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RESEARCH ARTICLE-MECHANICAL ENGINEERING

A Robust Aluminum Material Selection Process in the Aviation Industry: A Linear Discrete System Stability Test Perspective for Fuzzy Multicriteria Decision-Making

Yusuf Tansel Ic[1] · **Burak Meriç Hamzaoğlu**[2] · **Mustafa Yurdakul**[3]

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Abstract

Aluminum parts are used in the aviation industry because of the need for light. However, in addition to lightness, critical parts that must have high strength properties have also been developed. The corrosion resistance, resistance to high temperatures, and workability were investigated in this case. It becomes difficult to choose among many aluminum materials that can be alternatives to each other when these features are included. The developed approach, which considers many of the features listed above and ultimately recommends to the user the most suitable aluminum material for the relevant critical part, will be used in overcoming the difficulties in this process. A material selection model is proposed in this paper for this purpose, and the decision-making model is demonstrated with examples from the aviation industry. Therefore, the developed model, which will enable the selection of the most suitable materials among alternative materials, especially for critical parts in the aviation industry, will guide professionals working in this field. For this purpose, the fuzzy TOPSIS method is used in the study, and suitable alternatives are determined. Finally, a robustness analysis is proposed to determine the most suitable aluminum material for highly uncertain situations. We apply a stability evaluation study based on process control theory in the robustness analysis.

Keywords Aluminum · Material selection · Mechanical properties · Fuzzy TOPSIS · Robust material selection · Aerospace industry · Stability analysis · Linear control systems

1 Introduction

The aviation industry is developing rapidly in terms of both commercial aircraft production and military aircraft/helicopter production. This development necessitates the production of vehicles with better quality and suitable materials, and the effect of competition necessitates realizing this situation at the lowest possible cost. Therefore, the development of models that will enable the selection of the most suitable materials among alternative materials, especially in the production of critically important parts in the field of aviation, is a guide for professionals working in this field.

For more than 80 years, increasing concerns in energy conservation and environmental protection have turned their attention to lightweight constructions and made the cost reduction policy of airline companies the main criterion. Aluminum, which is the primary material choice in the aviation industry, is the second most abundant metallic element on earth, and its versatility has led to additional research and study of aluminum in the aviation industry [1, 2]. Although modern composites seem to displace aluminum due to their excellent fatigue strength, corrosion resistance, lightness, and high specific properties, their use in airframes is limited by high initial and maintenance costs. Aluminum is a high-performance material that can be exposed to high stress levels and can be produced easily at a lower cost. Highly customized aluminum alloys are used to meet the requirements of aerospace enterprises [2].

Multicriteria decision-making (MCDM) methods are proposed for selecting appropriate aluminum alloys for the

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✉ Yusuf Tansel Ic
yustanic@baskent.edu.tr

[1] Department of Industrial Engineering, Baskent University, 06790 Ankara, Turkey

[2] Department of Defense Platforms, Institute of Science, Baskent University, 06790 Ankara, Turkey

[3] Department of Mechanical Engineering, Gazi University, 06570 Ankara, Turkey

critical parts used in the aviation industry. New approaches can be developed to improve classical decision-making methods for selecting more suitable materials in this field. In the literature, there are very few studies on the selection of aluminum alloys in aviation. For example, Huda and Edi [1] reviewed developments in material selection for applications in structures and engines and made material recommendations for future supersonic aircraft. Wanhill [2] discussed the material and fabrication property requirements for the selection and application of 3rd generation aluminum–lithium (Al-Li) alloys in aircraft and spacecraft. Jayakrishna et al. [3] described their recommendations for material selection for aerospace components and the evolution of advanced materials in the aerospace industry based on their specific properties and applications, as observed in the available literature. Giummarra et al. [4] discussed two aluminum–lithium alloys. Alloys for aerospace applications evaluate the elements and thermal–mechanical machining and properties of the alloy, including the relationship between 2099 and 2199 alloys. Alloys with optimized properties for weight and performance advantages were selected for aircraft applications. Yurdakul et al. [5] proposed an expert system for the selection of aluminum alloys for various aerospace applications by evaluating the mechanical properties of the alloys. The prepared program determines the required properties according to the information given by the user and selects the appropriate alloys among the alloys in the database. Arnold et al. [6] proposed a systematic design-oriented five-stage approach to material selection in aerospace: (i) identifying design requirements, (ii) screening materials, (iii) ranking, (iv) searching for specific candidates, and (v) applying specific constraints to the selection process. At the core of this approach are definition performance indices (determining certain combinations of material properties to embody the performance of a particular component) in conjunction with material property charts. Coppola et al. [7] presented a material selection study for major physical storage technologies typically used for aerospace applications. Hamerton and Kratz [8] introduced thermoset polymers (thermosets) used in the modern aerospace industry and determined the selection criteria for thermosets. The basic requirements of the materials were examined in terms of resin, reinforcement, and composite materials. Huda and Edi [1] presented a paper reviewing advances in material selection for applications in structures and engines of current and future supersonic aircraft. In this study, a brief overview of the configuration design of supersonic aircraft was presented. Then, techniques for improving the configuration design for future supersonic aircraft were described. The operating and environmental conditions during supersonic flight and the resulting material requirements were discussed, and as a result, recommendations were made for various aerospace aluminum alloys, titanium alloys, superalloys, and composites. Yavuz [9], on the other hand, applied Ashby's [10, 11] material selection methodology by accepting bending plates as the best candidate materials for creating aircraft cladding panels; according to this material selection approach, continuous fiber-reinforced epoxy composites are the best candidates for use as materials. Adhikari and Mirshams [12] provide an overview of knowledge-based systems in the context of decision-making methodologies used in material selection for the design of light aircraft metallic structures. In this study, a material selection study was presented by comparing the results of the analytical hierarchy process and the TOPSIS method, which are two different multicriteria decision-making (MCDM) methodologies, with the results of Asby's [10, 11] material selection methodology. Calado et al. [13] developed a computer-aided material selection tool to assist designers in selecting the most suitable carbon fiber-reinforced composite configuration for aircraft structures. The selection procedure was based on technical, economic, and environmental performance targets for a given design in a multidisciplinary and multiobjective optimization scenario. Torrez [14] presented a decision analysis study for the material selection process for high-speed marine vessels using a method called modified digital logic (MDL). Fayazbakhsh et al. [15] proposed the Z-transform method for scaling material properties to overcome the shortcomings of the MDL method. The results obtained in the present study showed that despite the simple scaling function used, the sequencing procedure is as powerful as the MDL method. Anojkumar et al. [16] used four MCDM approaches for the material selection problem in the sugar industry. The authors used FAHP-VIKOR, FAHP-ELECTRE, FAHP-PROMTHEE, and FAHP-TOPSIS to select the best alternative materials. Tian et al. [17] proposed the AHP and gray correlation integrated TOPSIS models to select green decoration materials based on interior environmental characteristics, i.e., physiological comfort, psychological satisfaction, and interior environmental effects. Chen et al. [18] developed a hybrid multicriteria group decision-making model for sustainable building material selection under uncertainty. The authors used Basic Uncertain Linguistic Information, the Consensus Reaching Process, Quality Function Deployment, and the ELECTRE III methodology. Govindan et al. [19] proposed a two-phase solution methodology to evaluate the best sustainable construction material based on sustainable indicators through hybrid DEMATEL ANP and TOPSIS approaches. Yadav [20] explored the fabrication of dental restorative composite materials and the ranking order of the materials using different approaches, such as the preference selection index approach. Yadav and Lee [21] used AHP and TOPSIS and

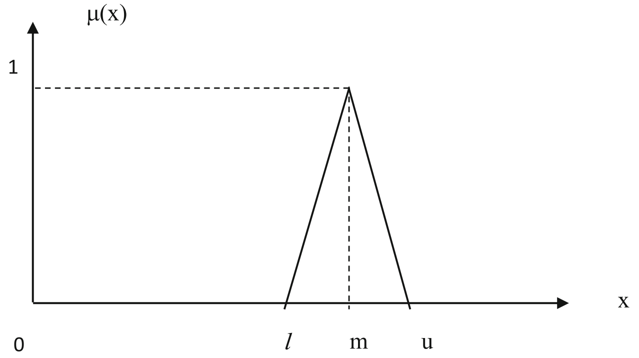


Fig. 1 Triangular fuzzy number

fuzzy AHP and fuzzy TOPSIS [22, 23] under a set of conflicting performance attributes. Yadav et al. [24] applied the entropy-VIKOR model to the same problem.

A literature survey showed that material selection studies are focused mainly on specific applications. No study has presented a robust material selection model for the aviation industry using linear control system-based stability analysis. For the first time, in this paper, we propose a control theory-based stability analysis for MCDM models. According to the results of a literature survey, distance-based MCDM approaches, such as TOPSIS and VIKOR, and their fuzzy versions are widely used in material selection problems. The main reason for using distance-based MCDM methods to rank materials is their simple, controllable, and modifiable calculation procedures based on matrix algebra. This suitable structure is also preferable for stability or robustness analysis. Therefore, we use a modified fuzzy TOPSIS model to propose aluminum material selection in the aviation industry in this paper for these reasons.

The organization of the paper is as follows: In Sect. 2, the methodological details are presented. In Sect. 3, an application is presented. In Sect. 4, robust aluminum selection approach details are provided. In Sect. 5, the stable ranges for the TFNs are provided. The conclusions are provided in Sect. 6.

2 Fuzzy TOPSIS

The fuzzy TOPSIS approach is used in this paper for aluminum alloy selection. In this study, triangular fuzzy numbers (TFNs) are used for linguistic expression (see Fig. 1), and their linguistic equivalents are presented in Table 1 [25, 26]. Linguistic evaluation is necessary for complex decision-making problems. The decision maker evaluates a criterion weight; for example, the criterion is highly important or moderately crucial for the related MCDM problem. Therefore, crisp versions are not suitable for the criterion weighting process, and it is necessary to use a linguistic evaluation.

Table 1 Triangular fuzzy numbers and linguistic expressions

Linguistic expression	Saaty's 1–9 scale	Triangular Fuzzy Number (TFN) (l, m, u)	Invers TFN (1/u, 1/m, 1/l)
Worst	1	(1, 1, 1)	(1/1, 1/1, 1/1)
Appropriate	3	(1, 3, 5)	(1/5, 1/3, 1/1)
Medium	5	(3, 5, 7)	(1/7, 1/5, 1/3)
Good	7	(5, 7, 9)	(1/9, 1/7, 1/,5)
Excellent	9	(7, 9, 9)	(1/9, 1/9, 1/7)

Fuzzy logic-related applications are appropriate for the criterion weighting stage in MCDM models. Researchers have used triangular fuzzy numbers (TFNs) for this type of evaluation in the literature. In the weighting operation in the TOPSIS method, an expert can make a qualitative assignment well based on five intensities: extreme, moderate, very strong, strong, and equal. Moreover, experts are generally unable to compare very large and small samples. However, they can evaluate the transition gradually from clusters of smaller elements to larger ones [26]. The Saaty scale ranges from 1 to 9 and is a logical scale that uses five possible absolute importance values for TOPSIS. Therefore, in the TFN-based linguistic evaluation operation in the material selection problem, each of the five possible linguistic importance expressions is used in the TOPSIS model.

This decision theory-related requirement enforced the stability analysis considering the transitions between the basic linguistic expressions. The steps of the Fuzzy Arithmetic and Fuzzy TOPSIS methods are as follows:

(i) TFN operations [25]:

Let $\tilde{A} = (l_1, m_1, u_1)$ and $\tilde{B} = (l_2, m_2, u_2)$ be positive TFN numbers; the arithmetic operations are as follows:

$$\tilde{A} \oplus \tilde{B} = (l_1 + l_2,\ m_1 + m_2,\ u_1 + u_2) \tag{1}$$

$$\tilde{A} \oplus \tilde{B} = (l_1 \times l_2,\ m_1 \times m_2,\ u_1 \times u_2) \tag{2}$$

$$\tilde{A} \odot \tilde{B} = (l_1/u_2,\ m_1/m_2,\ u_1/l_2) \tag{3}$$

Now, we can present the fuzzy TOPSIS application steps: [25, 27–35]:

Step 1: Determine the fuzzy decision matrix ($\widetilde{\boldsymbol{D}}$)

$$\widetilde{\boldsymbol{D}} = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \dots & C_n \end{array} \\ \begin{bmatrix} \widetilde{x}_{11} & \widetilde{x}_{12} & \dots & \widetilde{x}_{1n} \\ \widetilde{x}_{21} & \widetilde{x}_{22} & \cdots & \widetilde{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \widetilde{x}_{m1} & \widetilde{x}_{m2} & \dots & \widetilde{x}_{mn} \end{bmatrix} \end{array} \tag{4}$$

$$i=1,2,\dots,m; j=1,2,\dots,n$$

where $\widetilde{x}_{ij}$ is the performance rating of alternative A_i considering criterion C_j and $\widetilde{x}_{ij} = (l_{ij}, m_{ij}, u_{ij})$.
Step 2: Obtain the normalized fuzzy decision matrix

$$\widetilde{\boldsymbol{R}} = \left[\widetilde{r}_{ij}\right]_{m\times n} i = 1, 2, \dots, m;\ j = 1, 2, \dots, n. \tag{5}$$

The normalization process can be performed by the following formula:

$$\tilde{r}_{ij} = \frac{\tilde{x}_{ij}}{\sqrt{\sum_{i=1}^{m} \tilde{x}_{ij}^2}}\ i = 1, 2, \dots, m;\ j = 1, 2, \dots, n \tag{6}$$

Step 3: Set the weighted normalized decision matrix ($\widetilde{\boldsymbol{V}}$)

$$\widetilde{\boldsymbol{V}} = \left[\widetilde{v}_{ij}\right]_{m\times n} \tag{7}$$

$$\tilde{v}_{ij} = \tilde{w}_j \otimes \tilde{r}_{ij} \quad i = 1, \dots, m; \quad j = 1, \dots, n \tag{8}$$

where $\tilde{w}_j$ is the criteria weight.
Step 4: Defuzzification
Let $\widetilde{A} = \left(l_{ij}, m_{ij}, u_{ij}\right)$ be a TFN; this approach can be applied using Eqs. (9) and (10):

$$\bar{x}(\widetilde{A}) = \frac{\int x\mu_{\widetilde{A}}(x)dx}{\int \mu_{\widetilde{A}}(x)dx} \tag{9}$$

$$\bar{x}(\widetilde{A}) = \frac{(l_{ij} + m_{ij} + u_{ij})}{3} \tag{10}$$

Then, we can obtain the defuzzified matrix ($\boldsymbol{V}$):

$$\boldsymbol{V} = \left[v_{ij}\right]_{m\times n} \tag{11}$$

Step 5: Calculate the positive and negative ideal solutions

$$A^* = \left\{(\max_i v_{ij} \middle| j \in I), (\min_i v_{ij} \middle| j \in I' \right\} \tag{12}$$

$$A^- = \left\{(\min_i v_{ij} \middle| j \in I), (\max_{ij} v_{ij} \middle| j \in I' \right\} \tag{13}$$

where *I* is a benefit-type measure and *I'* is the cost-type measure.
Step 6: Calculate the separation measures

$$D_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_i^*)^2}\ i = 1, 2, \dots, m;\ j = 1, 2, \dots, n \tag{14}$$

$$D_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_i^-)^2}\ i = 1, 2, \dots, m;\ j = 1, 2, \dots, n \tag{15}$$

Step 7: Calculate the ranking scores

$$C_i^* = \frac{D_i^-}{D_i^- + D_i^+}\ i = 1, \dots, m \tag{16}$$

3 Application

The helibasket for multiperson helicopter rescue operations is made from aluminum alloys (Fig. 2). The helibasket personnel transport device system (PTCS), shown in Fig. 1, allows one or two standing personnel to perform maintenance activities on live power lines while suspended below a helicopter. PTCSs can be modified to attach to helicopters using company-defined and verified payload components. Depending on the maintenance activities carried out on live power lines, additional platforms can be attached to the PTCS. Therefore, the main frame and connection material must be aluminum to maintain the stiffness and lightness of the transport system.

The fundamental criteria for manufacturing helibasket components are shown schematically in Fig. 3. Helibasket productions are developed with critical parts in aviation whose strength properties should be at the highest level, as well as the need for lightness. The candidate aluminum materials and their properties are evaluated with linguistic expressions in the table below using reference [36] (Table 2).

The fuzzy TOPSIS method is used to determine which alternative is the most suitable within the scope of these features. The most suitable alloy is 6082, followed by 6061, which is the second most suitable alloy. Additionally, 5052 is the third most suitable alloy according to the obtained results (Table 3).

In this case, corrosion resistance, resistance to high temperatures, and machinability are the most important criteria. Selecting the best alternative among many alternative aluminum materials is a difficult task. We set a decision matrix with linguistic expressions using the reports from the Metal

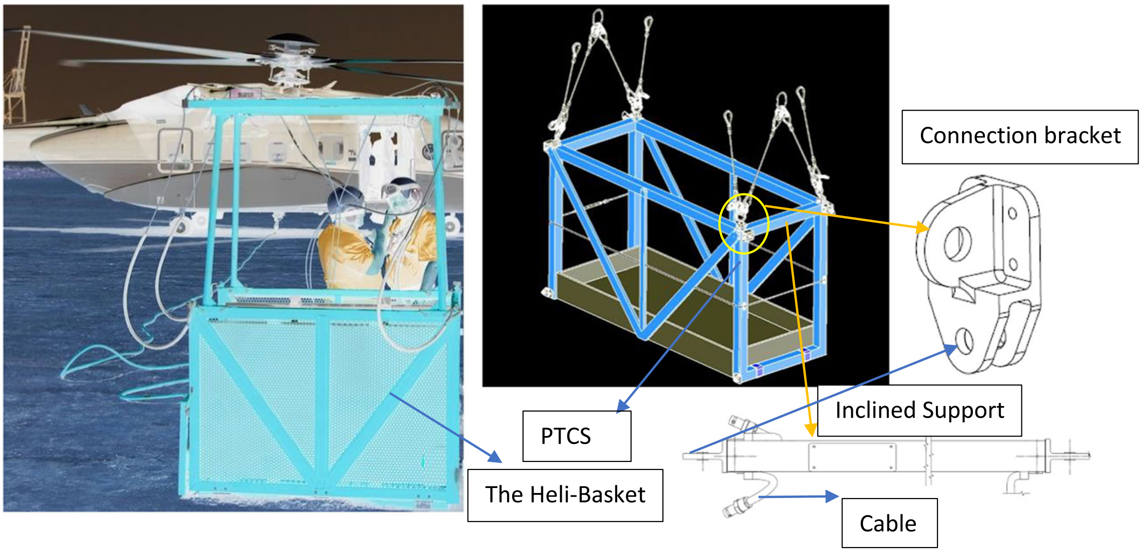


Fig. 2 The helibasket for multiperson helicopter rescue operations

Fig. 3 Basic elements used for mathematical modeling

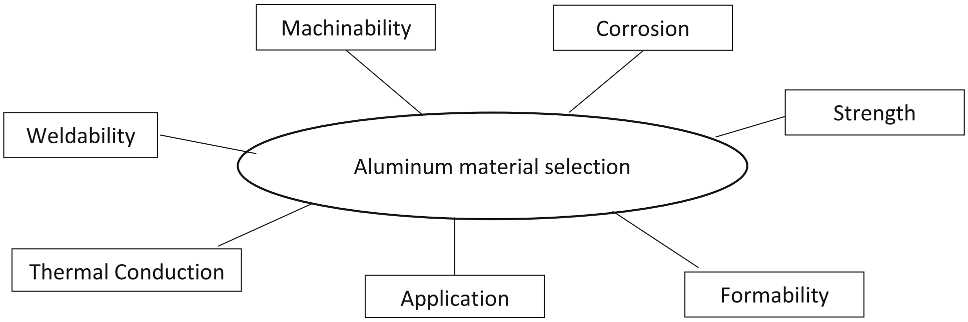


Table 2 Evaluation of aluminum materials [36]

Material	Machinability	Weldability	Formability	Corrosion	Heat treatment	Strength	Application
1100	Excellent	Excellent	Good	Excellent	No	Worst	Metal spinning
2011	Good	Worst	Excellent	Worst	Yes	Good	General machining
3003	Good	Worst	Appropriate	Worst	Yes	Good	Aerospace
5052	Good	Good	Appropriate	Excellent	No	Medium	Marine application
6061	Good	Good	Good	Excellent	Yes	Medium	Structural applications
6063	Good	Good	Appropriate	Good	Yes	Medium	Architect
6082	Good	Good	Good	Excellent	Yes	Medium	Aerospace
7075	Worst	Worst	Appropriate	Medium	Yes	Good	Aerospace

Table 3 Fuzzy TOPSIS result

Criteria	Machinability			Weldability			Formability			Corrosion		
Weight	5	7	9	5	7	9	3	5	7	7	9	9
Normalized weight	0.11	0.18	0.31	0.11	0.18	0.31	0.07	0.13	0.24	0.16	0.23	0.31
Alternative materials	Decision matrix											
1100	5	7	9	1	1	1	5	7	9	7	9	9
2011	5	7	9	1	1	1	7	9	9	1	1	1
3003	5	7	9	5	7	9	3	5	7	1	1	1
5052	5	7	9	5	7	9	3	5	7	7	9	9
6061	5	7	9	5	7	9	5	7	9	7	9	9
6063	5	7	9	5	7	9	3	5	7	3	5	7
6082	5	7	9	5	7	9	5	7	9	7	9	9
7075	1	1	1	1	1	1	3	5	7	5	5	5
Material	Normalized decision matrix											
1100	0.079	0.143	0.257	0.021	0.027	0.037	0.088	0.156	0.290	0.156	0.209	0.273
2011	0.079	0.143	0.257	0.021	0.027	0.037	0.123	0.200	0.290	0.022	0.023	0.030
3003	0.079	0.143	0.257	0.106	0.189	0.333	0.053	0.111	0.226	0.022	0.023	0.030
5052	0.079	0.143	0.257	0.106	0.189	0.333	0.053	0.111	0.226	0.156	0.209	0.273
6061	0.079	0.143	0.257	0.106	0.189	0.333	0.088	0.156	0.290	0.156	0.209	0.273
6063	0.079	0.143	0.257	0.106	0.189	0.333	0.053	0.111	0.226	0.067	0.116	0.212
6082	0.079	0.143	0.257	0.106	0.189	0.333	0.088	0.156	0.290	0.156	0.209	0.273
7075	0.016	0.020	0.029	0.021	0.027	0.037	0.053	0.111	0.226	0.111	0.116	0.152
Material	Weighted normalized decision matrix											
1100	0.009	0.026	0.080	0.002	0.005	0.011	0.006	0.020	0.070	0.024	0.048	0.085
2011	0.009	0.026	0.080	0.002	0.005	0.011	0.008	0.026	0.070	0.003	0.005	0.009
3003	0.009	0.026	0.080	0.012	0.034	0.103	0.004	0.014	0.055	0.003	0.005	0.009
5052	0.009	0.026	0.080	0.012	0.034	0.103	0.004	0.014	0.055	0.024	0.048	0.085
6061	0.009	0.026	0.080	0.012	0.034	0.103	0.006	0.020	0.070	0.024	0.048	0.085
6063	0.009	0.026	0.080	0.012	0.034	0.103	0.004	0.014	0.055	0.010	0.027	0.066
6082	0.009	0.026	0.080	0.012	0.034	0.103	0.006	0.020	0.070	0.024	0.048	0.085
7075	0.002	0.004	0.009	0.002	0.005	0.011	0.004	0.014	0.055	0.017	0.027	0.047
Material	Defuzzification							(D +)	(D−)	C*	Rank	
1100	0.0381	0.0062	0.0320	0.0523	0.0110	0.0078	0.0010	0.0695	0.0584	0.45660	8	
2011	0.0381	0.0062	0.0346	0.0060	0.0013	0.0614	0.0010	0.0647	0.0640	0.49699	6	
3003	0.0381	0.0497	0.0241	0.0060	0.0013	0.0614	0.0088	0.0485	0.0770	0.61376	5	
5052	0.0381	0.0497	0.0241	0.0523	0.0110	0.0458	0.0010	0.0204	0.0818	0.80049	3	
6061	0.0381	0.0497	0.0320	0.0523	0.0013	0.0458	0.0078	0.0186	0.0818	0.81467	2	
6063	0.0381	0.0497	0.0241	0.0343	0.0013	0.0458	0.0010	0.0289	0.0724	0.71474	4	
6082	0.0381	0.0497	0.0320	0.0523	0.0013	0.0458	0.0088	0.0186	0.0819	0.81510	1	
7075	0.0048	0.0062	0.0241	0.0303	0.0013	0.0614	0.0088	0.0608	0.0593	0.49407	7	
A*	0.0381	0.0497	0.0346	0.0524	0.0110	0.0614	0.0088					
A−	0.0048	0.0062	0.0241	0.0061	0.0013	0.0078	0.0010					

Table 3 (continued)

Criteria	Heat treatment			Strength			Application		
Weight	1	1	1	7	9	9	1	1	1
Normalized weight	0.02	0.03	0.03	0.16	0.23	0.31	0.02	0.03	0.03
Alternative materials	Decision matrix								
1100	7	9	9	1	1	1	1	1	1
2011	1	1	1	5	7	9	1	1	1
3003	1	1	1	5	7	9	7	9	9
5052	7	9	9	3	5	7	1	1	1
6061	1	1	1	3	5	7	5	7	9
6063	1	1	1	3	5	7	1	1	1
6082	1	1	1	3	5	7	7	9	9
7075	1	1	1	5	7	9	7	9	9
Material	Normalized decision matrix								
1100	0.304	0.391	0.474	0.021	0.029	0.043	0.032	0.034	0.043
2011	0.043	0.043	0.053	0.106	0.200	0.391	0.032	0.034	0.043
3003	0.043	0.043	0.053	0.106	0.200	0.391	0.226	0.310	0.391
5052	0.304	0.391	0.474	0.064	0.143	0.304	0.032	0.034	0.043
6061	0.043	0.043	0.053	0.064	0.143	0.304	0.161	0.241	0.391
6063	0.043	0.043	0.053	0.064	0.143	0.304	0.032	0.034	0.043
6082	0.043	0.043	0.053	0.064	0.143	0.304	0.226	0.310	0.391
7075	0.043	0.043	0.053	0.106	0.200	0.391	0.226	0.310	0.391
Material	Weighted normalized decision matrix								
1100	0.007	0.010	0.016	0.003	0.007	0.013	0.001	0.001	0.001
2011	0.001	0.001	0.002	0.017	0.046	0.121	0.001	0.001	0.001
3003	0.001	0.001	0.002	0.017	0.046	0.121	0.005	0.008	0.013
5052	0.007	0.010	0.016	0.010	0.033	0.094	0.001	0.001	0.001
6061	0.001	0.001	0.002	0.010	0.033	0.094	0.004	0.006	0.013
6063	0.001	0.001	0.002	0.010	0.033	0.094	0.001	0.001	0.001
6082	0.001	0.001	0.002	0.010	0.033	0.094	0.005	0.008	0.013
7075	0.001	0.001	0.002	0.017	0.046	0.121	0.005	0.008	0.013

Table 4 Weight scenarios

Criteria	Machinability			Weldability			Formability			Corrosion			Heat treatment			Strength			Application		
Scenario 1	1	1	1	3	5	7	7	9	9	3	5	7	3	5	7	7	9	9	1	1	1
Scenario 2	7	9	9	1	1	1	7	9	9	7	9	9	3	5	7	1	1	1	1	1	1

Markets website [36]. Since 1985, metal markets have been the world's largest small-quantity metal supplier, with more than 100 brick-and-mortar stores across the U.S., Canada, and the United Kingdom. Then, we convert the linguistic expressions into appropriate triangular fuzzy numbers. Finally, the steps of the TOPSIS method are applied, and the results are obtained. The Al6082 material is determined to be the most suitable alternative because of the ranking scores. We use the new criterion weights for the comparative analysis and rank the materials in the scenario analysis. The ranking results change when the criteria weights are differentiated (Tables 4 and 5).

These results show that the results are sensitive to the criterion weights and that the selection of suitable alloys

Table 5 Scenario results

Materials	Scenario 1-Rank	Scenario 2-Rank
1100	4	1
2011	8	6
3003	5	7
5052	1	2
6061	3	4
6063	6	5
6082	2	3
7075	7	8

according to different preferences can be achieved with the fuzzy TOPSIS method. However, the criteria weights in scenario analysis are not suitable for aerospace applications. The dependencies on the weight values for ranking are crucial issues in choosing the most suitable material. The original scenario is suitable for weighting criteria for selecting aluminum materials for aviation applications. However, linguistic evaluations of alternative ratings are critical to obtaining the final rating. Therefore, we must reach a robust solution. A robustness analysis is required for the final decision. Therefore, we propose a robustness analysis in the next section to model the uncertainty conditions for the selection of the most suitable alternative.

4 Robustness Analysis

The material selection among various alternatives in the manufacturing and construction sectors has always been a dilemma, which leads to adverse solution results for decision makers [37]. It is necessary to choose from a wide range of alternatives with different mechanical, physical, and chemical properties to select the most suitable material to meet the requirements of an engineering design problem. We need consistent methods that enable the relevant criteria and alternatives to be evaluated appropriately for a particular material selection problem, as the possibility of bias and inconsistency may arise in the decision-making process, such as in the analytical hierarchy process, where the decision maker must make pairwise comparisons between criteria and alternatives [38]. Athawale and Chakraborty [38] examined the ten most commonly used MCDM approaches and their relative performance to compare the ranking results while selecting suitable materials for (a) a flywheel, (b) a cryogenic storage tank, and (c) a sailing boat mast. The ten methods gave almost the same rankings as did the alternative materials. However, distance-based models such as VIKOR and TOPSIS have relatively better performances than others due to their computational simplicity. Therefore, the TOPSIS model is a suitable alternative for the material selection problem because of its low computational complexity, validity, and reliability.

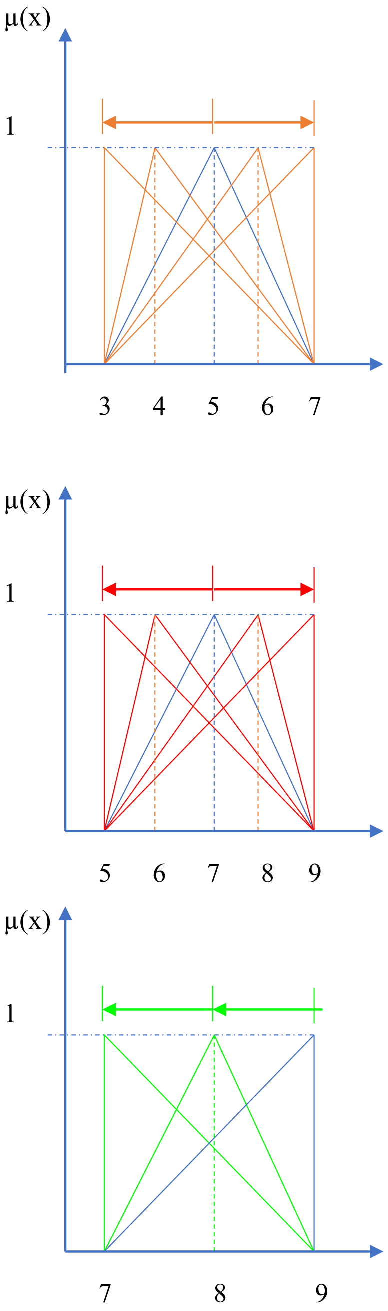


Fig. 4 Modifications of TFNs

In this section, we propose a robustness analysis for the ranking process. The criteria weights and decision matrix are obtained in the original scenario via linguistic evaluations from expert opinions. Therefore, the differentiations from these evaluations can be diversified in terms of the ranking scores. We propose a tuning operation for this reason (Fig. 4).

Table 6 An example of a new decision matrix using different randomly generated *m* values for TFNs

Criteria	Machinability			Weldability			Formability			Corrosion		
Weight	5	8	9	5	6	9	3	3	7	7	8	9
Normalized weight	0.11	0.23	0.31	0.11	0.17	0.31	0.07	0.09	0.24	0.16	0.23	0.31
Materials												
1100	5	8	9	1	1	1	5	5	9	7	9	9
2011	5	8	9	1	1	1	7	7	9	1	1	1
3003	5	6	9	5	9	9	3	5	7	1	1	1
5052	5	7	9	5	8	9	3	3	7	7	7	9
6061	5	5	9	5	5	9	5	7	9	7	8	9
6063	5	8	9	5	6	9	3	7	7	3	7	7
6082	5	9	9	5	6	9	5	9	9	7	8	9
7075	1	1	1	1	1	1	3	6	7	5	5	5

Criteria	Heat treatment			Strength			Application		
Weight	1	1	1	7	8	9	1	1	1
Normalized Weight	0.02	0.03	0.03	0.16	0.23	0.31	0.02	0.03	0.03
Materials	Decision matrix								
1100	7	7	9	1	1	1	1	1	1
2011	1	1	1	5	6	9	1	1	1
3003	1	1	1	5	7	9	7	9	9
5052	7	7	9	3	5	7	1	1	1
6061	1	1	1	3	6	7	5	5	9
6063	1	1	1	3	6	7	1	1	1
6082	1	1	1	3	6	7	7	7	9
7075	1	1	1	5	7	9	7	7	9

Therefore, we have new linguistic expression equivalent TFNs for the analysis (Table 6):

The newly generated “medium” linguistic terms are as follows:

(3,3,7), (3,4,7), (3,5,7), (3,6,7), and (3,7,7).

For the newly generated “good” linguistic terms:

(5,5,9), (5,6,9), (5,7,9), (5,8,9), (5,9,9).

For the newly generated “Excellent” linguistic terms:

(7,7,9), (7,8,9), (7,9,9).

New ranking scores are obtained using these new TFNs in Scenario 1 (Table 7). Then, we extended the appropriate lower and upper values of the TFNs to consider additional uncertain conditions when selecting the aluminum material (Fig. 5 and Table 8). New ranking scores are obtained using these new TFNs for Scenario 2 (Table 9).

4.1 Stability Test

The essence of stability tests in discrete data systems is that in the z plane, all the roots of characteristic equations must lie within the unit circle z = 1 (Fig. 6). The Nyquist criterion, originally developed for continuous systems, root loci, and Bode diagrams, can be adapted to systems with discrete data [39].

4.2 Bileneer Method

The Rought–Hurwitz criterion can also be used for systems with discrete data if a transformation is found that converts the unit circle in the z-plane to the imaginary axis in another complex plane. In this section, we analyze the stability of the tuning operations using the stability test for discrete linear systems in control theory [39, 40]. These stability tests are suitable for our problem. Cohen [41], Jury [42], Jury and Anderson [43], and Raible [44] proposed stability tests. However, the application of these tests is difficult, especially for equations that are higher than the second order and have unknown parameters. Therefore, we prefer a simple test, namely, bilinear transformation, which is used in this study [39]. A stable linear discrete system’s characteristic equation can be defined as follows:

$$F(z) = a_n z^n + a_{n-1} z^{n-1} + \ldots + a_1 z + a_0 = 0 \qquad (17)$$

Table 7 The new TOPSIS ranking results using modified TFNs

Alternatives	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Mode
1100	6	8	8	8	7	7	8	6	7	8	7	7	7	8	7	7	8	6	7
2011	7	7	6	6	6	6	6	7	6	6	6	6	8	6	6	6	7	7	6
3003	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
5052	3	2	1	3	1	2	2	1	2	3	2	3	3	3	3	1	1	2	3
6061	2	3	3	1	2	3	1	3	1	1	3	2	1	1	2	3	3	1	2
6063	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
6082	1	1	2	2	3	1	3	2	3	2	1	1	2	2	1	2	2	3	1
7075	8	6	7	7	8	8	7	8	8	7	8	8	6	7	8	8	6	8	8

Alternatives	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	Mode
1100	8	8	8	6	8	7	8	7	8	7	7	7	7	7	7	7	7	7
2011	6	6	6	7	6	6	6	6	6	6	6	6	6	6	6	6	6	6
3003	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
5052	2	3	2	3	3	1	2	1	1	3	2	1	3	3	1	1	3	3
6061	1	2	1	2	2	3	3	2	3	1	3	2	2	2	3	2	2	2
6063	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
6082	3	1	3	1	1	2	1	3	2	2	1	3	1	1	2	3	1	1
7075	7	7	7	8	7	8	7	8	7	8	8	8	8	8	8	8	8	8

When the Jury test [42, 43] is satisfied, no F(z) roots are found outside the unit circle. Therefore, the necessary conditions for stability are

$$\begin{aligned}&\mathrm{F}(1) > 0\\&\mathrm{F}(-1) > 0,\ \text{ if n is an even integer number}\\&\mathrm{F}(-1) < 0,\ \text{ if n is an odd integer,}\\&|a_0| < a_n\end{aligned} \tag{18}$$

If one of the equations is not satisfied, at least one of the poles is not within the unit circle, and the system is unstable.

4.3 Stability Evaluation for Newly Generated TFNs

In this section, we analyzed the stability of the newly generated TFNs. We modified the medium, lower, and upper values. For (3,5,7) and (5,7,9), the possible modifications of m = 5 are

$$\mathrm{F(m)} = (\mathrm{m}-2)(\mathrm{m}-1)(\mathrm{m}+1)(\mathrm{m}+2) \tag{19}$$

$$\mathrm{F(m)} = \mathrm{m}^4 - 4\mathrm{m}^2 + 2\mathrm{m} + 4 \tag{20}$$

Therefore,

$$\begin{aligned}&\mathrm{F}(1) = 3,\ \mathrm{F}(1) > 0\\&\mathrm{F}(-1) = -1,\ \ \mathrm{F}(-1) < 0 \rightarrow \text{unstable}\\&|a_0| = 4,\ |a_0| > a_n = 1 \rightarrow \text{unstable}\end{aligned} \tag{21}$$

For (7, 7, 9), the possible modifications of m = 7 are

$$\mathrm{F(m)} = (\mathrm{m}+1)(\mathrm{m}+2) \tag{22}$$

$$\mathrm{F(m)} = \mathrm{m}^2 + 3\mathrm{m} + 2 \tag{23}$$

Therefore,

$$\begin{aligned}&\mathrm{F}(1) = 6,\ \mathrm{F}(1) > 0\\&\mathrm{F}(-1) =\ 0 \rightarrow \text{unstable}\\&|a_0| = 2,\ |a_0| > a_n = 1 \rightarrow \text{unstable}\end{aligned} \tag{24}$$

A similar analysis can be used for the modifications in Fig. 4. We modified the lower and upper values for TFNs. For (3,5,7), the possible modifications of $l = 3$ and u = 7 are

$$\mathrm{F(z)} = \left(\mathrm{z}^4 - 4\mathrm{z}^2 + 2\mathrm{z} + 4\right)(\mathrm{z}-1)(\mathrm{z}-2)(\mathrm{z}+1)(\mathrm{z}+2) \tag{25}$$

$$\begin{aligned}\mathrm{F(z)} &= \mathrm{z}^8 - 9\mathrm{z}^6 + 2\mathrm{z}^5 + 24\mathrm{z}^4 - 10\mathrm{z}^3 + 24\mathrm{z}^2 + 8\mathrm{z}\\&= 0\end{aligned} \tag{26}$$

Therefore,

$$\begin{aligned}&\mathrm{F}(1) = 40,\ \mathrm{F}(1) > 0\\&\mathrm{F}(-1) = 40 \rightarrow \text{unstable}\\&|a_0| = 0,\ |a_0| < a_n = 1\end{aligned} \tag{27}$$

Table 8 An example of a new decision matrix using different randomly generated l values for TFNs

Criteria	Machinability			Weldability			Formability			Corrosion		
Weight	4	5	9	3	7	9	3	7	9	7	8	9
Normalized weight	0.09	0.14	0.38	0.06	0.19	0.38	0.06	0.19	0.38	0.15	0.22	0.38
Materials	Decision matrix											
1100	4	6	9	1	1	1	4	8	9	5	8	9
2011	3	9	9	1	1	1	5	7	9	1	1	1
3003	5	8	9	5	6	9	2	4	7	1	1	1
5052	4	6	9	3	9	9	1	5	9	5	7	9
6061	4	6	9	3	8	9	3	7	9	5	9	9
6063	4	8	9	3	7	9	3	7	8	1	5	9
6082	3	9	9	4	5	9	4	8	9	6	9	9
7075	1	1	1	1	1	1	3	7	8	3	5	5

Criteria	Heat treatment			Strength			Application		
Weight	1	1	1	5	7	9	1	1	1
Normalized weight	0.02	0.03	0.04	0.11	0.19	0.38	0.02	0.03	0.04
Materials	Decision matrix								
1100	7	9	9	1	1	1	1	1	1
2011	1	1	1	4	8	9	1	1	1
3003	1	1	1	4	9	9	6	7	9
5052	6	9	9	1	5	9	1	1	1
6061	1	1	1	1	3	8	3	9	9
6063	1	1	1	1	6	8	1	1	1
6082	1	1	1	2	7	7	7	8	9
7075	1	1	1	5	7	9	6	7	9

For (5, 7, 9), the possible modifications of $l = 5$ are

$$\mathrm{F(z)} = \left(\mathrm{z}^4 - 4\mathrm{z}^2 + 2\mathrm{z} + 4\right)(\mathrm{z} - 1)(\mathrm{z} - 2) = 0 \tag{28}$$

$$\mathrm{F(z)} = \mathrm{z}^6 - 3\mathrm{z}^5 - 2\mathrm{z}^4 + 14\mathrm{z}^3 - 14\mathrm{z}^2 + 4\mathrm{z} = 0 \tag{29}$$

Therefore,

$$\begin{aligned} &\mathrm{F}(1) = 0, \rightarrow \text{unstable} \\ &\mathrm{F}(-1) = -30 \rightarrow \text{unstable} \\ &|a_0| = 0, \; |a_0| < a_n = 1 \end{aligned} \tag{30}$$

For (7, 8, 9), the possible modifications of $l = 7$ are

$$\mathrm{F(z)} = \left(\mathrm{z}^2 + 3\mathrm{z} + 2\right)(\mathrm{z} - 1)(\mathrm{z} - 2) \tag{31}$$

$$\mathrm{F(z)} = \mathrm{z}^4 - 5\mathrm{z}^2 + 4 \tag{32}$$

Therefore,

$$\begin{aligned} &\mathrm{F}(1) = 0, \rightarrow \text{unstable} \\ &\mathrm{F}(-1) = \; 0 \rightarrow \text{unstable} \\ &|a_0| = 4, \; |a_0| > a_n = 1 \rightarrow \text{unstable} \end{aligned} \tag{33}$$

The examined tuning operations are not stable for the assignment process of the determined criteria. We generated new scenarios using randomly generated unstable linguistic terms that reflect possible linguistic expressions considering newly generated TFNs, according to Fig. 3. We developed thirty-five scenarios (Table 7). Then, the TOPSIS rankings are recalculated using the randomly generated new TFNs according to Fig. 4 (Table 9). Hence, we obtain the mode values for thirty-five scenarios for each set. The Al6082, Al 6061, and Al 5052 alternatives are candidates for the aerospace industry as a result of the proposed fuzzy TOPSIS application. Additionally, Al 5052 can be preferred over Al6061 in more unstable situations, as shown in Table 9. Al 5052 has second place in the ranking results in Table 9. This analysis showed that the criteria weights are not stable, and the ranking scores are differentiated based on the unstable

Table 9 The new TOPSIS ranging results for modification of the lower and upper values of the TFNs

Alternatives	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Mode
1100	8	7	8	8	8	8	8	8	7	8	8	8	7	8	6	8	8	8	8
2011	6	6	6	6	6	6	6	6	6	6	7	6	6	6	7	6	6	6	6
3003	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
5052	4	3	2	1	3	1	1	2	3	2	1	2	3	4	1	4	1	2	2
6061	3	1	3	2	1	2	2	3	2	3	3	4	2	3	3	1	2	4	3
6063	2	4	4	4	4	4	3	4	4	4	2	3	4	2	4	2	4	3	4
6082	1	2	1	3	2	3	4	1	1	1	4	1	1	1	2	3	3	1	1
7075	7	8	7	7	7	7	7	7	8	7	6	7	8	7	8	7	7	7	7

Alternatives	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	Mode
1100	7	8	7	7	8	8	7	7	7	8	7	8	7	8	8	8	8	8
2011	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
3003	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
5052	3	1	3	1	2	2	2	1	2	2	3	2	3	1	3	1	3	2
6061	1	2	4	3	1	1	1	2	3	3	2	4	2	3	2	4	1	3
6063	4	4	2	4	4	3	4	4	4	4	4	3	4	4	4	3	4	4
6082	2	3	1	2	3	4	3	3	1	1	1	1	1	2	1	2	2	1
7075	8	7	8	8	7	7	8	8	8	7	8	7	8	7	7	7	7	7

weighting process. Therefore, we should find stable weighting conditions for robust ranking results. In the next section, we present such an analysis.

5 Finding Tuning Ranges for Weights to Reach Stable Ranking Results

In this section, we present an analysis to determine stable weighting conditions in the TFN assignment process. If we use integer value-based moving operations for the*l*, m, and u values of the TFNs, the weighting conditions will be unstable. Therefore, we test the decimal moving operations for the *l*, m, and u values. For (3, 5, 7) and (5, 7, 9),

$$\begin{aligned}\mathrm{F(x)} &= (\mathrm{x}-0.5)(\mathrm{x}+0.5)\\ &= 0\end{aligned} \tag{34}$$

$$\begin{aligned}\mathrm{F(x)} &= \mathrm{x}^2-0.25\\ &= 0\end{aligned} \tag{35}$$

Therefore,

$$\begin{aligned}&\mathrm{F}(1) = 0.75,\\ &\mathrm{F}(-1) = 0.75,\end{aligned} \tag{36}$$

$|a_0| = 0.25,\ |a_0| < a_n = 1.$

We can see that this condition is stable. Additionally, we use other examples as follows:

Example 1:

$$\begin{aligned}\mathrm{F(x)} &= (\mathrm{x}-0.5)(\mathrm{x}+0.3)\\ &= 0\end{aligned} \tag{37}$$

$$\begin{aligned}\mathrm{F(x)} &= \mathrm{x}^2-0.2\mathrm{x}-0.15\\ &= 0\end{aligned} \tag{38}$$

Therefore,

$$\begin{aligned}&\mathrm{F}(1) = 0.65,\\ &\mathrm{F}(-1) = 1.05,\\ &|a_0| = 0.15,\ |a_0| < a_n = 1.\end{aligned} \tag{39}$$

Example 2:

$$\begin{aligned}\mathrm{F(x)} &= (\mathrm{x}-0.5)(\mathrm{x}+0.3)(\mathrm{x}-0.8)\\ &= 0\end{aligned} \tag{40}$$

$$\begin{aligned}\mathrm{F(x)} &= \mathrm{x}^3-\mathrm{x}^2+0.01\mathrm{x}+0.12\\ &= 0\end{aligned} \tag{41}$$

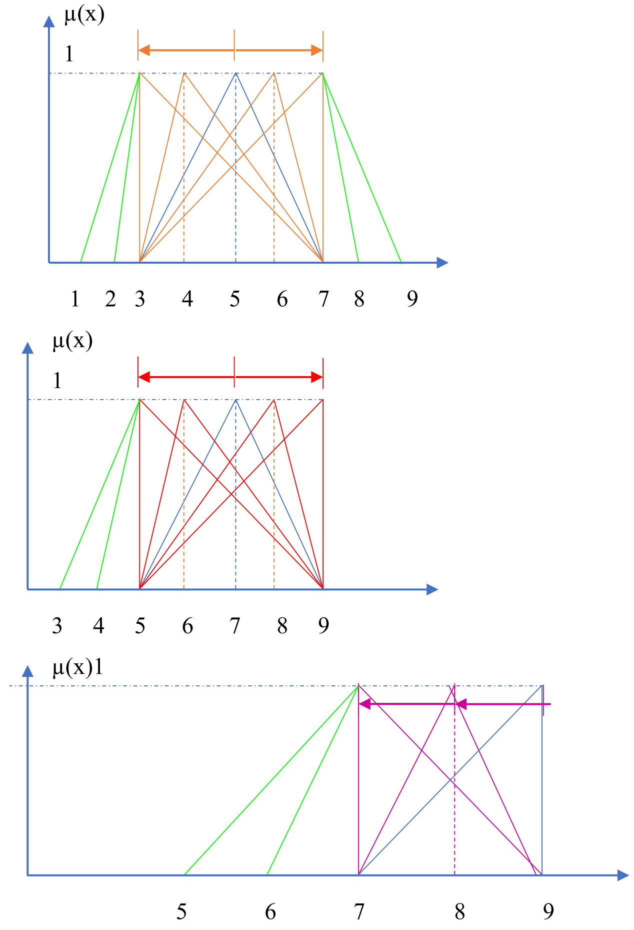


Fig. 5 Modifications in the lower and upper values of the TFNs

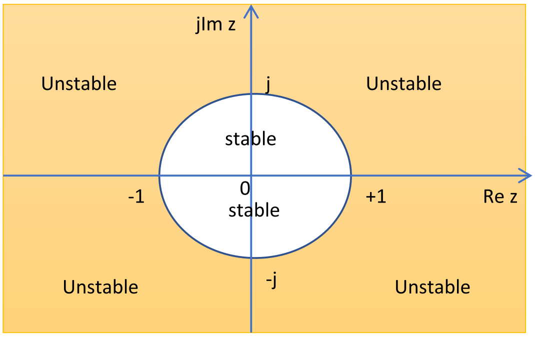


Fig. 6 The stable and unstable regions in the z-plane

Therefore,

$$\begin{aligned} &F(1) = 0.13, \\ &F(-1) = -1.87, \\ &|a_0| = 0.12,\ |a_0| < a_n = 1. \end{aligned} \tag{42}$$

Example 3

$$F(x) = (x - 0.2)\,(x - 0.5)\,(x + 0.7)(x + 0.9) = 0 \tag{43}$$

$$F(x) = x^4 + 0.9x^3 + 0.1x^2 + 0.16x + 0.063 = 0 \tag{44}$$

Therefore,

$$\begin{aligned} &F(1) = 2.223, \\ &F(-1) = 0.103, \\ &|a_0| = 0.063,\ |a_0| < a_n = 1. \end{aligned} \tag{45}$$

The examples show that the modification processes are stable. Then, we used new TFN weight values under stable conditions in Scenario 3 and determined a new decision matrix of randomly generated TFNs to select the aluminum material (Tables 10 and 11).

The obtained results show that the stable weighting process provides a more robust ranking result for the alternatives. The robust rankings for the aluminum alternatives are 6082, 6061, 5052, 6063, 3003, 2011, 7075, and 1100 (Table 11 and Fig. 7).

6 Conclusions

In this paper, we present a perspective for aluminum alloy selection studies. Fuzzy multicriteria decision-making (FMCDM) models are used to select the most appropriate aluminum alloy. However, criteria weighting and alternative rating processes are the most critical stages. Sometimes, the criteria weighting and alternative rating stages are difficult tasks considering the objective value setting for criteria weights and alternative rating scores. In this situation, expert opinions using linguistic expressions are critical. Therefore, we analyzed this issue using the fuzzy TOPSIS method, which includes triangular fuzzy number-based linguistic evaluations.

First, we presented classical fuzzy TOPSIS scores. Then, we developed additional uncertain scenarios using TFN modifications. As a result of this scenario analysis, Al 6082 is the most suitable material for determining selection priorities in even more uncertain situations. However, the Al5052 and Al6061 alternatives are strong alternatives to Al6082. Therefore, it is difficult to determine which alternative is the best under the different scenarios.

The criterion weighting process for different conditions should be performed under stable weighting conditions. If we assign TFN values under unstable conditions, the ranking results will differ between scenario 1 and scenario 2. Therefore, the original weights must be modified only under stable conditions. Based on this crucial process control perspective,

Table 10 An example of a new decision matrix using different randomly generated values for TFNs under the stable weighting process

Criteria	Machinability			Weldability			Formability			Corrosion		
Weight	4.558	6.360	8.392	4.628	6.341	8.098	2.383	4.131	6.150	6.274	8.686	8.580
Normalized Weight	0.11	0.17	0.32	0.11	0.17	0.31	0.06	0.11	0.23	0.15	0.24	0.33
Materials	Decision matrix											
1100	4.530	6.550	8.052	1.000	1.000	1.000	4.162	6.014	8.387	6.616	8.932	8.831
2011	4.233	6.812	8.696	1.000	1.000	1.000	6.904	8.259	8.585	1.000	1.000	1.000
3003	4.667	6.062	8.621	4.982	6.923	8.996	2.799	4.257	6.861	1.000	1.000	1.000
5052	4.689	6.641	8.780	4.285	6.490	8.102	2.762	4.526	6.143	6.732	8.307	8.234
6061	4.654	6.269	8.716	4.707	6.462	8.694	4.681	6.397	8.297	6.986	8.899	8.735
6063	4.098	6.609	8.735	4.759	6.331	8.179	2.979	4.163	6.396	2.978	4.057	6.393
6082	4.135	6.981	8.543	4.953	6.637	8.830	4.728	6.556	8.045	6.443	8.558	8.896
7075	1.000	1.000	1.000	1.000	1.000	1.000	2.420	4.735	6.664	4.558	4.002	4.709

Criteria	Heat treatment			Strength			Application		
Weight	1.000	1.000	1.000	6.403	8.996	8.436	1.000	1.000	1.000
Normalized Weight	0.02	0.03	0.04	0.15	0.25	0.32	0.02	0.03	0.04
Materials	Decision matrix								
1100	6.664	8.433	8.318	1.000	1.000	1.000	1.000	1.000	1.000
2011	1.000	1.000	1.000	4.079	6.046	8.659	1.000	1.000	1.000
3003	1.000	1.000	1.000	4.935	6.237	8.961	6.186	8.606	8.638
5052	6.484	8.699	8.180	2.331	4.604	6.171	1.000	1.000	1.000
6061	1.000	1.000	1.000	2.895	4.992	6.333	4.780	6.712	8.489
6063	1.000	1.000	1.000	2.841	4.589	6.019	1.000	1.000	1.000
6082	1.000	1.000	1.000	2.999	4.383	6.758	6.742	8.616	8.938
7075	1.000	1.000	1.000	4.367	6.163	8.546	6.622	8.479	8.026

this paper presents an analysis of multicriteria decision-making models based on the system control theory.

We provide scenario 3 using weight values and alternative ranking scores under stable conditions. According to the results of scenario 3, Al 6082 is the most suitable and robust alternative for different kinds of applications under the setting criteria priorities in the stable criteria weighting process conditions.

6.1 Limitations and Future Scope

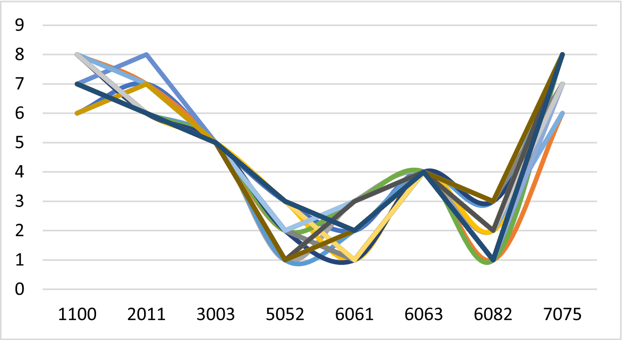
This paper uses the linguistic characteristics of aluminum materials and provides a robust perspective on the most appropriate material selection method in the aviation industry. This paper proposes a fuzzy TOPSIS model using TFNs to set the criteria weights and alternative performance scores. Distance-based MCDM models such as TOPSIS, VIKOR, and MOORA are usable and simple methods for solving material selection problems. According to the literature, the TOPSIS and VIKOR methods use similar solution procedures. However, TOPSIS uses a final ranking procedure in which the closest alternative to the positive ideal solution is the best alternative approach. On the other hand, the VIKOR method uses the v parameter to set different solutions, which are introduced as weights for the strategy of maximum group utility, whereas $1 - v$ is the weight of the individual regret. This compromise result is stable within an MCDM process and could be the strategy of maximum group utility (when $v > 0.5$ is required), “by consensus” v approximately 0.5, or “with veto” $v < 0.5$). Therefore, the proposed robustness analysis can be used in combination with the VIKOR model for the same problem in the future. On the other hand, several uncertainty modeling approaches, such as hesitant or intuitionistic fuzzy TOPSIS models, can be used to solve the same problem, and their results can be compared with those of the proposed model in this paper.

The stability analysis shows that the proposed methodology is based on decimal distributions from TFNs and is logically more robust than integer diversifications in TFNs. This result indicates that the proposed stability model is suitable for minimal diversification in decision-maker evaluations. A more uncertain situation requires different stability analysis models in the future.

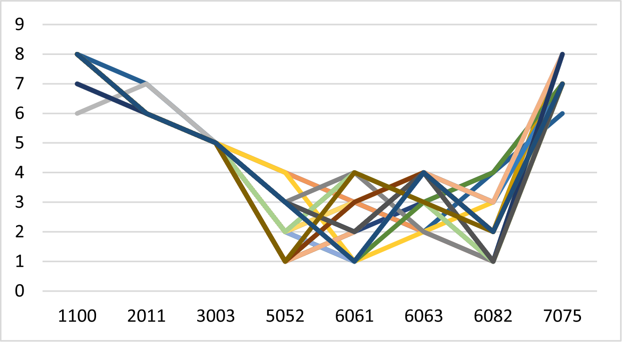
Table 11 The new TOPSIS ranging results for modification of the lower and upper values of the TFNs under the stable weighting process

Alternatives	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Mode
1100	7	8	8	7	7	8	7	8	8	8	7	8	7	6	8	7	8	7	8
2011	6	6	6	6	6	6	6	6	6	6	6	6	6	7	6	6	6	6	6
3003	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
5052	1	3	3	2	3	3	3	3	2	3	1	3	3	3	1	1	2	3	3
6061	2	1	2	1	2	2	1	2	3	2	2	2	2	2	3	2	1	2	2
6063	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
6082	3	2	1	3	1	1	2	1	1	1	3	1	1	1	2	3	3	1	1
7075	8	7	7	8	8	7	8	7	7	7	8	7	8	8	7	8	7	8	7

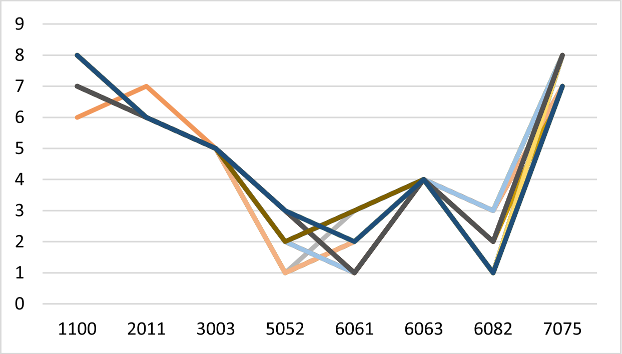
Alternatives	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	Mode
1100	8	8	7	8	7	8	7	8	8	7	7	8	7	7	7	8	8	8
2011	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
3003	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
5052	2	2	3	3	2	3	3	1	3	3	2	3	3	3	3	2	3	3
6061	3	1	2	1	3	2	1	2	2	2	1	2	1	1	1	3	2	2
6063	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
6082	1	3	1	2	1	1	2	3	1	1	3	1	2	2	2	1	1	1
7075	7	7	8	7	8	7	8	7	7	8	8	7	8	8	8	7	7	7



a) Scenario 1: unstable



b) Scenario 2: unstable



c) Scenario 3: Stable

Fig. 7 A comparison of the unstable and stable weighting process results

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Data Availability No data were used for the research described in the article.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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