Journal of Engineering

journal homepage: www.joe.uobaghdad.edu.iq

Volume 30 Number 3 March 2024

Material Selection Using Hybrid Grey Relation Analysis Approach Based on Weighted Entropy for Ranking: The Case of Helicopter Rotor Blade

Alya I. AL-Taie[1,*], Qasim M. Doos[2]

Department of Mechanical Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq
alya_altaie@yahoo.com[1], kasim_daws@yahoo.com[2]

ABSTRACT

Engineering design relies highly on the selection of suitable materials. Because there are many engineering materials, selecting a suitable material for a product requires a systematic selection approach. This paper provides a hybrid strategy for choosing the best material for an engineering design to give the best performance at the lowest cost based on Ashby's performance indices. Then, it ranks the result by the grey relational approach integrated with the Weighted Entropy Method to choose the optimum material for the main rotor blade of a helicopter. Different materials used for manufacturing rotor blades, such as Aluminium alloys, titanium alloys, steel, composites, and wood, have been discussed. The performance indices chosen are stiffness, strength, and fracture toughness. The performance indices proved that the composite material has excellent structural strength, stiffness, and toughness. The result shows that CFRP is the best material for manufacturing helicopter rotors, while wood and steel were the best and cheapest when the design had to be economical.

Keywords: Material selection, Helicopter rotor blades, Material performance index, Grey relation analysis, Weighted entropy method.

---

*Corresponding author

Peer review under the responsibility of University of Baghdad.
https://doi.org/10.31026/j.eng.2024.03.03

Article received: 04/01/2023
Article accepted: 13/04/2023
Article published: 01/03/2024

أختيار المواد باستخدام نهج تحليل العلاقة الرمادي الهجين استنادًا إلى الانتروبيا الموزونة للترتيب: حالة الشفرة الدوارة للمروحية

عالية عصام الطائي*، قاسم محمد دوس

قسم الهندسة الميكانيكية، كلية الهندسة، جامعة بغداد، بغداد، العراق

الخلاصة

يعتمد التصميم الهندسي بشكل كبير على اختيار المواد المناسبة. نظرًا لوجود العديد من المواد الهندسية ، فإن اختيار مادة مناسبة للمنتج يتطلب نهج اختيار منهجي. يقدم هذا البحث إستراتيجية مختلطة لاختيار أفضل مادة للتصميم الهندسي لإعطاء أفضل أداء بأقل تكلفة بناءً على مؤشرات أداء اشبي ومن ثم ترتيب النتيجة من خلال نهج العلائقية الرمادي المدمج مع طريقة الانتروبيا الموزونة لاختيار المادة المثلى لشفرة الدوار الرئيسية لطائرة هليكوبتر. تمت مناقشة المواد المختلفة المستخدمة في تصنيع الشفرات الدوارة ، مثل سبائك الألومنيوم وسبائك التيتانيوم والفولاذ والمركبات والخشب. مؤشرات الأداء المختارة هي الصلابة والقوة وصلابة الكسر. أثبتت مؤشرات الأداء أن المادة المركبة تتمتع بقوة هيكلية وصلابة وصلابة كسر ممتازة. تظهر النتيجة أن المواد المركبة هي أفضل مادة لتصنيع دوارات طائرات الهليكوبتر ، بينما كان الخشب و الفولاذ أفضل وأرخص المواد عندما كان على التصميم أن يكون اقتصادياً.

الكلمات المفتاحية: اختيار المواد ، شفرات دوارة الهليكوبتر، مؤشر أداء المواد ، تحليل العلاقة الرمادية ، طريقة الانتروبيا المرجحة.

1. INTRODUCTION

The Selection of materials is one of the most practical but challenging problems developers face since it is linked to process performance. Designers, engineers, and manufacturers continuously seek new and improved materials to enhance performance and lower the cost of the items to stay market competitive **(Al-Mendwi, 2009; Mehmood et al., 2018)**.

A helicopter, unlike a normal fixed-wing aircraft, uses rotary blades. A helicopter's wings, or blades, are part of a more extensive dynamic system called the rotor**(Edwards and Davenport, 2006)**. The rotor is the significant component of the helicopter, consisting of blades attached to the center of the rotor. The main rotor blades achieve the vehicle's lift, which provides thrust and generates lift. Regarding design considerations, the rotor blade is considered a one-dimensional beam**(Mishra et al., 2020)**. **Fig. 1** shows the helicopter rotor blade profile.

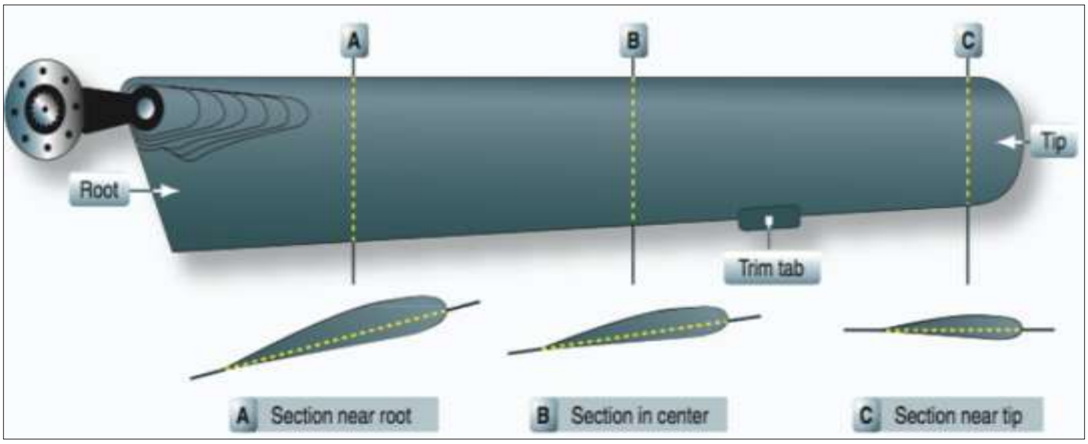

Figure 1. Helicopter blade profile **(Bagheinia and Ghassemi, 2018)**

Selecting a material for the rotor blade frame is a critical component of the design process for a helicopter. Rotor blade frames can be constructed using a variety of materials. Metals and composites are the broad categories that cover these materials. Wood, aluminium, steel, titanium, fiber composites (glass, carbon, and aramid fibers), and other metals are used to make rotor blades.

According to Balaji and his colleagues carbon epoxy and boron epoxy are recommended design considerations for the helicopter blade due to their good strength-to-weight ratio. They are also compared to Aluminium material using the ANSYS simulation tool **(Balaji et al., 2016)**. **(Mishra et al., 2020)** propose a technique for analyzing the vibration of a rotor blade using FEM methods, which is achieved by designing a rotor blade using Composite materials (Glass Epoxy 2024).

Generally, many methods are available to make the material selection **(Emovon and Oghenenyerovwho,2020)**. Design engineers and decision-makers utilize a variety of approaches to select the best material from several alternatives. Identifying the objective, constructing the selection criteria, defining the suitable options, and final selection are the four stages of the selection process **(Erzaij and Bidan, 2016)**. **(Patil et al., 2017)** illustrate using a Fuzzy Analytical Hierarchical Approach in parallel with Grey Relation Analysis to choose the most suitable automobile. **(Radhi and Burhan,2022; Hasan and Jaber, 2023; Erzaij and Bidan, 2016; Zakeri et al., 2023)** intended to examine the appropriateness of various MC-DM strategies. In **(Wu et al., 2018),** A hybrid systematic evaluation model was suggested, which integrates grey relational analysis (GRA) with the analytic hierarchy process (AHP) and a unique entropy-based method to derive the objective weighting of indices. **(Unal et al., 2018; Lee et al., 2020)** illustrated the material selection procedure; they accomplished the study with the use of a design performance index together with Ashby charts.

This research outlines an integrated (hybrid) strategy for selecting the best material for an engineering design that provides the best performance at the lowest cost. The primary purpose is to identify the best candidate material for the rotor based on Ashby's performance indices and then rank the result by the grey relational approach based on the entropy weight method. The Entropy Weight Method computes the weights of criteria (performance indices).

2. MATERIALS SELECTION METHODOLOGY

Material selection is a crucial step in the design process and manufacturing. Generally, material selection aims to minimize cost while meeting customer requirements and performance goals **(Rahim et al., 2020)**.

2.1 Short-Listed Materials and Relevant Attributes

Developing a lightweight rotor blade for a helicopter aims to improve mechanical attributes and reduce costs. Depending upon those basic parameters, material density, yield strength, Young's modulus, fracture toughness, and cost are relevant attributes. Different materials used for manufacturing rotor blades, such as Aluminium alloys, titanium alloys, steel, composites, and wood, have been discussed. The performance indices chosen are stiffness, strength, and fracture toughness.

A list of materials meeting these requirements is shown in **Table 1**. The short-listed materials were then optimized using the performance indices. The performance weight was calculated using the entropy-weighted method, and the results were ranked using the grey relational analysis method.

Table 1. Material short-list and their properties.

Materials	ρ (mg/m^3)	σy (MPa)	E (GPa)	$k1c$ ($MPa.m^5$)	Cm ($/kg)
CFRP	1.55	800	109.5	47.05	42
GFRP	1.86	151	21.5	15	20
Al-alloys	2.7	265	75	28.5	1.6
Ti-alloys	4.6	747.5	105	67	70.5
Steel	7.85	750	209	107	0.85
Wood	0.7	50	13	7	0.9

2.2 Material Performance Index

The selection of rotor blade material depends mostly on structural strength and cost-effectiveness **(Mishra et al., 2020)**. Consequently, the material's mechanical attributes, including high strength, stiffness, and fracture toughness, are listed as the material requirement.

The strength-to-weight ratio of a material is among the most important requirements to consider when selecting the material in aero engineering applications **(Mohammed, 2017)**. The index that maximizes the ratio of strength to weight is as follows:

$$M1 = \sigma y^{2/3}/\rho \tag{1}$$

for cost-effectiveness:

$$M1 = \sigma y^{2/3}/\rho Cm \tag{2}$$

The rotor blade structure must be rigid enough not to bend or buckle. Maximizing fracture stiffest index is as follows:

$$M2 = E^{1/2}/\rho \tag{3}$$

for cost-effectiveness:

$$M2 = E^{1/2}/\rho Cm \tag{4}$$

The material's fracture toughness is another important attribute to consider. Increasing the fatigue life of the blades requires a material with high fracture toughness. The maximizing fracture toughness index is as follows:

$$M3 = k1c/\rho \tag{5}$$

for cost-effectiveness:

$$M3 = k1c/\rho Cm \tag{6}$$

The optimum materials are evaluated using the indices. The material with the maximum M value is best fitted for rotor blade construction. Additional criteria, such as cost, will also be considered in the material selection. Supporting information is then gathered to ranking materials to a final choice, providing a close match between design requirements and material attributes.

2.3 An Overview of Grey Relational Analysis Method

The GRA method was developed based on the grey system theory **(Vatansever and Akgűl, 2018)**. The grey relational grade, often known as the GRG, can represent the degree of the relationship between multiple responses **(Hammood, 2021)**; better solutions will have a higher GRG. As a result, GRG can be utilized as an evaluation index for problems with multiple objectives; GRA is used to determine a priority ranking for all possible design phases **(Zhang et al., 2022)**. This theory is widely used in various research fields because of its advantages in evaluating complex systems with several linked indicators. This concept has been demonstrated to aid in processing uncertain, incomplete, or inaccurate data**(Maidin et al., 2022; Wu et al., 2018)**. GRA is often used to measure financial performance, logistic performance, and process optimization**(Patil et al., 2017; Al-Taie, and Doos, 2023)**. The following are the procedures involved in the traditional grey relational analysis **(Kuo et al., 2008; Tosun, 2006; Leong et al., 2022; Sumesh et al., 2022; Asaad et al., 2022; Hustedt et al., 2016; Özgür et al., 2023; Hsiao et al., 2017)**:

2.3.1 Grey Relational Sequence Generation

The grey relational sequence was formed by normalizing the decision matrix and producing the attribute comparability sequence. The indices can be normalized, for which the bigger the better (or benefit attributes), as follows **(Wu et al., 2018)**:

$$y_{ij} = \frac{x_{ij} - min(x_{ij})}{max(x_{ij}) - min(x_{ij})}, (1 \leq i \leq n, 1 \leq j \leq m) \tag{7}$$

Additionally, the cost attribute index, where the smaller the better, can be normalized as follows **(Wu et al., 2018)**:

$$y_{ij} = \frac{max(x_{ij}) - x_{ij}}{max(x_{ij}) - min(x_{ij})}, (1 \leq i \leq n, 1 \leq j \leq m) \tag{8}$$

where x_{ij} is the value of performance indices for each material and y_{ij} is the linear scale standardized matrix **(Wu et al., 2018)**.

2.3.2 Derivation of the Reference Sequence

After the grey relational sequence was generated, a reference sequence, X0, with values equal to 1, was defined and compared to the generated sequence. The following is the reference sequence **(Maidin et al., 2022)**:

$$X0 = (x01, x02, ..., x0j, ..., x0n) = (1,1, ..., 1..., 1) \tag{9}$$

where $X0$ is the reference sequence value.
The matrix can be written as **(Wu et al., 2018)**:

$$Z = (z_{ij})_{n*m} = |x_{0j} - x_{ij}|, (1 \leq i \leq n, 1 \leq j \leq m) \tag{10}$$

where z is the reference sequence matrix.

2.3.3 Calculating the Grey Relational Coefficient

The grey relational coefficient shows a degree of grey relation between the reference sequence and experiment sequence that can be computed using the equations below **(Wu et al., 2018)**:

$$\xi_{ij} = \frac{minmin\{z_{ij}\} + \rho \, max \, max\{z_{ij}\}}{z_{ij} + \rho max \, max\{z_{ij}\}}, (1 \leq i \leq n, 1 \leq j \leq m) \tag{11}$$

where ξ_{ij} is the grey relational coefficient of the jth index of the ith alternative.
The factor ρ ∈ [0, 1] is the distinguishing coefficient and is usually set to 0.5 **(Sarraf and Nejad, 2020)**.

2.3.4 Grey Relational Grade

The grey relational grade is distributed between zero and one **(Sarraf and Nejad, 2020)** Grey relational quality is obtained by using the formula below:

$$\Gamma(x_0, x_i) = \sum_{j=1}^{n} W_j \; \xi_{ij} \tag{12}$$

where W_j is the weight assigned to the attribute j. The total weight assigned to the attributes is unity **(Zhang et al., 2022)**

$$\sum_{j=1}^{n} W_j = 1 \tag{13}$$

2.4 An Overview of Entropy Weighting Method

The Entropy technique is used to assign weights to the requirements. It is an essential information-weighting method that eliminates the effects of personal factors on variable weighting. It is widely applied and has several uses in engineering and other industries **(Vatansever and Akgűl, 2018)**. The weight determination procedure is outlined below.
The first step is the building of a decision matrix (X). The decision matrix of the n*m performance matrix can be written as follows **(Xing et al., 2023; Sahoo et al., 2023; Wu et al., 2018; Kumar et al., 2021; Chen, 2020; Chodha et al., 2021)**:

$$X = (x_{ij})_{n*m}, i = 1,2,\dots,n; j, 1,2,\dots,m \tag{14}$$

where x_{ij} is a numerical number indicating the alternative's performance. The second step is the normalization of the decision matrix (performance indices) as follows **(Zhu et al., 2020)**:

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}}, i = 1,2,\dots,n; j = 1,2,\dots,m \tag{15}$$

The third step is to calculate the entropy **(Zhu et al., 2020)**

$$e_j = \frac{\sum_{i=1}^{n} p_{ij} ln p_{ij}}{ln\, n} \tag{16}$$

The fourth step is to calculate the objective weight value:

$$w_j = \frac{1-e_j}{\sum_{j=1}^{m}(1-e_j)}, j = 1,2,\dots,m \tag{17}$$

3. APPLICATION AND RESULTS

This research aims to determine the optimal material for designing helicopter rotor blades. The design must be stiff, strong, and tough while light and cheap for a better design. Regarding Ashby's method, the importance of benefit and non-benefit attributes in the design is essential for identifying the differences between attributes when generating the material indices. The goal is always to enhance the value of the benefits characteristic and minimize that of the non-benefit attribute. Among the considered attributes, density and cost are classified as non-benefit features, whereas the remaining attributes are benefit attributes. The following material indices are maximized or minimized based on what needs to be maximized or minimized. The following indices confirm that a given design's component performs at an optimum level:

- Young's modulus versus density $E^{1/2}/\rho$
- Young's modulus versus cost $E^{1/2}/\rho Cm$
- Yield strength versus density $\sigma y^{2/3}/\rho$
- Yield strength versus cost $\sigma y^{2/3}/\rho Cm$
- Fracture toughness versus density $k1c/\rho$

- Fracture toughness versus cost $k1c/\rho Cm$

3.1 Performance Evaluation without Cost Criteria

The study's application is divided into three sections. The first includes calculating the rotor blade performance indices. The Entropy Weight Method is used in the second step to determine the indices' weights. In the last step, the performance indices were ranked using Grey Relational Analysis to select the optimal material.

Table 2 shows the rotor blade performance indices. The indices are calculated using the values of the individual properties in **Table 1** by applying Eqs. (1, 3, and 5) without cost-effectiveness. Composites, Aluminum alloys, Titanium alloys, steel, and wood are the five alternative materials. It indicates that each material's index is different. The best material in each category has the most significant index value. CFRP has the highest values according to the stiffness, toughness, and strength indices. It is understood from the decision matrix that CFRP is a good material alternative. **Fig. 2** illustrates the result obtained from **Table 2.**

Table 2. Performance indices and their values for each alternative.

Materials	Stiffness ($GPa^{1/2} . m^3/Mg$)	Toughness ($MPa. m^{1/2}$).(Mg/m^3)	Strength ($MPa^{2/3} . m^3/Mg$)
CFRP	6.7510	30.3540	56.8511
GFRP	2.4930	8.0640	15.5025
Al-alloys	3.2070	10.5550	15.5672
Ti-alloys	2.2270	14.5650	18.3047
Steel	1.8390	13.5030	10.7503
Wood	4.5740	6.7857	15.7625

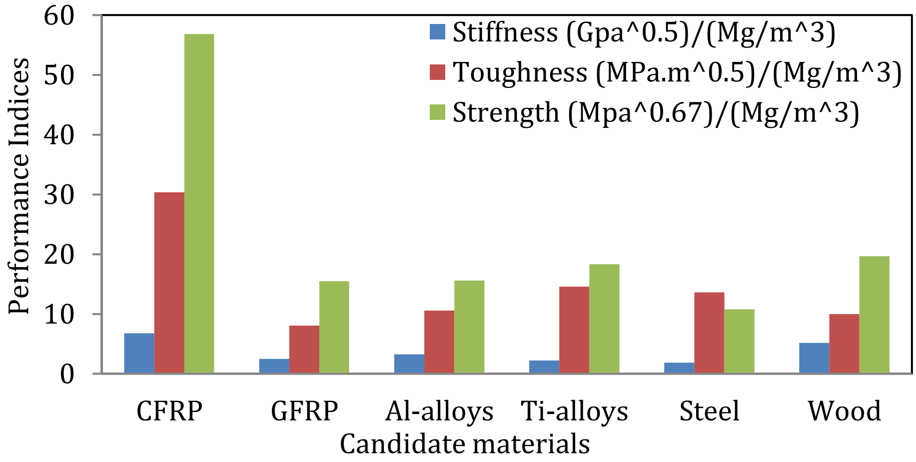

Figure 2. Performance indices and their values for each alternative.

3.1.1 The Entropy Weight Method to Determine the Weights of the Indices

The entropy-weighted method was used to determine each alternative's performance weight by applying Eq.s, (14–17) to the performance values in **Table 2**, which is written as a decision matrix. **Table 3** shows the normalization procedure using Eqn. 15. The following procedure is for finding the entropy value using Eqn.16, as in **Table 4**. The last step is calculating the weight using Eq. (17), as shown in **Table 5**, which illustrates the weights of the indices. Examining these values reveals that the criteria weights are quite close, as shown in **Fig. 3.**

Table 3. The normalized matrix for indices

Stiffness	Toughness	Strength
0.3201	0.3621	0.4283
0.1182	0.0962	0.1168
0.1521	0.1259	0.1173
0.1056	0.1737	0.1379
0.0872	0.1611	0.0810
0.2168	0.0809	0.1187

Table 4. Entropy value for indices

Entropy value	Stiffness	Toughness	Strength
E_j	1.5338	1.5071	1.4519

Table 5. Performance indices weight according to entropy weighted method.

Entropy weight	Stiffness	Toughness	Strength
W_j	0.358	0.340	0.303

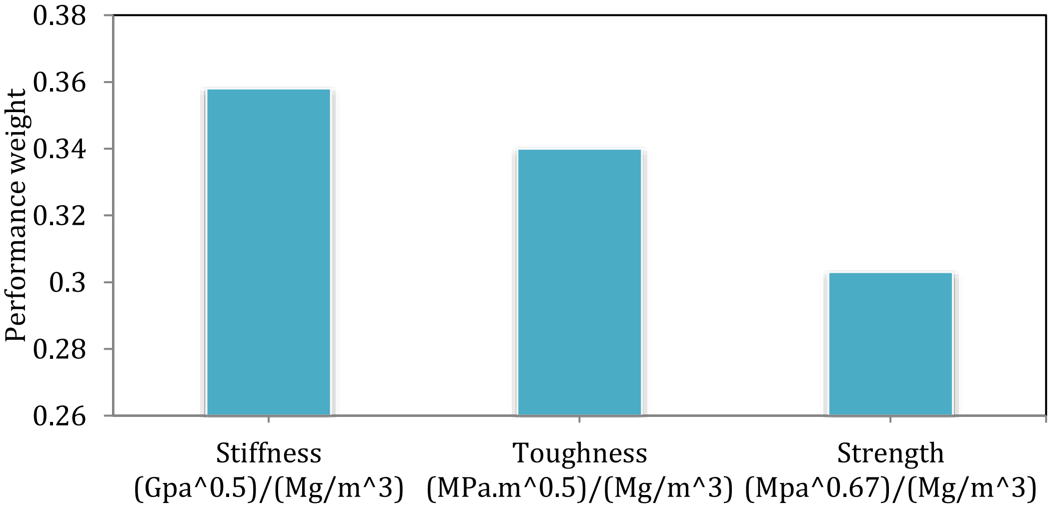

Figure 3. Performance indices weight according to entropy weighted method.

3.1.2 Performance ranking utilizing grey relational analysis

Table 6 shows the normalization matrix derived from Eq. (7), where the more significant, the better (or benefit attributes). The grey relational coefficient is determined by calculating the deviation after normalization. **Table 7** illustrates the deviation of the reference sequence value derived using the Eq.s (9, 10), and **Table 8** shows the grey relation coefficient and grade derived using the Eq.s (11, 12). Ranking the results obtained, the best material alternative, as shown in **Fig. 4**, according to the GRA method, is CFRP.

Table 6. Performance indices normalization for benefit attributes.

Materials	Stiffness	Toughness	Strength
CFRP	1.000	1.000	1.000
GFRP	0.133	0.054	0.103
Al-alloys	0.279	0.160	0.104
Ti-alloys	0.079	0.330	0.164
Steel	0.000	0.285	0.000
Wood	0.557	0.000	0.109

Table 7. Deviation sequence.

Materials	Stiffness	Toughness	Strength
CFRP	0.000	0.000	0.000
GFRP	0.867	0.946	0.897
Al-alloys	0.721	0.840	0.896
Ti-alloys	0.921	0.670	0.836
Steel	1.000	0.715	1.000
Wood	0.443	1.000	0.891

Table 8. Weighted grey relational coefficients and grad results

Materials	Stiffness	Toughness	Strength	Grad	Rank
CFRP	0.358	0.340	0.303	0.3333	1
GFRP	0.131	0.117	0.108	0.1189	6
Al-alloys	0.146	0.127	0.108	0.1272	4
Ti-alloys	0.126	0.145	0.113	0.1281	3
Steel	0.119	0.140	0.101	0.120	5
Wood	0.190	0.113	0.109	0.1372	2

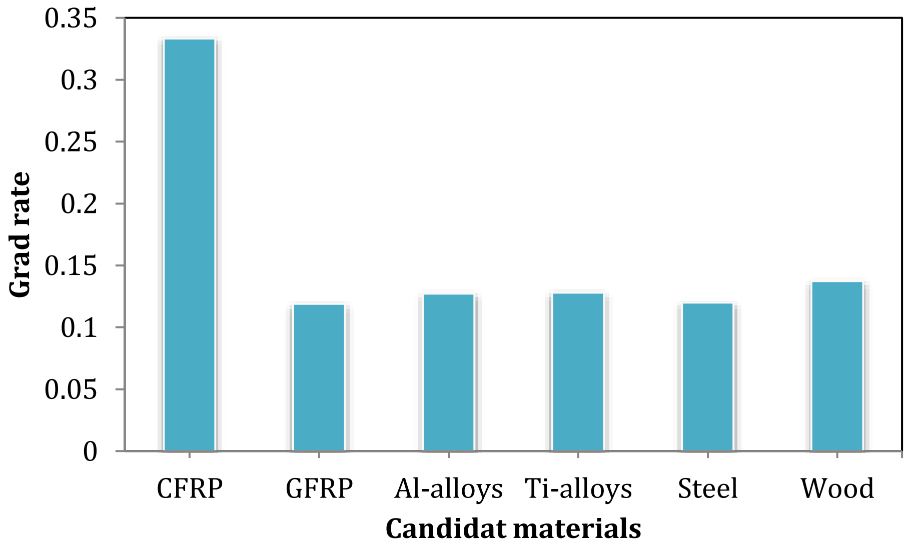

Figure 4. Weighted grey relational coefficients and grad results

3.2 Performance Evaluation with Cost Criteria

The rotor blade performance indices with cost attributes are given in **Table 9**. The indices are calculated using the values of the individual properties in **Table 1** by applying Eq.s (2, 4, and 6) for cost-effectiveness. The cheapest material in each category has a maximum index value. Wood and Steel have maximum values according to the stiffness, toughness and strength indices. As a result, it is understood from the decision matrix that wood and Steel a good material alternative. **Fig. 5** illustrates the result obtained from **Table 9.** The performance weight was calculated. **Table 10** demonstrates the weights of the indices with cost-effectiveness. The performance weight of each alternative is determined by applying Eq.s (15–17) to the performance values in **Table 9,** which is written as a decision matrix as described previously. Examining these values reveals that the toughness and strength criteria weights are highest compared to the stiffness, as shown in **Fig. 6**.

Table 9. Cost performance indices and their values for each alternative

Materials	Stiffness $((GPa^{1/2})\,(m^3/Mg)(\$/Mg))$	Toughness $((MPa.\,m^{1/2})(Mg/m^3)(\$/Mg))$	Strength $((MPa^{\frac{2}{3}}.)(m^3/Mg)(\$/Mg))$
CFRP	0.161	0.723	1.354
GFRP	0.125	0.403	0.775
Al-alloys	2.005	6.597	9.730
Ti-alloys	0.032	0.207	0.260
Steel	2.167	16.036	12.647
Wood	5.723	11.111	21.826

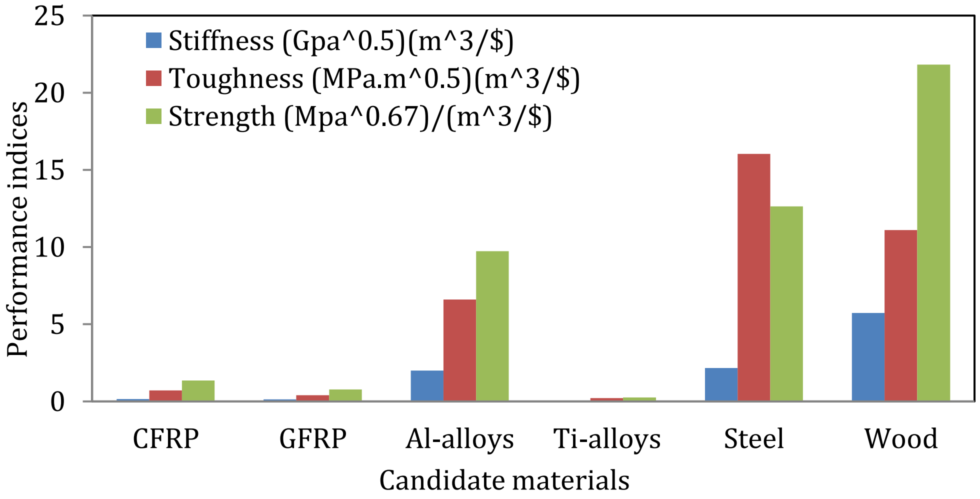

Figure 5. Cost performance indices and their values for each alternative

Table 10. Cost Performance indices weight according to entropy weighted method.

Entropy weight	Stiffness	Toughness	Strength
W_j	0.046	0.400	0.554

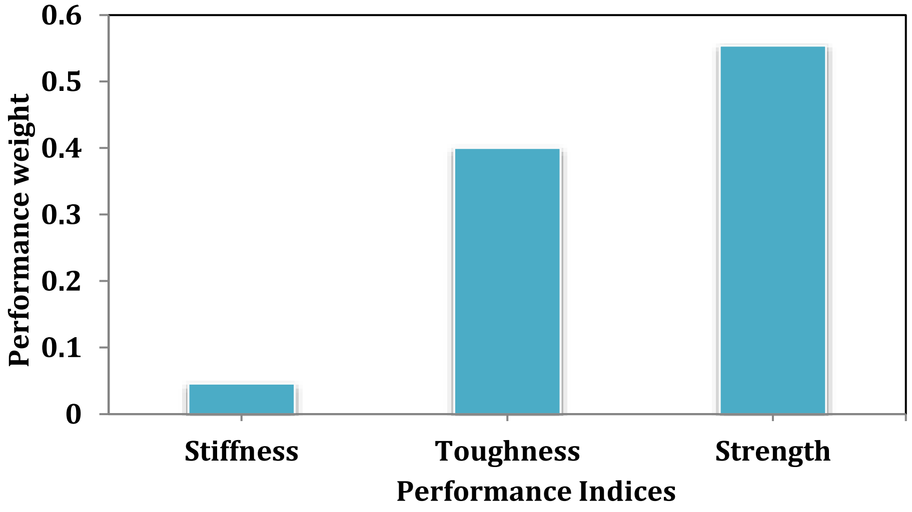

Figure 6. Cost Performance indices weight according to entropy weighted method.

Now, utilizing grey relational analysis for ranking the Cost performance indices in **Table 9** is considered maximized indices. The normalization matrix provided in **Table 11** is calculated using Eq. 7; the larger it is the better, as described previously. The grey relation coefficient is determined by calculating the deviation; **Table 12** illustrates the deviation value of the reference sequence derived using the Eqs. (9, 10), whereas **Table 13** shows the grey relation coefficient and grey grade derived using the Eq.s (11, 12). Ranking the results obtained by the GRA method according to the GRA method, the cheapest material alternative is wood, followed by steel, as shown in **Fig. 7.**

Table 11. Cost Performance indices normalization.

Materials	Stiffness	Toughness	Strength
CFRP	0.023	0.033	0.051
GFRP	0.016	0.012	0.024
Al-alloys	0.347	0.404	0.439
Ti-alloys	0.000	0.000	0.000
Steel	0.375	1.000	0.574
Wood	1.000	0.689	1.000

Table 12. Deviation sequence.

Materials	Stiffness	Toughness	Strength
CFRP	0.977	0.967	0.949
GFRP	0.984	0.988	0.976
Al-alloys	0.653	0.596	0.561
Ti-alloys	1.000	1.000	1.000
Steel	0.625	0.000	0.426
Wood	0.000	0.311	0.000

Table 13. Weighted grey relational coefficients and grad results.

Materials	Stiffness	Toughness	Strength	Grad	Rank
CFRP	0.016	0.136	0.191	0.1143	4
GFRP	0.016	0.134	0.188	0.1125	5
Al-alloys	0.020	0.182	0.261	0.1545	3
Ti-alloys	0.015	0.133	0.185	0.1111	6
Steel	0.021	0.400	0.299	0.2398	2
Wood	0.046	0.246	0.554	0.2822	1

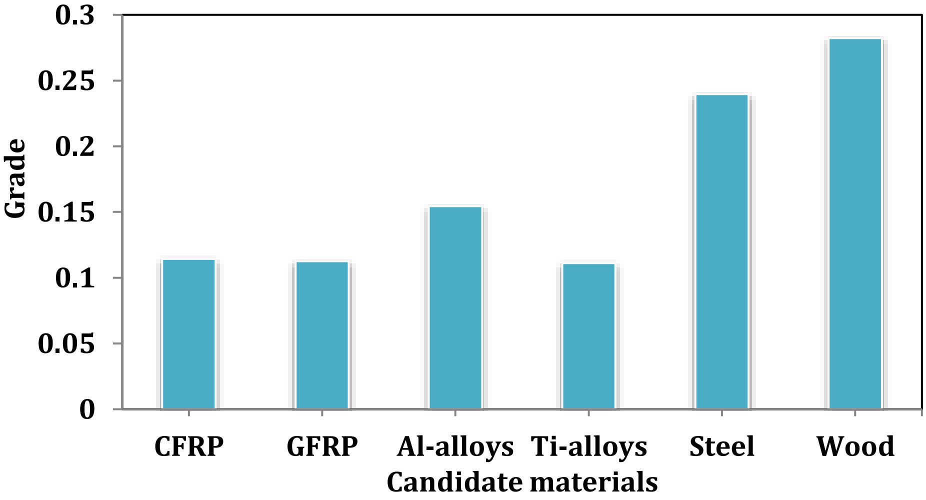

Figure 7. Weighted grey relational coefficients and grad results.

4. CONCLUSIONS

The helicopter rotor blade material was successfully selected using the integrated material selection strategy for choosing the best material for an engineering design based on the performance indices. Different materials used for manufacturing rotor blades, such as aluminum alloys, titanium alloys, steel, composites, and wood, have been discussed. The performance indices chosen are stiffness, strength, and fracture toughness. The performance weight was calculated using the entropy-weighted method, and the results were ranked using the grey relational analysis method.

Based on the results obtained, we come to the following significant conclusions:

- The performance indices proved that the composite material has excellent structural strength, stiffness, and toughness.
- The method used in this research found that CFRP is the best material for manufacturing helicopter rotors without cost consideration. The results are logical and reasonable because CFRP has low density and high strength but is also very expensive.
- Wood, followed by steel, was the best and cheapest material when the design had to be economical.
- Steel has more than 4 times the density of the CFRP and less strength. But it is cheaper than CFRP many times.

- Wood is low in density, strength, and cost, but its manufacturing process is complicated and unproductive.

REFERENCES

Al-Mendwi, K.A., 2009. Computer aided selection of materials by use of ashby's charts (casmac): a balance state by dimensionless ranking. The 6th Engineering Conference, College of Engineering, University of Baghdad, Baghdad - Iraq, Mechanical & Nuclear Engineering

Al-Taie, A. I., and Doos, Q. M., 2023. Material selection for Unmanned Aerial Vehicles (UAVs) wings using Ashby Indices integrated with grey relation analysis approach based on weighted entropy for ranking. *Journal of Engineering*, 29(7), pp. 189–200. Doi:10.31026/j.eng.2023.07.12

Asaad, W., Al-Ethari, H., and Kareem, S.J., 2022, July. Using grey relation analysis to improve tool life in medium carbon steel turning by coating multilayer HSS insert. *In 2022 13th International Conference on Mechanical and Aerospace Engineering (ICMAE),* pp. 507-513. Doi:10.1109/ICMAE56000.2022.9852876.

Bagheinia, R., and Ghassemi, A., 2018. Simulated and experimental investigation of the airfoil contour forming of 301 austenitic stainless steel considering the springback. *International Journal of Mechanical and Materials Engineering*, 13(1), pp.1-12.

Balaji, N., Aishwarya, S., and Prabakaran, V., 2016. An Investigation of design and modal analysis of the different material on helicopter blade. *RA Journal of Applied Research*, 2(6), pp. 483-490. Doi:10.18535/rajar/v2i6.02

Chen, C.H., 2020. A novel multi-criteria decision-making model for building material supplier selection based on entropy-AHP weighted TOPSIS. *Entropy*, 22(2), P. 259. Doi:10.3390/e22020259

Chodha, V., Dubey, R., Kumar, R., Singh, S., and Kaur, S., 2022. Selection of industrial arc welding robot with TOPSIS and Entropy MCDM techniques. *Materials Today: Proceedings*, 50, pp. 709-715. Doi:10.1016/j.matpr.2021.04.487

Edwards, K.L., and Davenport, C., 2006. Materials for rotationally dynamic components: rationale for higher performance rotor-blade design. *Materials & Design*, 27(1), pp. 31-35. Doi:10.1016/j.matdes.2004.09.007

Emovon, I., and Oghenenyerovwho, O.S., 2020. Application of MCDM method in material selection for optimal design: A review. *Results in Materials*, 7, P. 100115. Doi:10.1016/j.rinma.2020.100115

Erzaij, K.R., and Bidan, A.S., 2016. Management model for evaluation and selection of engineering equipment suppliers for construction projects in Iraq. *Journal of Engineering, 22(6)*, pp. 1-16. Doi:10.31026/j.eng.2016.06.01

Hammood, S.A., 2021. Optimization of cutting parameters for milling process of (4032) Al-alloy using Taguchi-based grey relational analysis. *Al-Khwarizmi Engineering Journal*, 17(3), pp. 1-12. Doi:10.22153/kej.2021.06.001

Hasan, A.E., and Jaber, F.K., 2023. The applicability of multiple MCDM techniques for implementation in the priority of road maintenance. *Journal of Engineering*, 29(10), pp. 106–125. Doi:10.31026/j.eng.2023.10.07

Hsiao, S.W., Lin, H.H., and Ko, Y.C., 2017. Application of grey relational analysis to decision-making during product development. *Eurasia Journal of Mathematics, Science and Technology Education*, 13(6), pp. 2581-2600. Doi:10.12973/eurasia.2017.01242a

Hustedt, T., Ossadnik, W., and Burrey, F., 2016. Improving informational bases of performance measurement with grey relation analysis. *In Operations The Art of Making Good Decisions*. Doi:10.5772/65286.

Kumar, R., Singh, S., Bilga, P.S., Singh, J., Singh, S., Scutaru, M.L., and Pruncu, C.I., 2021. Revealing the benefits of entropy weights method for multi-objective optimization in machining operations: A critical review. *Journal of Materials Research and Technology*, 10, pp. 1471-1492. Doi:10.1016/j.jmrt.2020.12.114

Kuo, Y., Yang, T., and Huang, G.W., 2008. The use of grey relational analysis in solving multiple attribute decision-making problems. *Computers & industrial engineering*, 55(1), pp. 80-93. Doi:10.1016/j.cie.2007.12.002.

Lee, D., Lee, D., Lee, M., Kim, M., Kim, T., 2020. Analytic hierarchy process-based construction material selection for performance improvement of building construction: The case of a concrete system form. *Materials 13(7),* P. 1738. Doi:10.3390/ma13071738

Leong, W.Y., Wong, K.Y., and Wong, W.P., 2022., A new integrated multi-criteria decision-making model for resilient supplier selection. *Applied System Innovation*, 5(1), P. 8. Doi:10.3390/asi5010008

Maidin, N.A., Mohd Sapuan, S., Taha, M.M., and Yusoff, M.M., 2022. Material selection of natural fibre using a grey relational analysis (GRA) approach. *BioResources 17(1)* P. 109. Doi:10.15376/biores.17.1.109-131

Mehmood, Z., Haneef, I., and Udrea, F., 2018. Material selection for Micro-Electro-Mechanical-Systems (MEMS) using Ashby's approach. *Materials & Design 157(1)* pp. 412-430. Doi:.10.1016/j.matdes.2018.07.058

Mishra, A., Pal, S., and Singh, P., 2020. Design & vibration analysis of helicopter main rotor blade. *International Journal of Advance Science and Technology,* 29(10S), pp. 4897-4906

Mohammed, F.M., 2017. Mechanical properties investigation of composite material under different parameters variations. *Al-Khwarizmi Engineering Journal, 13(1),* pp. 74-83. Doi:10.22153/kej.2017.09.001

Özgür, E., Sabir, E.C., and Sarpkaya, Ç., 2023. Multi-objective optimization of thermal and sound insulation properties of basalt and carbon fabric reinforced composites using the Taguchi grey relations analysis. *Journal of Natural Fibers,* 20(1), P. 2178580. Doi:10.1080/15440478.2023.2178580.

Patil, A.N., Bhale, N.G.P., Raikar, N., and Prabhakaran, M., 2017. Car selection using hybrid fuzzy AHP and grey relation analysis approach. *International Journal of Performability Engineering*, 13(5), P. 569. Doi:10.23940/ijpe.17.05.p2.569576

Radhi , A. R. ., and Burhan, A. M., 2022. Multi-criteria optimization for governmental projects priority ranking depending on fuzzified experts' opinion using hygiene approach. *Journal of Engineering*, 28(12), pp. 113–124. Doi:10.31026/j.eng.2022.12.08

Rahim, A.A., Musa, S.N., Ramesh, S., and Lim, M.K., 2020. A systematic review on material selection methods. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications, 234(7),* pp. 1032-1059. Doi:10.1177/1464420720916765

Sahoo, S., Choudhury, B., 2022. Optimal selection of an electric power wheelchair using an integrated COPRAS and EDAS approach based on Entropy weighting technique. *Decision Science Letters*, 11(1), pp. 21-34. Doi:10.5267/j.dsl.2021.10.002

Sarraf, F., and Nejad, S.H., 2020. Improving performance evaluation based on balanced scorecard with grey relational analysis and data envelopment analysis approaches: Case study in water and wastewater companies. *Evaluation and Program Planning, 79,* pp. 101762. Doi:10.1016/j.evalprogplan.2019.101762

Sumesh, K.R., and Kanthavel, K., 2022. Optimizing various parameters influencing mechanical properties of banana/coir natural fiber composites using grey relational analysis and artificial neural network models. *Journal of Industrial Textiles*, 51(4_suppl), pp. 6705S-6727S. Doi:10.1177/1528083720930304

Tosun, N., 2006. Determination of optimum parameters for multi-performance characteristics in drilling by using grey relational analysis. *The International Journal of Advanced Manufacturing Technology*, 28, pp. 450-455. Doi:10.1007/s00170-004-2386-y

Unal, R., Najam, H., and Bal, B., 2018. Material selection for Knee exoskeleton frame. The International Conference on Materials Science, Mechanical and Automotive Engineering and Technology, Çeşme/İZMİR

Vatansever, K., and Akgűl, Y., 2018. Performance evaluation of websites using entropy and grey relational analysis methods: The case of airline companies. *Decision Science Letters 7(2)* pp. 119-130. Doi:10.5267/j.dsl.2017.6.005

Wu, D. et al., 2018. Comprehensive evaluation of coal-fired power units using grey relational analysis and a hybrid entropy-based weighting method. *Entropy,* 20(4), P. 215. Doi:10.3390/e20040215

Xing, D., Yan, T., Han, Z., Liu, J., 2023. Supplier evaluation model based on entropy-TOPSIS and 0-1 programming algorithm. *In International Conference on Computer, Artificial Intelligence, and Control Engineering (CAICE 2023)*. 12645, pp. 863-868. Doi:10.1117/12.2680793

Zhang, S., Song, H., Cai, K., and Xu, L., 2022. Multiobjective optimization design for lightweight and crash safety of body-in-white based on entropy weighted grey relational analysis and MNSGA-II. *IEEE Access, 10,* pp. 67413-67436. Doi:10.1038/s41598-023-35405-z

Zhu, Y., Tian, D., and Yan, F., 2020. Effectiveness of entropy weight method in decision-making. *Mathematical Problems in Engineering*, pp. 3564835. Doi:10.1155/2020/3564835