditional C30 concrete without the addition of any additives, as stated by the manufacturer. By sourcing cement from nearby locations, transportation costs were minimized, simplifying logistical requirements for delivery. Secondly, the residence features walls printed to a thickness of 250 mm and boasts earthquake resistance of up to Richter scale magnitude 8, providing robust structural integrity.

In a collaboration between the American 3D printing company Apis Cor and the Russian real estate developer PIK, the world's first 3D-printed house was constructed within 24 hours using Apis Cor's mobile printer designed for this purpose. The entire structure, including exterior walls and interior partitions, was built as a single unit. Unlike the conventional approach of manufacturing individual panels in a factory and transporting them to the construction site for assembly, this innovative project involved the use of a mobile 3D printer with crane-like capabilities, allowing for on-site printing and construction. The project "3D Housing 05" emerged from a collaborative research effort involving multiple companies from various sectors, with the aim of providing a rapid and sustainable housing solution to meet the increasing demand for housing. The circular floor plan design, conceived by CLS Architetti, was transformed into a constructible form with the assistance of Arup. The construction was facilitated by a robot arm designed by CyBe Construction, utilizing materials developed by Italcementi. This innovative approach combines architectural design, engineering support, and advanced construction technology to achieve its goals. Established in 2014 in Amsterdam, MX3D is a company dedicated to enabling the construction of buildings through additive manufacturing techniques using metal. Their production principle involves the operation of welding machines in the form of 3D printers. The MX3D Bridge is a collaborative project involving design by Joris Laarman Lab, primary structural engineering by Arup, and construction expertise by Heijmans. Expertise in metallurgy was provided by ArcelorMittal, while Autodesk contributed knowledge in digital manufacturing tools, Lenovo provided computational hardware, ABB offered expertise in robotics, Air Liquide & Oerlikon provided insights into welding, and support for maintaining optimal air quality during research was obtained from AMS Institute and TU Delft with assistance from Plymovent. The purpose of the Trabeculae Pavilion is to introduce an architectural concept produced through 3D printing, which aims to enhance the efficient utilization of material resources due to the significant environmental impact associated with building production, particularly in terms of CO2 emissions and greenhouse gas production. Drawing inspiration from bone structures, the design focuses on lightweight construction. The pavilion has been developed as a component-based, double-curved surface, offering structural sustainability, ease of assembly, maintenance, and adaptability to different designs. This innovative approach addresses environmental concerns while promoting structural and functional versatility in architectural design.

Gaia House serves as an exemplar of sustainable architecture, showcasing the potential for constructing low-cost housing with nearly zero environmental impact. Notably, it stands as one of the first houses ever built using 3D printing technology in conjunction with soil. This dwelling, printed in Italy using a printer developed by WASP, was realized in October 2018. It leverages additive manufacturing techniques to layer and cure a viscous material, resulting in walls that serve both as load-bearing elements and protective enclosures. The Dubai Municipality Building, completed in October 2019, represents a structure constructed using additive manufacturing technology with the assistance of a robotic arm developed by the company Apis Cor. This two-story building stands at a height of 9.5 meters and was assembled on-site. It gained recognition as the world's largest 3D-printed structure at the time, characterized by a unique architectural form created by combining various geometric shapes. The total floor area of the building is 640 square meters, exceeding the printing capacity of the fixed Apis Cor 3D printer. Consequently, the mobile robotic arm was maneuvered around the construction site with the aid of a crane for the printing process. The Boashan Pedestrian Bridge was designed and produced through collaboration between Shanghai Wisdom Bay Investment Management Company and a team led by Professor Xu Weiguo from the architecture department of Tsinghua University. This pedestrian bridge, characterized by its arched structure, was constructed using concrete components created through 3D printing technology, encompassing structural elements, railings, and decorative flooring panels. One of the projects undertaken by the WASP company is the circular housing concept named “TECLA,” derived from the fusion of the words “Technology” and “Clay.” WASP’s objectives include the construction of sustainable buildings that are also financially accessible to a wide range of individuals. This project is rooted in these aims, emphasizing both technological innovation and affordability in housing solutions.

To be able to make the comparison between construction techniques, this paper considers seven different parameters which are cost, speed of the construction, the safety of the building, flexibility, building safety responsibility, building size, and workplace safety in a construction site. Costs represent the cumulative of the rent of a robot, used construction material, and workers’ salary for additive manufacturing, but for the traditional construction techniques cost is mostly based on used construction material, workers’ salary, and mold (if it is necessary for the construction) (Pegna, 1997; Valente et al.,2019). The speed of the construction means the duration of the construction (Han et al., 2003). The safety of the building parameters is mostly related to the durability and stability of the building (Han et al., 2003). Flexibility refers to the ability to construct something unique according to design (Pegna, 1997; Valente et al.,2019). Building safety responsibility refers to knowing who is legally responsible for problems in the process (Buswell et al., 2007). Building size means the limitations in terms of dimensions that can be constructed with that technique (Valente et al., 2019). Workplace safety in a construction site refers to the implementation of measures and procedures to protect the physical health and safety of workers (Pegna, 1997; Valente et al.,2019).

The main motivation of the article is the selection of appropriate construction methods for architectural applications. Within the scope of the study, the development of construction methods was discussed and the additive manufacturing method, which has become widespread today, was emphasized. In the study, various evaluation criteria were determined for the construction of architectural applications by using the literature and expert opinions. These determined criteria were evaluated by taking into account the applications handled by experts. In the evaluations, experts scored the construction methods for each application using a 5-point Likert scale, taking into account the determined criteria. Thus, the data necessary for the evaluation of criteria and alternative methods were obtained. Then, the construction methods that can be used for each architectural application were determined by multi-criteria decision-making methods that are widely used in the literature. Fuzzy Shannon’s Entropy Based on Alpha Level method has been preferred here because it is a comprehensive and objective approach that provides flexibility in application, data normalization, sensitivity analysis, and the ability to handle uncertainty with mathematical rigor. TOPSIS, another method used, is useful for evaluating and ranking multiple alternatives using the obtained criterion weights. Thus, the decision maker can have an idea about other alternatives. This study focuses on 13 architectural construction applications built using additive construction methods. The objective is to discuss and evaluate the effectiveness of different modern and traditional construction methods, seven criteria are defined for architectural construction applications. By Fuzzy Shannon’s Entropy Based on Alpha Level and Fuzzy TOPSIS methods, nine traditional construction methods are analyzed. The article seeks to contribute to the existing literature by offering a unique perspective on the use of construction robots and construction methods in construction applications. The conclusions and recommendations are intended to inform future research and practical decision-making in the construction industry.

2. Literature review

The Literature Review of this study delves into the historical evolution and the current landscape of construction methods, tracing the journey from traditional techniques to modern innovations. This exploration aims to contextualize the advancements in the field, emphasizing the transitions and comparing the strengths and drawbacks of various methods as seen in Table 1.

Historically, construction methods were heavily reliant on manual labor and the use of locally sourced materials. Traditional techniques such as brickwork, masonry, and timber framing have stood the test of time, showcasing durability and adaptation to local environments. However, these methods often come with limitations, including intensive labor demands, extended construction times, and constraints in design flexibility. The physical properties of traditional materials also imposed limitations on architectural creativity, often confining designs to the realms of practicality and local availability.

The latter part of the 20th century marked a significant shift with the advent of modern construction technologies. The introduction of Computer-Aided Design (CAD), Building Information Modeling (BIM), and advancements in material science catalyzed a new era in construction. Robotics, once a subject of academic research, began to find practical application in construction sites, driven by the widespread availability and affordability of CAD software during the late 1990s and early 2000s. This transition, as noted by Bidgoli (2015), allowed for intricate design solutions that were previously unattainable with conventional construction methods.

Among modern technologies, 3D printing, or additive manufacturing has emerged as a transformative force

Table 1. *Comparing additive, traditional, and modern construction techniques with pros and cons.*

Criteria	Additive Construction	Traditional Methods	Modern Methods
Cost	Higher due to technology costs	Lower, labor and material costs	Varies, often higher due to advanced materials and technology
Speed of Construction	Faster, automated processes	Slower, manual processes	Faster due to new technologies and materials
Building Safety	High, precision of robots	Depends on skill and materials	High, use of advanced materials and technology
Flexibility	High, complex designs possible	Limited by traditional techniques	High, adaptable to unique designs
Building Safety Responsibility	Shared with tech providers	On constructors	Often shared between tech providers and constructors
Building Size Limitations	Some constraints	Less restricted	Varies, often less restricted due to new methods

in construction. This technique, as shown by Ma et al. (2018), offers significant cost advantages over traditional methods, particularly in terms of labor and material utilization. Despite its benefits, challenges such as scalability, material diversity, and environmental adaptability continue to be areas of ongoing research and development (Tay et al., 2017).

Comparative studies, such as those conducted by Khajavi et al. (2021) and Tay et al. (2017), highlight the evolving competitiveness of modern construction techniques like 3D Concrete Printing (3DCP) against traditional methods. Also, Boll and Suermann (2022) studied on alternatives to traditional construction methods by evaluating additive manufacturing and as a result they showed that implimenting additive manufacturing in construction correctly has more potential than traditional methods. These studies underscore the potential of integrating technologies like 3D printing with BIM, enhancing safety, precision, and customization in construction projects.

Despite these advancements, there remains a notable gap in comprehensive comparative research that juxtaposes traditional and modern construction methods, particularly in their application to architectural construction. This study seeks to bridge this gap by evaluating various construction methods employed in architectural applications, with a focus on additive manufacturing. The analysis includes a diverse range of architectural structures, from the Radiolaria Pavilion to the Lewis Grand Hotel, which have leveraged different manufacturing techniques and materials. This array of case studies, referenced from works by Morgante (2017), Ghaffar et al. (2018), and others, illuminates the multifaceted applications and implications of construction robots and modern methodologies.

The article focuses on evaluating different construction methods for architectural construction applications built using additive construction. The study builds on where various architectural structures have been studied in the literature (Morgante, 2017; Ghaffar et al., 2018; Daas and Wit, 2018; Busta, 2016; Pessoa et al., 2021; Jordahn, 2018; Naboni et al., 2019; Chiusoli, 2018; Xu et al., 2020; Chiusoli, 2018). The 13 architectural additive manufactured building applications under consideration include the Radiolaria Pavilion, Lewis Grand Hotel, Floatsam and Jetsam Pavilions, Dubai Future Foundation Headquarters, HuaShang Tengda Mansion, Apis Cor Concrete House, 3D Housing 05, MX3D Pedestrian Bridge, Trabeculae Pavilion, Gaia House, Dubai City Hall, Boashan Pedestrian Bridge, and TECLA. By analyzing different manufacturing techniques and materials usage, the study sheds light on the potential contributions of construction robots. This research provides valuable insights into how these technologies can improve and reshape architectural construction practices, demonstrating their multifaceted applications and implications.

3. Method

In this study, where the production techniques that can be used for a selected sample of architectural buildings discussed in the literature are compared, the weighting of the criteria determined for the comparison was carried out with the Alpha Level Based Fuzzy Shannon's Entropy method. The criteria weights determined for each sample were used as the basis for the evaluation of alternative production techniques using the Fuzzy TOPSIS method. The main purpose of the study was to select the construction methods to be used for architectural applications. Within the scope of this purpose, there are objectives such as providing an objective evaluation method, including different expert opinions in the decision process, and ranking alternative construction methods. To achieve the aims and objectives of the study, Fuzzy Shannon's Entropy Based on Alpha Level and Fuzzy TOPSIS methods, which are among the frequently used methods in the literature, were used. These methods involve gathering data from a variety of sources, including expert opinion and academic input, to ensure a comprehensive and objective assessment. Furthermore, researchers could manage the uncertainty and inaccuracies inherent in the evaluation process with using these methods. In addition, they can provide a comprehensive overview of the potential advantages of each construction method for different architectural structures. In the study, the comparison of construction methods was made using cost, construction speed, operational safety, building safety, responsibility of building safety, building dimension and flexibility parameters. While determining these parameters, professionals who practice in this field and studies in the literature were taken as reference. In particular, the increase in the use of robots with new construction technologies has caused some parameters to vary in the literature and real-life applications.

3.1. Fuzzy Shannon's entropy based on alpha level

Zadeh (1965) proposed fuzzy set theory to address uncertainty in human and cognitive processes. A fuzzy set refers to a set of elements with a certain degree of membership (Jie et al., 2006). This theory allows only partial ownership of elements between zero (non-full membership) and one (full membership) (Huang and Ho, 2013). The main advantage of fuzzy set theory is the ability to represent uncertain data and to apply mathematical operators on the fuzzy domain (Mahmoodzadeh et al., 2007). Lotfi and Fallahnejad (2010) considered the Shannon entropy method based on a certain alpha level and extended it to interval data cases. This extension summarized the steps of fuzzy Shannon entropy based on α-level sets as follows:

The fuzzy data () containing the decision matrix according to different α-level sets are transformed into interval data using Equation 1.

$$\tilde{D} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \dots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \dots & \tilde{x}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \dots & \tilde{x}_{mn} \end{bmatrix}$$

Equation 1. *The transformation of decision matrix to interval data.*

The values of the fuzzy variables () are expressed using the interval formula in Equation 2. The fuzzy data are transformed into different sets of α levels by setting various confidence levels. The matrix of interval data is then obtained as described in Equation 3.

$$\left[(\tilde{x}_{ij})^L_\alpha, (\tilde{x}_{ij})^R_\alpha\right] = \left[\min x_{ij}\{x_{ij} \in \mathrm{R} | \mu\tilde{x}_{ij}(\mathrm{xij}) \geq \alpha\}, \max x_{ij}\{x_{ij} \in \mathrm{R} | \mu\tilde{x}_{ij}(\mathrm{xij}) \geq \alpha\}\right] 0 < \alpha \leq 1$$

Equation 2. *The matrix of interval data calculation.*

$$\mathrm{B} = \begin{bmatrix} [\mathrm{x}^L{}_{11}\mathrm{x}^R{}_{11}] & [\mathrm{x}^L{}_{12}\mathrm{x}^R{}_{12}] & \dots & [\mathrm{x}^L{}_{1n}\mathrm{x}^R{}_{1n}] \\ [\mathrm{x}^L{}_{21}\mathrm{x}^R{}_{21}] & [\mathrm{x}^L{}_{22}\mathrm{x}^R{}_{22}] & \dots & [\mathrm{x}^L{}_{2n}\mathrm{x}^R{}_{2n}] \\ \vdots & \vdots & \vdots & \vdots \\ [\mathrm{x}^L{}_{m1}\mathrm{x}^R{}_{m1}] & [\mathrm{x}^L{}_{m2}\mathrm{x}^R{}_{m2}] & \dots & [\mathrm{x}^L{}_{mn}\mathrm{x}^R{}_{mn}] \end{bmatrix}$$

Equation 3. *The transformation of decision matrix to interval data.*

The normalized values of the fuzzy variables (,) are calculated as shown in Equations 4 and 5 respectively.

$$p^L_{ij} = \frac{x^L_{ij}}{\sum_{j=1}^m x^L_{ij}} \ \mathrm{j} = 1,2,\dots,\mathrm{m}, \mathrm{i} = 1,2,\dots,\mathrm{n}$$

Equation 4. *The calculation of upper normalized values for the interval values.*

$$p^R_{ij} = \frac{x^R_{ij}}{\sum_{j=1}^m x^R_{ij}} \ \mathrm{j} = 1,2,\dots,\mathrm{m}, \mathrm{i} = 1,2,\dots,\mathrm{n}$$

Equation 5. *The calculation of lower normalized values for the interval values.*

The lower and upper bounds of the interval values () are calculated using the formulas given in equations 6 and 7 respectively.

$$e^L_i = \min\{-e_0 \sum_{j=1}^m p^L_{ij}\, lnp^L_{ij}, -e_0 \sum_{j=1}^m p^R_{ij}\, lnp^R_{ij},\}, i = 1,2,\dots,n$$

Equation 6. *The calculation of lower bounds for the interval values.*

$$e^R_i = \max\{-e_0 \sum_{j=1}^m p^L_{ij}\, lnp^L_{ij}, -e_0 \sum_{j=1}^m p^R_{ij}\, lnp^R_{ij},\}, i = 1,2,\dots,n$$

Equation 7. *The calculation of upper bounds for the interval values.*

Here; (lnm)-1, if and then are equal to 0.

The lower and upper bounds of the differentiation values () are calculated as in Equations 8 and 9 respectively.

$$d^L_i = 1 - e^R_i \ \ i = 1,2,\dots,n$$

Equation 8. *The calculation of lower bounds for the differentiation values.*

$$d^R_i = 1 - e^L_i \ \ i = 1,2,\dots,n$$

Equation 9. *The calculation of upper bounds for the differentiation values.*

The lower and upper bounds of the interval weight of the criteria () are calculated as shown in equations 10 and 11 respectively.

$$w^L_i = \frac{d^L_i}{\sum_{s=1}^n d^R_s} \ \ i = 1,2,\dots,n$$

Equation 10. *The calculation of lower bounds for interval criteria weights.*

$$w^R_i = \frac{d^R_i}{\sum_{s=1}^n d^L_s} \ \ i = 1,2,\dots,n$$

Equation 11. *The calculation of upper bounds for interval criteria weights.*

In the study by Aytekin and Karamaşa (2017), the final weights of the criteria are calculated as the average of the lower and upper bounds of the criteria weights as specified in Equation 12.

$$w^c_i = \frac{w^L_i + w^R_i}{2} \ \ i = 1,2,\dots,n$$

Equation 12. *The calculation of final criteria weights.*

In case the sum of the weights is not 1, equation 13 is used to ensure that the total weights are 1.

$$w_i = \frac{w^c_i}{\sum_{i=1}^n w^c_i} \ \ i = 1,2,\dots,n$$

Equation 13. *The normalization of final criteria weights.*

3.2. Fuzzy TOPSIS method

The TOPSIS method, introduced by Hwang and Yoon (1981), aims to select the shortest distance to the positive ideal solution and the longest distance to the negative ideal solution in order to achieve maximum gain or minimum cost among alternatives (Behzadian et al., 2012). However, in real-world applications, the TOPSIS method may be insufficient to evaluate criteria and alternatives in terms of shortest and longest distances due to incomplete and incorrect information. To solve this problem, the Fuzzy TOPSIS method has been developed and applied by many researchers. This method can be easily applied to countable and uncountable data with a very clear algorithm (Cavallaro et al., 2016). Many applications of fuzzy TOPSIS have been studied in the literature. In one of these studies, Chen and Hwang (1992) applied the TOPSIS method to the fuzzy environment and then Liang (1999) developed a method based on ideal and non-ideal points for multi-criteria decision-making problems. In this method, he used fuzzy set theory and the concept of hierarchical structure to determine criteria weights through decision matrices and evaluate alternatives according to each criterion (Liang, 1999).

The steps of the fuzzy TOPSIS method can be summarized as follows (Wang and Chang, 2007):

Construction of the fuzzy decision matrix: The fuzzy decision matrix () shown in Equation 14 is constructed from the fuzzy numbers () for alternatives and evaluation criteria.

$$\tilde{D} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix} \quad \mathrm{i} = 1, 2, \ldots, \mathrm{m} \; \mathrm{j} = 1, 2, \ldots, \mathrm{n}$$

Equation 14. *The calculation of construction for the fuzzy decision matrix.*

Normalization of the fuzzy decision matrix: The normalized fuzzy decision matrix (R) shown in Equation 15 is obtained using a linear scale transformation.

$$\tilde{R} = \begin{bmatrix} \tilde{r}_{11} & \tilde{r}_{12} & \cdots & \tilde{r}_{1n} \\ \tilde{r}_{21} & \tilde{r}_{22} & \cdots & \tilde{r}_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \tilde{r}_{m1} & \tilde{r}_{m2} & \cdots & \tilde{r}_{mn} \end{bmatrix} \quad \mathrm{i} = 1, 2, \ldots, \mathrm{m} \; \mathrm{j} = 1, 2, \ldots, \mathrm{n}$$

Equation 15. *The normalization of the fuzzy decision matrix.*

When obtaining the normalized fuzzy decision matrix elements, Equation 16 is used for the benefit criteria (for B) and Equation 17 is used for the cost criteria (for C).

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right) \; c_j^* = \max_i c_{ij} \; j \in B$$

Equation 16. *The calculation of the normalized fuzzy decision matrix elements (benefit criteria).*

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^-}, \frac{b_{ij}}{c_j^-}, \frac{c_{ij}}{c_j^-}\right) \; c_j^- = \min_i c_{ij} \; j \in C$$

Equation 17. *The calculation of the normalized fuzzy decision matrix elements (cost criteria).*

Obtaining the normalized weighted fuzzy decision matrix: Each element () of the normalized weighted fuzzy decision matrix () is calculated by Equation 18.

$$\tilde{v}_{ij} = \tilde{r}_{ij} \odot w_j$$

Equation 18. *The calculation of the normalized weighted fuzzy decision matrix.*

Where denotes the weight of criterion obtained from the Fuzzy Shannon Entropy method based on Alpha Level.

Determination of fuzzy positive ideal solution () and fuzzy negative ideal solution (): Fuzzy positive ideal solution () and fuzzy negative ideal solution () calculations are shown in Equations 19 and 20 respectively. If the fuzzy triangular numbers take values in the range [0,1], the positive and negative ideal solution values are as shown in Equation 21.

$$A^* = (\tilde{v}_1^*, \tilde{v}_2^*, \ldots, \tilde{v}_j^*) = \left\{(\max_i \tilde{v}_{ij}^* \mid \mathrm{j} \in \mathrm{J}), (\min_i \tilde{v}_{ij}^* \mid \mathrm{j} \in \mathrm{J}')\right\}$$

Equation 19. *The determination of fuzzy positive ideal solution.*

$$A^- = (\tilde{v}_1^-, \tilde{v}_2^-, \ldots, \tilde{v}_j^-) = \left\{(\max_i \tilde{v}_{ij}^- \mid \mathrm{j} \in \mathrm{J}), (\min_i \tilde{v}_{ij}^- \mid \mathrm{j} \in \mathrm{J}')\right\}$$

Equation 20. *The determination of fuzzy negative ideal solution.*

$$\tilde{v}_j^* = (1,1,1), \tilde{v}_j^- = (0,0,0) \; j = 1,2, \ldots, n$$

Equation 21. *The positive and negative ideal solution values.*

Calculating the distance between each alternative and and: The distances and of each alternative, denoted by the function, are calculated as shown in Equations 22 and 23 respectively.

$$d_i^* = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^*) \quad i = 1,2,\ldots,m$$

Equation 22. *The calculation of the distance between each alternative.*

$$d_i^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^-) \quad i = 1,2,\ldots,m$$

Equation 23. *The calculation of the distance between each alternative.*

Calculating the similarity coefficient of each alternative and ranking them in descending order: The similarity coefficient () of alternative i is calculated as in Equation 24.

$$CC_i = \frac{d_i^-}{d_i^- + d_i^*}, i = 1,2,\ldots,m$$

Equation 24. *The calculation of the similarity coefficient of each alternative and ranking.*

The alternatives are ranked in descending order considering the values of. The value of the alternative with the highest value approaches 1, while the value approaches 0.

4. Results and discussion

In this study, different construction methods were compared for architectural building applications which were studied by literature and built with the additive construction method. These architectural building applications are Radiolaria Pavilion (U1), Lewis Grand Hotel (U2), Floatsam and Jetsam Pavilions (U3), Dubai Future Foundation Headquarters (U4), HuaShang Tengda Mansion (U5), Apis Cor Concrete House (U6), 3D Housing 05 (U7), MX3D Pedestrian Bridge (U8), Trabeculae Pavilion (U9), Gaia House (U10), Dubai City Hall (U11), Boashan Pedestrian Bridge (U12), TECLA (U13). The comparisons were carried out using Fuzzy Shannon Entropy based on Alpha Level and Fuzzy TOPSIS methods. The criteria used in the relevant comparisons were determined as a result of the literature research. When the criteria determined within the scope of this research are evaluated, the first criterion stands out as Cost (C1). In addition to the importance of cost in construction, it can be said that in additive construction and traditional construction methods, the additional costs brought by technology and the costs spent on labor come face to face. Here, especially the rental or initial purchase costs of three-dimensional construction robots are compared with the labor costs required for the same job. In addition, additional expenses such as maintenance, repair and depreciation occur in three-dimensional construction robots, while costs such as insurance and taxes arise for the workforce (Pegna, 1997; Valente et al., 2019). Another criterion refers to the estimated completion time committed to the customer in construction projects, which is referred to as Build Speed or Time (C2) in the literature (Han et al., 2003). Depending on the type of structure built, an average construction time is determined at the beginning of the project in the construction industry, and this time is desired to be as short as possible for earlier deliveries. Building Safety (C3) is also one of the most important issues in construction construction. The building should be built in accordance with its intended use and density, especially in line with the designs and analyzes made by civil engineers and architects in accordance with the earthquake regulations. Another important issue is seen as Flexibility (C4) in the construction process (Pegna, 1997). This concept can be expressed as the ability to continue the construction process in unexpected situations such as unfavorable weather conditions, disruptions in the supply process, and epidemics. As technology becomes more involved in the construction process, another criterion that should be considered for the evaluation of traditional and additive construction methods is stated as Responsibility for Building Safety (C5) (Buswell et al., 2007). With the use of robots in many industries (including the construction industry), liability for occupational accidents or negative effects on products (instability of the structure) has become controversial. Some construction methods can be made specifically for the structure. This is because the Building Dimension (C6) or building type is not suitable for the relevant construction method (Valente et al., 2019). Finally, in addition to

Table 2. *Alternative construction methods for architectural building applications.*

	A1	A2	A3	A4	A5	A6	A7	A8	A9
U1	+	+	+	+	+	+	+	+	+
U2	+	+	+	+	+	+	+	+	+
U3	+	-	-	-	-	-	-	+	-
U4	+	+	+	+	+	+	+	+	+
U5	+	+	+	+	+	+	+	+	+
U6	+	+	+	+	+	+	+	+	+
U7	+	+	+	+	+	+	+	+	+
U8	+	+	+	-	-	-	+	+	-
U9	+	-	-	-	-	-	-	+	-
U10	+	+	+	+	+	+	+	+	+
U11	+	+	+	+	+	+	+	+	+
U12	+	+	+	-	+	-	+	+	-
U13	+	+	+	+	+	+	+	+	+

Table 3. *Scale of fuzzy triangular numbers.*

Crispy Number	Triangular Transformation
1	(1,1,2)
2	(1,2,3)
3	(2,3,4)
4	(3,4,5)
5	(4,5,5)

Table 4. *Differentiation, entropy and weights values.*

	d_i^L	d_i^R	e_i^L	e_i^R	w_i
C1	0.010	0.026	0.974	0.990	0.032
C2	0.016	0.173	0.827	0.984	0.210
C3	0.013	0.135	0.865	0.987	0.164
C4	0.005	0.134	0.866	0.995	0.162
C5	0.044	0.069	0.931	0.956	0.090
C6	0.006	0.117	0.883	0.994	0.141
C7	0.015	0.166	0.834	0.985	0.202

structural safety, Operational Safety (C7) affects the choice of construction method. While this is due to the fatigue and carelessness of people working in traditional methods, it may be due to reasons such as out of control or malfunction of construction robots used in additive construction methods (Pegna, 1997; Valente et al., 2019).

Nine building method alternatives were determined for the architectural construction applications discussed. These methods are Additive Construction (A1), Concrete Pouring with Mold (A2), Stone and Brick Construction (A3), Reinforced Soil Construction (A4), Masonry Stone Wall Construction (A5), Mud Brick Construction (A6), Rock Carving and Chipping (A7), Wooden Skeleton (A8), Wooden Stacking (A9). Architectural building applications where these construction methods can be used are shown in Table 2. Among the applications, the number of alternatives for the construction of Floatsam & Jetsam Pavilions and Trabeculae Pavilion structures could not be evaluated with the proposed method, as there were only two. The evaluations made for these structures were added to the conclusion part of the study in line with the opinions of the experts.

Evaluations of construction methods for architectural construction applications examined within the scope of the study were carried out by academicians and field experts working in this field. Evaluations were scored on a five-point Likert scale. In order for the evaluations to be used in the proposed method, the numbers must be blurred. The five-point Likert scale used was converted into fuzzy triangular numbers using the fuzzy number conversion scale shown in Table 3.

A fuzzy evaluation matrix was created by using the fuzzy number transformation scale for each architectural building examined. The fuzzy evaluation matrix for the Radiolaria Pavilion structure was created. Fuzzy evaluation matrices of other architectural structures examined are calculated in a similar way. By applying the fuzzy Shannon's entropy method based on the α level to the created fuzzy evaluation matrices, criterion weights were obtained for each structure examined.

After the fuzzy evaluation matrices were created, the fuzzy data were converted into interval data by considering the α= 0.5 (neutral) level set, and interval decision matrices were obtained. The normalized interval decision matrix obtained for the Radiolaria Pavilion structure by applying normalization to the interval data. Normalized interval decision matrices created for other architectural buildings are calculated in a similar way.

The upper and lower limits of entropy and differentiation values were obtained by using normalized interval decision values for each application. The entropy (), differentiation () and criterion weight values () obtained for the Radiolaria Pavilion structure are shown in Table 4. The entropy, differentiation and criterion weight values obtained for other applications are calculated in a similar way.

The importance levels of the criteria for each architectural application were found by using Equation (18) and Equation (19) and are shown in Figure 2.

As can be seen in Figure 2, the evaluation of the criteria determined for the architectural construction applications discussed differs from application to application. However, in general, the building size (C7) and construction time (C2) criteria were found to be the two most important criteria in 9 of the 11 architectural building applications evaluated. In the other two applications, the most important criterion was again the building size, while the second most important criterion was found to be cost (C1) and building safety responsibility (C5). Considering the evaluations made for architectural building applications, it is seen in the literature that the size of the building and the construction period are very important (Valente et al., 2019; Han et al., 2003). Apart from this, one of the important criteria especially mentioned in the literature has been evaluated as cost (Pagna, 1997; Valente et al., 2019). Finally, the responsibility of building safety has emerged with the active use of construction robots and is a topic that is currently being discussed. Here, in direct proportion to the size and duration of the architectural construction application, it becomes important who will take responsibility for any danger or accident that may occur in the building (Han et al., 2003).

The fuzzy TOPSIS method was used to evaluate nine construction methods that can be used in architectural building applications after criterion weighting. In this context, the normalized fuzzy decision matrix created for the Radiolaria Pavilion structure, and for

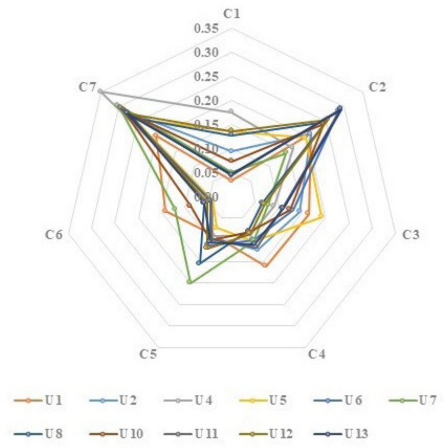

Figure 2. *Criteria weights for each architecture application.*

other applications, these matrices calculated in a similar way.

The weighted normalized fuzzy decision matrix for all applications was found using the weights of the criteria. Normalized fuzzy decision matrices of these architectural construction applications are calculated by Equation 18.

The distances of each alternative to and were found using the weighted normalized matrix. By using the distances, the final performance values of the construction methods were reached for each architectural construction application. Table 5 shows the distances and similarity values of each construction method for the Radiolaria Pavilion structure. The distance and similarity values of the construction methods for other architectural construction applications are calculated in a similar way.

The ranking of alternative methods that can be used in the construction of these structures, as a result of the evaluations made for the architectural building applications, is given in Table 6.

The evaluations made for 11 of the 13 architectural structures that are stated to be built with the additive construction method in the literature show that different construction methods are more advantageous for some buildings. In the evaluations, the most used method as an alternative to the Additive Construction (A1) method in the construction of architectural structures was the Wooden Skeleton (A8) method. In addition, in 3D Housing 05 (U7) and MX3D Pedestrian Bridge

Table 5. Distance and similarity values of construction methods.

	d^*	d^-	CC_i
A1	10.69	1.45	0.12
A2	10.90	1.26	0.10
A3	11.06	1.10	0.09
A4	11.17	1.00	0.08
A5	11.24	0.93	0.08
A6	11.19	0.98	0.08
A7	11.02	1.15	0.09
A8	11.11	1.06	0.09
A9	11.14	1.03	0.08

Table 6. Ranking of construction methods for architectural building applications.

	A1	A2	A3	A4	A5	A6	A7	A8	A9
U1	1	2	4	7	9	8	3	5	6
U2	1	2	5	3	6	7	8	1	4
U4	2	3	4	6	5	8	9	1	7
U5	2	3	5	7	4	8	9	1	6
U6	1	3	5	4	6	8	9	2	7
U7	4	1	2	5	7	8	9	3	6
U8	2	1	3	-	-	-	5	4	-
U10	1	3	6	5	7	8	9	2	4
U11	1	5	6	4	3	8	9	2	7

(U8) applications, the most advantageous construction method was determined as Concrete Pouring with Formwork (A2).

5. Conclusion

Architectural building applications are evolving to a side where construction robots are frequently used with technological developments. The construction robots obtain the desired forms as desired and work accidents during construction, cost, construction time, etc. The advantages it provides are undeniable. However, it is argued in the literature that these robots are not yet used at the desired level in terms of structure size, investment and/or rental costs, building safety, etc., as well as the use and advantages of these robots. In this study, 13 architectural building applications built with the Additive Construction Method are discussed. Seven criteria were determined for the architectural construction applications discussed, and nine construction methods that can be used in the construction of these structures were evaluated using Fuzzy Shannon's Entropy Based on Alpha Level and Fuzzy TOPSIS methods. Since only Additive Construction and Wooden Skeleton methods can be used for the Floatsam & Jetsam Pavilions and Trabeculae Pavilion applications, which are among the architectural construction applications, the evaluation could not be carried out with the proposed method in the study.

The results of the study have developed in line with the evaluations of academicians and field experts working on architectural building applications. Accordingly, the most important criteria are determined in the majority of architectural construction applications were determined as building size and construction time. In addition, cost and building safety have taken their places among the criteria that are given high importance. It is natural for each of the architectural construction projects to focus on different criteria due to their internal dynamics, project duration, budget, and requirements such as building requirements. This study showed that criteria with high importance for different projects are mostly common.

As a result of the evaluation of alternative construction methods on the criteria determined by considering the specific requirements and features of the architectural structures, it has been seen that there are more advantageous construction methods for architectural construction applications built with the Additive Construction method. Accordingly, it is seen that the Wooden Frame method is equally advantageous as the Additive Construction method for the Lewis Grand Hotel. Similarly, the Wood Skeleton method for Dubai Future Foundation Headquarters and Tengda Mansion, the Concrete Cast method for 3D Housing 05 and MX3D Pedestrian Bridge were clearly found to be more advantageous construction methods. In addition, the general opinion of the experts for the Floatsam & Jetsam Pavilions, which are not included in the evaluation, is that the Wooden Skeleton method should be used, and the Additive Construction method for the Trabeculae Pavilion application.

Based on the available research, there appears to be a notable gap as no other study has been identified that evaluates different construction methods for architectural construction applications using the Fuzzy Shannon's Entropy Based on Alpha Level and Fuzzy TOPSIS method.

This scenario highlights the necessity of making application-oriented choices in the selection of construction methods, despite the numerous advantages of construction robots discussed in the literature. Experts can enhance their cost-benefit analysis during the planning phase of architectural projects, as per this study, enabling them to make more objective decisions by considering multiple criteria. The methodology proposed in this study exhibits a versatile structure applicable to a wide array of scenarios, rendering it directly applicable to real-world situations. The study meticulously outlines the methodology, facilitating its correct comprehension and implementation. Experts utilizing the methodology can assess the consistency of their results with the application context. To ensure successful utilization of the proposed methodology in relevant architectural projects, experts must acknowledge the following limitations:

- While the established criteria possess general validity, experts may need to supplement specific criteria for individual applications.
- The influence of evaluations by experienced and expert individuals in the field impacts decision-making.
- A minimum of three alternative construction methods must be available for selection in architectural applications.
- It is crucial that the identified alternatives are suitable for practical implementation.

In future studies, evaluation of different construction methods for architectural construction applications can be made using more and/or new criteria, different weighting and ranking methods can be used, and evaluations can be made for more architectural building applications. The methodology proposed in this study can be further refined into a modular tool integrated within the framework of Building Information Modeling (BIM), facilitating collaboration between construction and architectural disciplines. This integration enables all stakeholders involved in architectural projects to readily assess alternative methods. Moreover, the modular structure of this tool ensures that appropriate evaluators influence decisions based on predefined criteria.

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