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SUSTAINABLE MATERIAL SELECTION UNDER FUZZY ENVIRONMENT: A MULTI-CRITERIA DECISION-MAKING APPROACH

Deep Saha
Production Engineering Department, Jadavpur University, Kolkata, India
Email: deep20222023@gmail.com

Bijan Sarkar
Production Engineering Department, Jadavpur University, Kolkata, India
Email: bijan.sarkar@jadavpuruniversity.in

Abstract

The choice of materials is crucial when it comes to the environmental, financial, and social effects of construction and goods in the modern push for sustainability. In order to improve the sustainable material selection process, this research study investigates the integration of fuzzy logic with multi-criteria decision-making (MCDM) methodologies. Given the inherent subjectivity and ambiguities in assessing sustainability standards, the fuzzy environment offers a strong framework to manage human judgment and imprecise information. The goal of this research is to create a thorough decision support model that takes social, economic, and environmental aspects into account to enable more sustainable and knowledgeable material choices. The usefulness and practical implementation of the suggested model will be demonstrated through case studies in the manufacturing and construction industries.

Keywords: Sustainability, Fuzzy, multi-criteria, decision making

INTRODUCTION

It is a difficult effort to obtain and maintain competitive edge when choosing the right materials for new goods and continuously improving existing ones to match the ever-changing service needs. A component's performance with regard to functionality, life cycle costs, environmental effects, maintainability, and manufacturing feasibility is determined by the material used for it. The selection of materials necessitates a multi-criteria decision analysis approach that can concurrently account for the relative importance of each criterion and the deviations of each criterion's performance levels from its ideal values. The choice of material has a significant role in product design. Finding the material or materials that, once created, have the qualities, dimensions, and shape required for the product to fulfill its function in the most effective and efficient way possible while simultaneously posing the fewest financial burdens on the producer, the consumer, and the environment/society is the task at hand [1-4]. A product's or component's performance in terms of environmental effect, life cycle costs, maintainability, manufacturing, and usefulness is determined by the material used for it [3,4,6]. Therefore, choosing the right material for a given design is essential.

The design of new items is not the only use for material selection. In order to get and/or preserve a competitive advantage in the market, existing products are frequently changed, and the majority of these redesigns call for the use of new materials. Product service requirements are dynamic. They are always evolving. For example, in the 1950s, when turbine gas temperatures were typically 4500C, forged steel components were used to create turbine discs for aero-engines. At this temperature, the steel disc satisfied all specifications; but, at higher temperatures, its strength and resistance to oxidation rapidly decreased. Increased thermodynamic cycle efficiency, fuel savings, and a decrease in pollutant emissions all require higher temperatures. In the middle of the 1960s, forged steel discs were replaced with Ni-Fe alloys to satisfy this need of a higher temperature.

As advancements continued, the disc temperature rose to nearly 6000C in the 1970s, beyond which Ni-Fe alloy stability was no longer sufficient. Ni-based superalloys with improved precipitation hardening and thermal stability were introduced to increase disc capabilities above 6000C. Since the efficiency of an aero-engine turbine is directly correlated with temperature, researchers studying turbine technology and power plants are looking for ways to raise the temperature even more [7-9]. The rim parts of modern high-pressure turbine discs operate at temperatures close to 7600C, and in some specific military applications, they can reach as high as 8150C [10,11]. Therefore, in order to obtain both technical and commercial advantages in the current market, material selection plays a critical role in both the design of new goods and the ongoing drive for improvement of current ones [5].

Choosing the right material for a product can be difficult for a variety of reasons. (1) The full product/component life cycle, including production, operation and maintenance, and product retirement, is taken into consideration when choosing materials.

Manufacturers, business owners, consumers, product users, and regulatory bodies are growing more and more concerned with manufacturing costs, total cost of ownership over the product's life, including retirement, and environmental impact. It is not an easy task to choose materials that will best satisfy the technical, financial, and environmental requirements over the course of the product's life [3,12–17]. (2) The designers have access to more than 40,000 metal alloys and nearly as many non-metals, ceramics, plastics, and composites. The last ten years have seen the discovery of a multitude of new materials with differing degrees of improved properties by the research community. The design space is constantly growing because materials are evolving quicker now than they have ever done before. With the wide variety of materials available and new materials being developed, it is challenging for designers to choose the best material choices to solve design challenges even when they are schooled in the principles of materials and engineering [5, 17, 18]. (3) There are a lot of contradictory requirements that the product/component must fulfill. For example, the material needs to fulfill the service requirements, which might vary depending on a variety of characteristics for a mechanical design, including creep, wear resistance, ultimate tensile strength, toughness, etc. Other factors like manufacturability (weldability, machinability, etc.) and economic factors (unit cost, cost-to-mass ratio, etc.) must be taken into consideration because the material must be processed to achieve the dimensions and shape required for the component to serve its purpose in the most cost-effective manner. Because it is impossible to satisfy one criterion without also lowering the satisfaction of one or more other requirements, these requirements have varying degrees of relevance and are frequently incompatible. (4) In addition to disagreements among the many needs, there are disagreements among stakeholders. An example would be if the designer wanted a composite material that was extremely light in weight and had a high strength-to-mass ratio, but the recycler wanted a material that was pure and simple to recycle [19–23]. The difficulty for the designer is determining which of the many materials to use in order to best satisfy the many competing needs. To help the designer choose which material to use, a methodical methodology or mathematical tool is needed. In the end, material selection is a multi-criteria process that involves weighing trade-offs between a variety of competing and divergent performance criteria [16, 24].

MATERIAL SELECTION PROBLEM

The following traits of a material selection problem are present: (i) a finite set of performance criteria, typically incompatible, with non-commensurable units and disparate order of magnitudes; (ii) the criteria are of differing degrees of significance, and weights are allocated to each to represent their relative significance. (iii) The designer's level of worry over significant deviations;(iv) There is a finite range of possible materials from which the most suitable or best is to be selected. The challenge lies in choosing the optimal material from the range of available options while considering the current circumstances to ensure that the designer's goals are fully realized.

If adequate data is available and there is no ambiguity, the problem can be solved easily; however, this is not always the case. To address the ambiguous and hazy character of the problem, fuzzy theory is introduced in this study, and a model employing Fuzzy AHP and M TOPSIS is developed to select the ideal material.

RESEARCH METHODOLOGY

At first the problem is identified and a brainstorming session has been organized to identify the appropriate criteria for selecting the optimum material from the available alternative materials.

Then pairwise comparison matrix for the different criteria have been formed by the help of stakeholders during the brainstorming session and the respective weights of the criteria have been evaluated using Fuzzy AHP [25,26].

After getting the criteria weights, the initial decision matrix have been developed by the stakeholders considering the available materials with respect to the chosen criteria.

Then finally, the ranking of the alternatives has been done by M TOPSIS by using the following steps-

Step I: First step is to frame normalized decision matrix. Let ND represent normalized decision matrix which measures relative performance of formulated design alternatives, with element Nd_{ir}.a

$$ND_{ip} = \frac{a_{ip} - min(a_{ip})}{maxa_{ip} - mina_{ip}} \quad (i=1,2\ldots n;\ p=1,2\ldots s) \tag{1}$$

where a_{ir} measure the performance of i^{th} alternative with respect to p^{th} criterion.

$$ND_{ip} = \frac{Maxa_{ip} - a_{ip}}{maxa_{ip} - mina_{ip}} \tag{2}$$

Step 2: In this step, weight is provided to each attribute and evaluate weighted decision matrix. Let WD represent a weighted decision matrix, then WD = $\{L_{i,\,p}|1,2\ldots n;\ p=1,2\ldots s\}$

$$L_{ir} = W_i \frac{a_{ip}}{i\sqrt{\sum_{p=1}^{s} a_{ip}^2}} \tag{3}$$

where W_i is the weight of i^{th} criteria.

Step 3: In weighted decision matrix (WD), there is need to determine positive ideal solution (QI) along with negative ideal solution (MI).

$$QI = \{(maxL_{ip}|i\in L)\} \tag{4}$$

$$MI=\{(minL_{ip}|i\in L)\} \tag{5}$$

where L= {1,2,. ...., n}

Step 4: Each design alternative is deviated from positive ideal solution as well as negative ideal solution and this deviation is measured by an Euclidian distance method. Let E_r + and E_r - represent distance of ith design alternative from the QI and MI, respectively.

$$E_r^{+} = \sqrt{\sum_{i=1}^{n} (E_{i,p} - E_i^{+})^2} \quad p = 1,2,3,4\ldots\ldots s \tag{6}$$

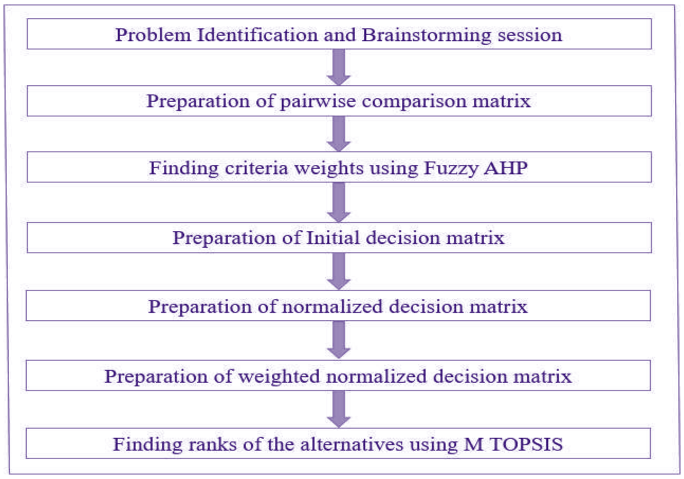
$$E_r^{-} = \sqrt{\sum_{i=1}^{n} (E_{i,p} - E_i^{-})^2} \quad p = 1,2,3,4\ldots\ldots s \tag{7}$$

Step 5: Establish E^+, E^- plane. E^+ in the x axis and E^- in the y axis. The point (E^+, E^-) represent each alternative. Assume the point B min (E^+) and max (E^-) which is consider as an optimized ideal reference. The distance from each alternative point B is calculated. Calculate the relative closeness from the ideal solution.

$$CR_p = \sqrt{(E_p^{+} - min(E_p^{+}))^2 + (E_p^{-} - max(E_p^{-}))^2} \tag{8}$$
$$where\ p = 1,2,3,4\ldots\ldots s$$

$$CR_p = E_r^{+} - min(E_r^{+}) \quad p = x, y \tag{9}$$

Figure 1: Flowchart showing the research methodology for the present study



NUMERICAL EXAMPLE

In this study six criteria (beneficial and non-beneficial) have been identified taking sustainability into consideration. These six criteria were used to select the optimum material for constructing a shaft. The 6 chosen criteria and the 6 alternative materials have been shown in table 1.

Table 1: Brief description of the criteria and alternatives for the present study

Criteria	Criteria type 1	Criteria type 2	Materials	Code for alternative
Cost (C1)	Non-Beneficial	Economic	Carbon steel 1	CS_1
Tensile strength (C2)	Beneficial	Social	Carbon steel 2	CS_2
Density (C3)	Non-Beneficial	Social	Carbon steel 3	CS_3
Yield strength (C4)	Beneficial	Social	Carbon steel 4	CS_4
Micro hardness (C5)	Beneficial	Social	Stainless steel	SS
Thermal conductivity (C6)	Beneficial	Environmental	Forging Brass	FB

RESULTS AND DISCUSSION

Table 2 displays the Fuzzy AHP pairwise matrix that was created with the assistance of stakeholders. All of the values have been defuzzied, and Table 3 contains the defuzziedAHP pairwise comparison matrix. Each criterion's weight has been determined and is displayed in Table 4. Table 4 presents the results, which indicate that the Consistency Ratio (CR) value is less than 0.1 (0.09). Because the data must pass the consistency check in every instance, this value of CR shows that the data is consistent. It has also been observed that criterion number 1 has the largest weight, followed by criterion number 5 in second place, and criterion number 3 in lowest weight. These weights show how important a criterion is while making decisions. The ranking of every option has been determined after weighing the factors.

The following is how the M TOPSIS method has been used to calculate the rank: As indicated in Table 5, the initial decision matrix has been created for several alternatives based on various criteria. Following the creation of the decision matrix, the data was normalized using Eqs. (1) and (2) in order to facilitate additional computation, as indicated in Table 6. The computation of the weighted decision matrix involved multiplying every column in Table 6 by the corresponding criterion weights that were derived from Table 4. The decision matrix with weights, has been displayed in Table 7. Eqs. (6),(7),(8) and (9) have been used to determine the relative closeness of each alternative from the ideal solution. Based on this relative closeness, all of the alternatives have been ranked.

While the material with the lowest relative closeness receives the lowest rating, the alternative with the highest relative closeness has been awarded the highest rank. Table 8 displays the relative closeness values along with their ranking for each possibility. Table 8 demonstrates that, out of all the possibilities, the material SS has the highest relative closeness and is ranked first. The material that ranks first demonstrates that, when all sustainability-related factors are taken into account, it is the best of all the materials that were studied.

After ranking the alternatives single linked agglomerative dendogram clustering have been performed to cluster the materials based on their Euclidean distance from PIS and NIS. At first the relative distance between the alternative materials have been found out which is shown in table 9. From the relative distance table, the minimum relative distance is identified for example, in table 9, it is 0.00824786 between SS and CS2 as shown in table 10. Now SS is merged with CS2 and the respective row and column of SS is removed from table 10. The result of this step is shown in table 11. Now again the minimum relative distance is identified from table 11 and merging of the alternative is done similarly. This process is continued till we obtain the final result where there is only one relative distance left as shown in table 12.The final dendogram showing the clustering of the six materials has been shown in figure 2.

Table 2: Fuzzy AHP Comparison Matrix

	C1	C2	C3	C4	C5	C6
C1	1	5~	3~	5~	2~	7~
C2	1/5~	1	7~	2~	1/5~	3~
C3	1/3~	1/7~	1	1/7~	1/7~	1/5~
C4	1/5~	1/2~	7~	1	1/3~	3~
C5	1/2~	3~	7~	3~	1	5~
C6	1/7~	1/3~	5~	1/3~	1/5~	1

Table 3: De fuzzified AHP Comparison Matrix

	C1	C2	C3	C4	C5	C6
C1	1	5	3	5	2	7
C2	0.2083	1	7	2	0.2083	3
C3	0.375	0.148	1	0.148	0.148	0.2083
C4	0.2083	0.506	7	1	0.375	3
C5	0.506	3	7	3	1	5
C6	0.148	0.375	5	0.375	0.2083	1

Table 4: Calculated weightage of each criterion by Fuzzy AHP

Sl. No.	Criteria	Weight	
1	Cost (C1)	0.28	CI=0.136272 RI=1.41 CR=0.096647
2	Tensile strength (C2)	0.14	
3	Density (C3)	0.02	
4	Yield strength (C4)	0.11	
5	Micro hardness (C5)	0.23	
6	Thermal conductivity (C6)	.04	

Table 5: Initial decision matrix provided by stakeholders

Material	Cost (Rs/Kg) (C1)	Tensile strength (MPa) (C2)	Density (gm/cc) (C3)	Yield strength (MPa) (C4)	Micro hardness (Hv) (C5)	Thermal conductivity (cm^2/h) (C6)
CS_1	501.5	330	20	280	55	69.8
CS_2	601.8	360	20	300	62	51.8
CS_3	475.15	420	15	200	74	51.8
CS_4	334.9	520	12	450	78	48.6
SS	391	785	55	390	90	16.3
FB	430.1	365	30	140	75	120

Table 6: Normalized decision matrix

Material	Cost (Rs/Kg) (C1)	Tensile strength (MPa) (C2)	Density (gm/cc) (C3)	Yield strength (MPa) (C4)	Micro hardness (Hv) (C5)	Thermal conductivity (cm^2/h) (C6)
CS_1	0.38	0.00	0.81	0.45	0.00	0.52
CS_2	0.00	0.07	0.81	0.52	0.20	0.34
CS_3	0.47	0.20	0.93	0.19	0.54	0.34
CS_4	1.00	0.42	1.00	1.00	0.66	0.31
SS	0.79	1.00	0.00	0.81	1.00	0.00
FB	0.64	0.08	0.58	0.00	0.57	1.00

Table 7: Weighted normalized decision matrix

Material	Cost (Rs/Kg) (C1)	Tensile strength (MPa) (C2)	Density (gm/cc) (C3)	Yield strength (MPa) (C4)	Micro hardness (Hv) (C5)	Thermal conductivity (cm^2/h) (C6)
CS_1	0.11	0.00	0.02	0.05	0.00	0.02
CS_2	0.00	0.01	0.02	0.06	0.05	0.01
CS_3	0.13	0.03	0.02	0.02	0.12	0.01
CS_4	0.28	0.06	0.02	0.11	0.15	0.01
SS	0.22	0.14	0.00	0.09	0.23	0.00
FB	0.18	0.01	0.01	0.00	0.13	0.04

Table 8: Relative closeness and ranking of the alternatives

Material	E_r^+	E_r^-	RC_i	Rank of alternatives
CS_1	0.29640	0.18291	0.38161	6
CS_2	0.23398	0.28987	0.55335	**2**
CS_3	0.22412	0.19659	0.46728	3
CS_4	0.30402	0.19626	0.39230	4
SS	0.22574	0.29023	0.56249	**1**
FB	0.26664	0.17039	0.38989	5

Table 9: Relative distances between data points

	CS_1	**CS_2**	CS_3	CS_4	**SS**	FB
CS_1	0					
CS_2	0.123841	0				
CS_3	0.073563	0.09379967	0			
CS_4	0.015372	0.116912077	0.079901	0		
SS	0.128493	0.00824786	0.093654	0.122303	0	
FB	0.032286	0.123863417	0.049944	0.045459	0.126627	0

Table 10: An example to show the lowest value selection from relative distances between data point

	CS_1	**CS_2**	CS_3	CS_4	**SS**	FB
CS_1	0					
CS_2	0.123841	0				
CS_3	0.073563	0.09379967	0			
CS_4	0.015372	0.116912077	0.079901	0		
SS	0.128493	0.00824786	0.093654	0.122303	0	
FB	0.032286	0.123863417	0.049944	0.045459	0.126627	0

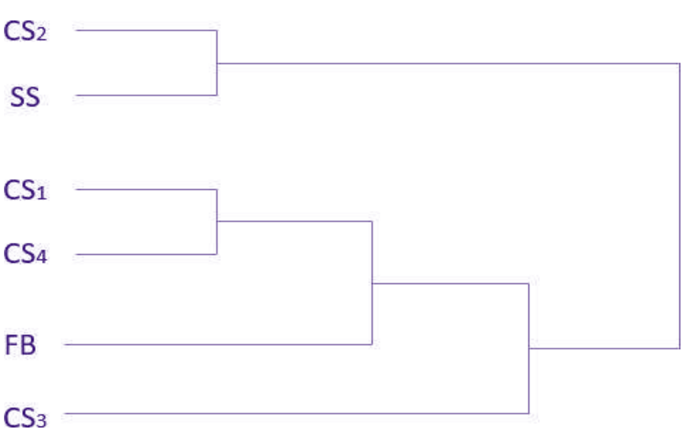
Table 11: Clustering by removing the lowest valued row and column

	CS_1	**CS_2**	CS_3	CS_4	**SS**
CS_1	0				
CS_2, SS	0.123841	0			
CS_3	0.073563	0.0938	0		
CS_4	0.015372	0.116912	0.079901	0	
FB	0.032286	0.123863	0.049944	0.045459	0

Table 12: Final result of clustering

	CS_1, CS_4, FB, CS_3	CS_2, SS
CS_1, CS_4, FB, CS_3	0	
CS_2, SS	0.123841423	0

Figure 2: Final Dendrogram showing the clustering of the materials



CONCLUSION

The challenge of decision making for sustainable material selection (SMS) is intricate and involves multiple factors. As society develops and becomes more complicated, it may entail large group decision making (LGDM). In recent years, the SMS has been a research hotspot due to the engagement of multiple stakeholder perspectives and the areas of disagreement among them. In order to bridge the gap with earlier research, this study suggests using a hybrid MC-LGDM model in an uncertain setting to build the study's framework. Fuzzy logic has been incorporated in the model to address uncertainty that arises during the expert evaluation process, allowing the reviewed material to get closer to human cognitive levels. Because new and improved features are always being added, making the right material choice for a given engineering application is one of the most important and difficult challenges for designers and manufacturers. This study helps the designer choose materials based on necessary characteristics and offers important data for the examination of different decision-making scenarios. The Fuzzy-AHP-TOPSIS approach is used to rank the qualities. Fuzzy AHP technique was used in the primary stage to calculate the weights of each criterion, and the M-TOPSIS technique was used in the secondary stage to determine the rank of each alternative (materials).

According to Table 6, stainless steel (SS) material comes out to be the most suitable sustainable material for making shaft considering the identified criteria under the present study conditions and the developed model. After alternative ranking, clustering of the materials has been performed which has been shown in figure 2. The dendogram gives a visual impression of the relationship between the materials. . This approach will become a dependable and easy way to choose the best option. In future, a variety of other MCDM techniques can be used to enhance the outcomes and further more machine learning tools could be introduced to deal with data with high veracity and huge volume.

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