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RESEARCH ARTICLE **OPEN ACCESS**

Selection of Building Materials Using Fuzzy Analytical Hierarchy Process

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Abstract:

Introduction: Building materials play a vital role in the construction industry as they are directly related to quality, cost, constructability, and location-specific availability of material and skill. Selection of building materials is critical when there are too many alternatives. Multi Criteria Decision Making (MCDM) techniques are widely used to make such decisions simpler. For accurate decision-making, the selection of the appropriate MCDM method is very important. Most of the researchers used TOPSIS or AHP as MCDM techniques for decision-making in the construction industry.

Methods: In the present study, the fuzzy analytical hierarchy process (AHP) was used as an MCDM technique. The criteria and alternatives were identified for decision-making. The alternatives selected were locations specific to Hanamkonda, Telangana state, India. The criteria and alternatives were chosen for the building materials like cement, bricks, sand, doors, pipes, and tiles. The weights were calculated for each alternative fuzzy AHP geometric mean method. The weights of alternatives were evaluated and ranked.

Results: The best materials for cement, bricks, sand, doors, pipes, and tiles were Portland pozzolana, burnt clay bricks, river sand, UPVC, UPVC/CPVC, and marble, respectively.

Conclusion: Thus, building materials can be selected using fuzzy AHP by the client for the successful execution of a project based on his/her preferences and the location of that project.

Keywords: MCDM techniques, Fuzzy AHP, Geometric mean method, Criteria, Alternatives, Criteria weights.

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1. INTRODUCTION

Multi-Criteria Decision Making (MCDM) techniques are used when multiple alternatives and criteria are involved in decision-making. The preferences of decision-makers are important in order to distinguish the solutions. The MCDM techniques play a vital role in making an accurate decision. Several MCDM techniques are used based on the problem and their criteria. The decisions in the construction industry play a vital role in the success of the project. Construction projects adopt multiple construction techniques and materials, which makes decision-making challenging. Though similar kinds of projects are executed, the adaptability of materials and construction techniques is important, which changes in the site location. Thus, MCDM plays a vital role in the success of a project. A few popular MCDM techniques used are WASPAS (Weighted Aggregate Sum Product Assessment), TOPSIS, NIKOR, AHP...*etc*. For accurate decision-making, the selection of appropriate methods is very important. Ikuobase Emovonet *et al*. (2020) [1], Obradovic *et al*. (2020) [2], and Edyta Plebankiewicz1 *et al*. (2015) concluded that TOPSIS and Fuzzy AHP are the precise tools for decision-making in construction industry. After selecting the MCDM method, criteria weights are assigned to evaluate among the alternatives. MCDM techniques are applied in various fields like energy, environment and sustainability, supply chain management, materials, quality management, construction and project management, safety and risk management, *etc*.

2. A REVIEW ON MCDM TECHNIQUES IN CIVIL ENGINEERIng

Vignesh Kumar Chellappa and Grzegorz Ginda (2023) [1], after analyzing different research articles, indicated that the Analytic Hierarchy Process (AHP) and its fuzzy version, FAHP, were applied mainly in safety risk assessment, safety culture, and safety programs. Zhu X *et al*. (2021) [2] analyzed the evolutionary development of multiple attribute decision-making (MADM) and multiple objective decision-making (MODM)in the general sense. A total of 530 construction articles published from 2000 to 2019 were selected for the study, and they were categorized into seven major application areas using a novel systematic literature review (SLR) methodology. The study contributes to the recommendation of future directions for the development of MCDM methods that would benefit construction research and practice. Ikuobase Emovonet *et al*. (2020) [3] detailed the highest applications of MCDM techniques in various Indian industries like automotive, manufacturing, construction, agriculture, *etc*. They indicated that the most used MCDM techniques in the construction industry are AHP and TOPSIS methods for selecting building materials. Radojko Obradovic *et al*. (2020) [4] described three phases of construction, *i.e*., preparation phase, construction phase, and exploitation phase. Based on the case studies, they concluded that the AHP method of the MCDM technique is suitable for selecting environmentally friendly materials for construction, and the TOPSIS method is applicable for selecting materials that are eco-friendly, economical, and energy efficient. They proposed a model using the Fuzzy logic of the MCDM technique, which has more advantages than others. ZiyuJin and John Gambatese (2020) [5] presented a systematic decision-making process based on fuzzy set theory through a hypothetical technology selection problem for concrete formwork monitoring. Mirko Stojˇci´c *et al*. (2019) [6] reviewed the literature corresponding to the application of MCDM methods in the field of sustainable engineering. The Web of Science (WoS) Core Collection database of 108 papers published from 2008 to 2018 was chosen for study, and the collection was classified into five categories, including construction and infrastructure, supply chains, transport and logistics, energy, and others. After review, they concluded that sustainable engineering is an area that is quite suitable for the use of MCDM based on traditional approaches, with a noticeable trend towards applying the theory of uncertainty, such as fuzzy, grey, rough, and neutrosophic theory. Daniel Maskell *et al*. (2018) [7] stated the characteristics to be considered and their grouping for statistical analysis in the selection of building materials. M. B. Babanliet *et al*. (2018) [8] reviewed many MCDM techniques used in the selection process and concluded that the Fuzzy approach yielded good results for the selection of the best materials. Natasa Prascevic and Zivojin Prascevic (2017) [9] proposed a new procedure for the determination of the weights of criteria and alternatives in the Fuzzy analytic hierarchy process (FAHP) with trapezoidal fuzzy numbers using a new method for finding eigenvalues and eigenvectors of the criteria and alternatives, which is based on expected values of the fuzzy numbers and their products. Local and global fuzzy weights of the alternatives are determined using linear programming. Further, they proposed a formula for ranking fuzzy numbers by reducing the generalized fuzzy mean since ranking by the coefficient of variation is not always reliable. The formula and procedures were validated with a case study, which gave accurate results. The method they proposed can be applied to different areas of construction project management to solve large-scale decision-making problems using personal computers. F.F. Abdel-Malak *et al*. (2017) [10] identified the pros and cons of using the Analytic Hierarchy Process (AHP) and Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (Fuzzy TOPSIS). Their study indicated that AHP is a simple technique that depends on pairwise comparisons of factors and natural attributes and has a structure that simplifies complicated problems. It is preferable for widely spread hierarchies, while Fuzzy TOPSIS needs more information. It works well for the one-tier decision tree as well, and it shows more flexibility when working in fuzzy environments. It uses the advantages of linguistic variables to solve the issue of undocumented data and ill-defined problems. Finally, they concluded that two techniques have the facility to be integrated and combined in a new module to support most of the decisions required in Construction Engineering Projects (CEPs). L.O. Ugur and U. Baykan (2016) [11] used AHP to select a material for a wall in a hotel building. Wall materials, such as brick blocks, pumice concrete blocks, and sand autoclaved aerated concrete (AAC) blocks, were chosen as decision alternatives, and mechanical properties, physical properties, ease of application, and costs of these materials were the decision factors. The analysis was performed based on the opinion of an expert, and the most suitable alternative was selected. The study concluded that the suitable material for wall construction was AAC blocks for the hotel building. Edyta Plebankiewicz1 *et al*. (2015) [12] adopted AHP and Fuzzy AHP Methods in the selection of building material suppliers. They explained the process of selection of building suppliers suitable for both Economical and Rational purposes. It was concluded that the Fuzzy AHP method is very advantageous for selecting the best supplier. Davood Sabaei *et al*. (2015) [13] reviewed and evaluated MCDM models from the maintenance point of view. They emphasized that the AHP method puts the decision makers' preferences first and helps them select a method for their decision-making in maintenance management without considering uncertainty rate and problem complexity. Osman Taylan *et al*. (2014) [14] used novel analytic tools to evaluate construction projects and their overall risks under incomplete and uncertain situations. They proposed hybrid methodologies with a survey for data collection, and a relative importance index (RII) method was applied to prioritize the project risks based on the data obtained. The construction projects were then categorized by fuzzy AHP and fuzzy TOPSIS methodologies. The study indicated the suitability of the fuzzy AHP(FAHP) and fuzzy TOPSIS methods. The authors analyzed thirty construction projects with respect to five main criteria: time, cost, quality, safety, and environmental sustainability. The results showed that these novel methodologies can assess the overall risks of construction projects. Adavi Balakrishna *et al*. (2011) [15] focused on the material selection at the initial stage of design. In this paper, the material was selected using fuzzy logic from the database given by the design engineer. A fuzzy approach was proposed to support the material selection decisions. The implementation of the methodology can be used to integrate material databases with designer criteria and assist designers in selecting material for the intended application.

From the Literature review, it was observed that the Analytical Hierarchy Process (AHP) and TOPSIS are used as tools for decision-making in the construction industry. As AHP yields accurate results, in the present research, the AHP method was used for selecting building materials. Most of the researchers have used decision-making tools on projects before the launch of the project (like choosing materials, construction techniques...*etc*.) and during execution. Hence, this study focuses on the application of decision-making techniques before the launch of the project.

3. STEPS IN DECISION MAKING

Decision-making may involve the following steps:

- Step 1: Defining a problem - Identifying the problem and analyzing it is the first step in decision-making. Information regarding the number of alternative criteria needs to be known. This serves as a base for selecting the appropriate decision-making method.
- Step 2: Determining requirements - The criteria that are important for decision-making are chosen, as they make a difference in the outcomes.
- Step 3: Establish goals – The positive, clear goals are identified.
- Step 4: Identifying alternatives - Different alternatives are selected based on the criteria. The best alternative amongst all the other alternatives needs to be evaluated.
- Step 5: Developing evaluation criteria - The weights of each criterion are set according to the preferences of the decision maker.
- Step 6: Selecting decision-making tool - Depending on the nature of the problem, the number of alternatives, and their complexity, a decision-making tool is selected.

3.1. Selection of Building Materials

Material selection for the client/owner is complex, with a lot of parameters like quality, cost, environmental, comfort, safety, reusability, recyclability, cost, eco-friendliness, *etc*., involved in decision-making. Selection based on a few references may lead to cost overrun or non-suitability of material in that location. Thus, the performance of the structure may not be satisfactory. Few materials are selected based on local availability, climate, technical skills to use the material, *etc*. The suitability of materials is unique for a client/owner based on the preferences selected. The use of MCDM makes decision-making easy and accurate based on preferences selected for that project.

4. METHODS

Fuzzy Analytic Hierarchy Process is a method of Analytic Hierarchy Process (AHP) developed with fuzzy logic theory. It uses the hierarchical principle. For decision-making, when data are not in crisp form and have range or uncertainties, fuzzy AHP is used. The fuzzy AHP involves the following steps:

- Defining Objective
- Listing criteria and alternatives
- Preparing pairwise comparison matrix
- Calculating weights
- Evaluating alternatives according to weights
- Ranking of alternatives

4.1. Selection of Criteria

The objectives of the projects were defined based on the requirements of the client/owner. Based on the objectives of the project, the criteria involved in decision-making are listed in level 1. The criteria were grouped into a few parameters based on their nature in level 2 and finally into single/two/three criteria in level 3 based on the tradeoff between the parameters. The criteria shall be common for the alternatives considered for the project.

4.2. Pairwise Comparison

A pairwise comparison between each criterion was done using Saaty's scale, as listed in Table **1**. It was performed using a scale of relative importance. Elements of the pairwise matrix for each group under levels 1, 2, and 3 were obtained by accessing the relative importance of the Row and Column elements. After the pairwise comparison, the normalized matrix was constructed.

4.3. Fuzzy Geometric Mean for the Matrix

In this step, the n^{th} root of the product of each row was calculated. Multiplication of fuzzy numbers was done by multiplying lower, middle, and upper values with corresponding lower, middle, and upper values, respectively, as detailed in Table **2**.

Table 1. Saaty's scale of relative importance.

Definition	Intensity of Importance	Fuzzy scale
Equal importance	1	(1,1,1)
Moderate	3	(2,3,4)
Strong importance	5	(4,5,6)
Very strong importance	7	(6,7,8)
Extreme importance	9	(9,9,9)
Intermediate values	2 4 6 8	(1,2,3) (3,4,5) (5,6,7) (7,8,9)

Table 2. Geometric mean value calculation.

-	Criteria 1	Criteria 2	…….	Criteria n	Fuzzy Geometric mean value(r_i)
Criteria 1	(l_{11},m_{11},u_{11})	(l_{12},m_{12},u_{12})	-	(l_{1n},m_{1n},u_{1n})	$(l_{11}*l_{12}*.....l_{1n})^{1/n}$, $(m_{11}*m_{12}*.....m_{1n})^{1/n}$, $(u_{11}*u_{12}*.....u_{1n})^{1/n}$
Criteria 2	(l_{21},m_{21},u_{21})	(l_{22},m_{22},u_{22})	-	(l_{2n},m_{2n},u_{2n})	$(l_{21}*l_{22}*.....l_{2n})^{1/n}$, $(m_{21}*m_{22}*.....m_{2n})^{1/n}$, $(u_{21}*u_{22}*.....u_{2n})^{1/n}$
Criteria n	(l_{n1},m_{n1},u_{n1})	(l_{n2},m_{n2},u_{n2})	-	(l_{nn},m_{nn},u_{nn})	$(l_{n1}*l_{n2}*.....l_{nn})^{1/n}$, $(m_{n1}*m_{n2}*.....m_{nn})^{1/n}$, $(u_{n1}*u_{n2}*.....u_{nn})^{1/n}$

Table 3. Weight calculation.

-	Fuzzy Geometric Mean Value(r_i)	Fuzzy Weights	Weights (l+m+u)/3	Normalized Weights
C_1	(l_1,m_1,u_1)	$(l_1*1/u,m_1*1/m,u_1*1/l)$	W_1	$W_1/\sum W$
C_2	(l_2,m_2,u_2)	$(l_2*1/u,m_2*1/m,u_2*1/l)$	W_2	$W_2/\sum W$
Cn	(l_n,m_n,u_n)	$(l_n*1/u,m_n*1/m,u_n*1/l)$	W_n	$W_n/\sum W$
Sum	(l,m,u)	-	$\sum W$	1
Inverse	(1/u,1/m,1/l)	-	-	-

4.4. Fuzzy Weights (w^i)

In this step, each geometric mean value was multiplied by the inverse of the sum of all the geometric mean values to get fuzzy weights, as shown in Table 3.

$w_i=(l_1+l_2,m_1+m_2,n_1+n_2)$, where w_i is the geometric mean value.

Reciprocal of fuzzy number = (1/u,1/m,1/l)

Multiplying each fuzzy geometric mean value by their respective reciprocal value

weight=(l, m, n)*(1/u,1/m,1/l)

4.5. De-fuzzification

De-fuzzification was performed to get the weight values of each criterion. The defuzzied weights are given by (w_n) = (l +m + u)/3.

4.6. Normalized Weight

The normalized weight is given by the formula stated below:

Normalized weight=weight/∑weights

The sum of all the normalized weights is equal to one.

5. SELECTION OF BUILDING MATERIALS: A CASE STUDY

5.1. Criteria Selection

A total of 34 criteria were selected for the building materials for a residential project in Hanamkonda, a city in Telangana state situated in India. The criteria were classified into three different levels. The basic criteria for the project were listed in level 1 criteria, grouped into level 2 criteria, and finally into two main criteria to make trade-offs, as shown in Table 4.

5.2. Pairwise Comparison Matrix

After the selection of criteria, the pair comparison matrix was created based on the database collected from a set of fifteen academic experts, construction company personnel, contractors, and local people who completed their own house construction. A Google form was created to indicate Saaty's relative importance scale. The collected database was processed to get the final table of pair-wise comparison tables at each level, as listed in Table 1. A sample table of level 1 is shown in Table 5.

5.2.1. Level 1- Pairwise Comparison

A sample pairwise comparison of level 1 criteria is shown in Table 5.

5.3. Weight Calculation Using Fuzzy Geometric Mean Method

A sample calculation of weights with sample data for each criterion is shown in Table 6.

6. CRITERIA WEIGHTS

After pairwise comparison for each criterion using the geometric mean method, the following weights were obtained for the criteria of level 1, level 2, and level 3. The criteria weights of level 1 are listed below in Table 7:

The above weights of level 1, level 2, and level 3 were used to calculate the alternatives ranking. In level 1, performance had the highest weight, followed by ease of transportation and Warranty/Guarantee. In level 2, risk factors had the highest weight, followed by environmental factors. In level 3, technical factors had the highest weight, followed by cost factors.

7. MATERIAL ALTERNATIVES AND RANKING

The materials and their alternatives for the construction of a building at Warangal (Telangana state of India) are listed in Table 8. The pairwise comparison was done, and weights were calculated using the geometric mean method, as stated in Table 6. The ranking result is listed in Table 8.

Table 4. Selected criteria.

Level 1	Level 2	Level 3
• Reduce owner risk (ROR) • Knowing final cost (KFC) • Single responsible supplier (SRS) • Time (TIME)	Risk factors	Technical Factor
• Climatic conditions • Sustainability • Storage conditions • Availability	Environment conditions	
• Aesthetics • Specifications • Strength • Durability • Workability	Quality	
• Life of material • Size of project • Complexity of project • Resource availability	Project Characteristics	
• Experience in supplying material. • Familiarity with local conditions • Maintenance • Ease of construction	Constructability	
• Ease of transportation • Service for material. • Warranty/ guarantee • Performance	Non-Technical factors	Non-Technical factors
• Cost	Cost	Cost

Table 5. Pair-wise comparison matrix of risk factors.

-	Reduce Owner's Risk	Knowing Final Cost	Single Responsible Supplier	Time
Reduce owner's risk	1	5	3	6
Knowing final cost	0.2	1	0.25	3
Single responsible supplier	0.33	4	1	5
Time	0.17	0.33	0.2	1

Table 6. Weights of criteria in risk factors.

Criteria	Fuzzy Geometric Mean			Fuzzy Weights			Weights	Normalized Weights
Reduce owner risk (ROR)	0.276	0.342	0.841	044	070	0.248	0.120	0.107
Knowing final cost (KFC)	0.931	1.906	2.280	0.148	0.392	0.671	0.404	0.357
Single responsible supplier (SRS)	1.627	1.906	2.280	0.258	0.392	0.671	0.441	0.389

(Table 6) contd.....

Criteria	Fuzzy Geometric Mean			Fuzzy Weights			Weights	Normalized Weights
Time (TIME)	0.562	0.705	0.901	089	0.145	0.265	0.167	0.147
Sum	3.395	4.860	6.301	-			1.132	100
Inverse	0.159	0.206	0.295				-	-

Table 7. Criteria weights in levels 1,2, and 3.

Level 1		Level 2		Level 3	
Criteria	**Weights**	**Criteria**	**Weights**	**Criteria**	**Weights**
Reduce owner risk	0.173	Risk	0.318	Technical factor	0.443
Knowing final cost	0.269	Environment	0.215	Non-Technical factor	0.181
Single responsible supplier	0.303	Quality	0.188	Cost	0.376
Time	0.255	Project characteristics	0.127	-	
Climatic conditions	0.325	Constructability	0.153		
Sustainability	0.266	-			
Storage conditions	0.232				
Availability	0.176				
Aesthetics	075				
Specifications	0.106				
Strength	0.353				
Durability	088				
Workability	0.267				
Life of material	0.112				
Size of project	0.368				
Complexity of project	0.277				
Resource availability	0.166				
Availability of skilled labor	0.189				
Experience in supplying material	0.130				
Familiarity with local conditions	0.239				
Maintenance	0.196				
Ease of transportation	0.435				
Service for material	0.118				
Warranty/Guarantee	0.403				
Performance	0.479				

Table 8. Materials and their alternatives.

S.No	Material	Alternatives	Result (Criteria wt.*Alternative wt.)	Rank
1.	Cement	i. Ordinary Portland cement (OPC)	0.788	3
		ii. Portland pozzolana cement (PPC)	3.714	1
		iii. Blast furnace slag	1.386	2
2.	Fine Aggregate	i. River sand	3.775	1
		ii. Robo sand	2.210	2
3.	Bricks	i. Burnt clay bricks	420	1
		ii. Fly ash bricks	1.964	2
4.	Wood	i. Teak wood	2.437	2
		ii. UPVC	3.547	1
5	Pipes	i. CPVC/UPVC	420	1
		ii. GI	1.964	2
6	Tiles	i. Marble	3.200	1
		ii. Vitrified tiles	2.787	2

8. RESULTS AND DISCUSSION

After the selection of criteria, the weights were calculated. The alternatives were chosen based on the preferences of the project by the client/owner. Using the criteria and each alternative weight, final alternative weights were calculated using which rankings were given to each alternative. For the case study chosen at Hanamkonda, the final rankings of alternatives were as follows:

i) For cement, we considered 3 alternatives, and PPC ranked 1st out of three.

ii) For sand, we considered 2 alternatives, and River sand ranked 1st.

iii) For Bricks, we considered 2 alternatives, and Burnt clay brick ranked 1st.

iv) For Doors/windows, we considered 2 alternatives, and UPVC ranked 1st.

v) For Pipes, we considered 2 alternatives, and UPVC ranked 1st.

vi) For tiles, we considered 2 alternatives, and Marble tiles ranked 1st.

CONCLUSION

The research helps the decision makers in choosing the best building material, especially considering technical and financial aspects. From the case study, it may be concluded that the selected materials are the best for the clients based on their location-specific preferences. Similar materials may be ranked differently if the preferences of the client and location change. The criteria selected for assessing the building material play a vital role in decision-making. The rankings of alternatives depend on each individual's preferences and the weights given to each criterion. The ranking of alternatives may change based on location and financial aspects. Finally, optimal building materials can be selected using fuzzy AHP by the client for the successful execution of a project based on client preferences for that project.

SCOPE FOR FUTURE WORK

Individuals, groups, enterprises, and government entities can use MCDM for most decisions involving ranking, prioritizing, or choosing amongst alternatives. The research can be extended to bigger projects for optimal selection of materials by creating software. Based on the priority of the client and the locality of the project, the parameters can be modified in the software, and a ranking can be given for the alternatives.

AUTHORS’ CONTRIBUTIONS

It is hereby acknowledged that all authors have accepted responsibility for the manuscript's content and consented to its submission. They have meticulously reviewed all results and unanimously approved the final version of the manuscript.

LIST OF ABBREVIATIONS

MCDM = Multi Criteria Decision Making
AHP = Analytical Hierarchy Process

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF DATA AND MATERIALS

The data and supportive information are available within the article.

FUNDING

None.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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