Application of the TOPSIS optimisation method with different weight selections on selected criteria in basalt, aramid, and carbon layered composite structures

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ABSTRACT – REZUMAT

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Composite materials have a wide range of applications today due to the advantages they offer, including durability and lightness, and are widely preferred as raw materials and products in industrial production. This study focuses on optimising certain performance criteria of these materials, which are critical in terms of engineering design. In the study, three different high-tech fabric materials (Basalt, Aramid, Carbon) were produced in 2 and 3 layers by the vacuum infusion method, and 6 composite plates were obtained. The TOPSIS optimisation technique was applied to determine the most suitable of these composites in terms of thermal and economic properties such as heat insulation, sound insulation, cost and lightness. Optimum alternatives were determined by giving weights according to the priority status of the criteria. As a result of the analysis in all three weight combinations, it was determined that the optimum composite material was the 3-layer structure with the Carbon/Aramid/Basalt combination.

Keywords: *hybrid composite, thermal insulation, sound insulation, cost, lightness*

Aplicarea metodei de optimizare TOPSIS cu diferite selecții de greutate pe baza unor criterii selectate în structuri compozite stratificate din bazalt, aramidă și carbon

Materialele compozite au astăzi o gamă largă de utilizări datorită avantajelor pe care le oferă, precum durabilitatea și greutatea redusă, și sunt preferate pe scară largă ca materii prime și produse în producția industrială. Acest studiu se concentrează pe procesul de optimizare a anumitor criterii de performanță ale acestor materiale, care sunt esențiale din punct de vedere al proiectării tehnice. În cadrul studiului, trei materiale textile diferite de înaltă tehnologie (bazalt, aramidă, carbon) au fost produse în 2 și 3 straturi prin metoda infuziei în vid și s-au obținut 6 plăci compozite. Tehnica de optimizare TOPSIS a fost aplicată pentru a determina cele mai potrivite dintre aceste compozite în ceea ce privește proprietățile termice și economice, cum ar fi izolația termică, izolația fonică, costul și greutatea redusă. Alternativele optime au fost determinate prin stabilirea de greutăți în funcție de statutul de prioritate al criteriilor. Ca rezultat al analizei în toate cele trei combinații de greutăți, s-a stabilit că materialul compozit optim este structura cu 3 straturi cu combinația carbon/aramidă/bazalt.

Cuvinte-cheie*: compozit hibrid, izolare termică, izolare fonică, cost, greutate redusă*

INTRODUCTION

Composite materials are widely used in many engineering fields such as aviation, automotive and marine due to their high strength and low weight properties. When different composite materials are brought together with a design framework where certain properties are prioritised, it is necessary to use multi-criteria decision-making techniques to make the most appropriate choice. These techniques guide engineering decisions in production processes and provide optimal solutions according to performance, cost and other critical parameters. TOPSIS, one of the frequently used optimisation methods, allows alternatives to be ranked as closest to the positive ideal solution and farthest from the negative ideal solution. This method is based on the principle that the most suitable alternative is the one with the least distance from the positive ideal solution and the most distance from the negative ideal solution, and is thus used as an effective selection tool in the decision-making process [1]. Various publications have been examined in the literature, especially in the textile field and in many other fields, where the TOPSIS method has been applied. Acar and Güner applied the TOPSIS method to solve the customer selection problem in a clothing company by using the selection criteria of customer return speed, high order variety, profit margin rate, sample approval speed and suitability of the order for the company [2]. Acar et al. [3] applied the TOPSIS method for sustainability performance measurement in the textile industry, Yükseloğlu et al. [4] in 2015 to determine the parameters of the Open-End spinning machine in yarn selection for the weaving process, Tekez [5] to analyse the type and effects of error using fuzzy TOPSIS in the knitting process, Öztürk [6] to select the most suitable fabric raw material supplier for a ready-made clothing company, Nazar et al. [7] to determine the most suitable supplier for this company from the raw materials used for the fabric weaving process in a woven fabric production factory.

Yilmazbilek et al. applied two different evaluation methods of composite waste. First, weighting was applied to the determined criteria, and ANP and TOP-IS methods were applied separately to the results obtained from each weighting method. In the ANP and TOPSIS results performed with all weighting methods used, the pyrolysis alternative was found to be the most suitable option [8]. Alp et al. comparatively examined the effects of rotation speed, feed rate and cutting tool type on cutting force, deformation factor and surface roughness of flax fibre reinforced polymer composites with a full factorial experimental design and TOPSIS method. At the end of the study, it was observed that the optimum cutting parameter WC cutting tool was obtained from high rotation speed and low feed rate. It was observed that the most important factor among the cutting parameters was rotation speed, then cutting tool type and feed rate, respectively [9].

Akhoundi and Modanloo used TOPSIS and MOORA techniques simultaneously to select the best printing condition [10]. A manufacturing device for continuous carbon fibre reinforced polycarbonate prepreg filament (CCFRPF) was designed by Chen et al., based on the resin fusion impregnation theory, and an optimisation method was proposed for the preparation process parameters according to the TOPSIS optimisation theory [11]. Xu et al. applied TOPSIS and PCA methods together for low-speed impact analysis and multi-objective optimisation of hybrid carbon/basalt fibre reinforced composite laminate [12]. TOPSIS evaluation analysis was used by Pei et al. to design a lightweight and cost-effective fire-resistant structure for steel bridges, and the structure proposed by the method was found to have the highest integrated performance [13].

Fabrics produced from basalt, aramid and carbon fibres are widely preferred in the production of composite materials due to their superior properties. These materials are used as reinforcement elements to increase performance in various sectors and significantly improve the properties of composites, such as design flexibility. In literature, studies on the mechanical and physical properties of composites formed by these fibres with different matrix materials are widely available. Deng et al. examined basalt continuous fibre composites with polypropylene (PP) and polycarbonate (PC) matrices. The processing of the composites was optimised. In BF-PC composites, optimising the material preparation and processing steps enabled the polymer to better impregnate the fibres and improved the mechanical properties [14]. Liu et al. discussed the chemical composition and production technology of BF and discussed its application potential in the field of electrical materials, creating a source for future applications [15]. Xiao et al. increased the interface bond strength with DGEBA resin by modifying the aramid fibre fabric (PPTA) surface with phthalic anhydride and anhydrous aluminium chloride ($AlCl_3$) catalysis. As a result of the modification, the tensile, flexural and interlayer shear strengths of the composite increased significantly, and the mechanical properties reached maximum values. This improvement made aramid fibre composites more suitable for structural applications [16]. Baltacı et al. produced aramid and carbon fibre reinforced thermoplastic composites with different angle orientations by the hot pressing method and investigated their vibration behaviour under impact loads [17]. Novotna et al. investigated the effect of surface layer material on impact strength, dielectric properties, electromagnetic interference (EMI) shielding and sound absorption performance in sandwich composites [18].

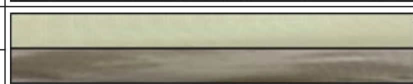
In this study, the use of the TOPSIS optimisation technique was investigated in determining the most suitable one according to the selected parameters of 6 different composite plates produced with the vacuum infusion method, where 3 different high-tech fabrics (Basalt, Aramid, Carbon) were used as reinforcement in 2 and 3 layers. In the study, the TOPSIS method was used to give the importance of the weights of selected features of composites obtained from basalt, aramid and carbon fabric, to rank the most suitable alternatives according to the determined criteria (selected parameters) and to determine the alternative that will rank first. The selected parameters are thermal properties in the form of heat and sound insulation, and cost and lightness properties. An optimum alternative was tried to be determined by applying different weights to the thermal properties.

MATERIAL AND METHODS

Material

In the experimental study, Basalt, Aramid and Carbon fabrics were used as composite reinforcement components. The fabric texture structures were selected as plain weave, with an areal density of 200 g/m². Basalt, Aramid and Carbon fabrics selected in the study have various superior properties. For example, Basalt fabric shows excellent mechanical properties, while Aramid fabric is a high-tech material that stands out with its high strength, excellent thermal stability and superior impact resistance. Although carbon fabric is much lighter than steel with its high mechanical strength and low density, it offers high tensile and compressive strength, providing significant advantages in structural applications. These fabrics were chosen to monitor the effects of the different advantages that will be obtained by different placements of these features in the layers of the layered composite design. The experimental plan is given in table 1. Six different layered composite plates were produced. For the matrix component of the composite, MGS Lamination Epoxy Resin L160 was used in combination with MGS Lamination Epoxy Hardener H160. The resin-to-hardener ratio was 100:25, and the gelation time was 40 minutes at room temperature. The reinforcement-to-resin ratio in the composites was maintained at 70% to 30%.

Table 1

EXPERIMENTAL PLAN			
No.	**Sample code***	**Arrangement of layers**	
1	CAB	1st: Carbon	
		2nd: Aramid	
		3rd: Basalt	
2	ACB	1st: Aramid	
		2nd: Carbon	
		3rd: Basalt	
3	ABC	1st: Aramid	
		2nd: Basalt	
		3rd: Carbon	
4	AB	1st: Aramid	
		2nd: Basalt	
5	BC	1st: Basalt	
		2nd: Carbon	
6	CA	1st: Carbon	
		2nd: Aramid	

Note: * C – Carbon fabric, A – Aramid fabric, B – Basalt fabric

Method

In this study, the TOPSIS optimisation method was applied to selected properties of composite plates produced using a combination of the hand lay-up method and the vacuum infusion method, in accordance with the test plan. Among the selected parameters for thermal properties, thermal insulation and sound insulation were evaluated, alongside other parameters such as cost and lightness. These parameters were given weights according to the selection priority, and the optimum alternative was evaluated by giving high weights to the most important properties, respectively. The heat transfer coefficient test for thermal insulation was carried out in accordance with TS EN 12667 standard, and the sound transmission loss test for sound insulation was carried out in accordance with ASTM E-2611:2009 standard. Cost and lightness parameters were calculated for a 1 m^2 composite plate produced, considering the reinforcement and resin ratio (70:30). Cost data were made according to November 2024 data and calculated in TL/m^2 [19, 20].

TOPSIS optimisation method

The TOPSIS optimisation technique, positive ideal solution maximises the benefit criterion or attributes and minimises the cost criterion or attributes; negative ideal solution maximises the cost criterion or attributes and minimises the benefit criterion or attributes. The selected criterion is expected to have the minimum distance from the positive ideal solution and the maximum distance from the negative ideal solution. The steps used for the TOPSIS method are summarised in figure 1, and table 2 shows the equations used in these steps [3, 6, 7, 13].

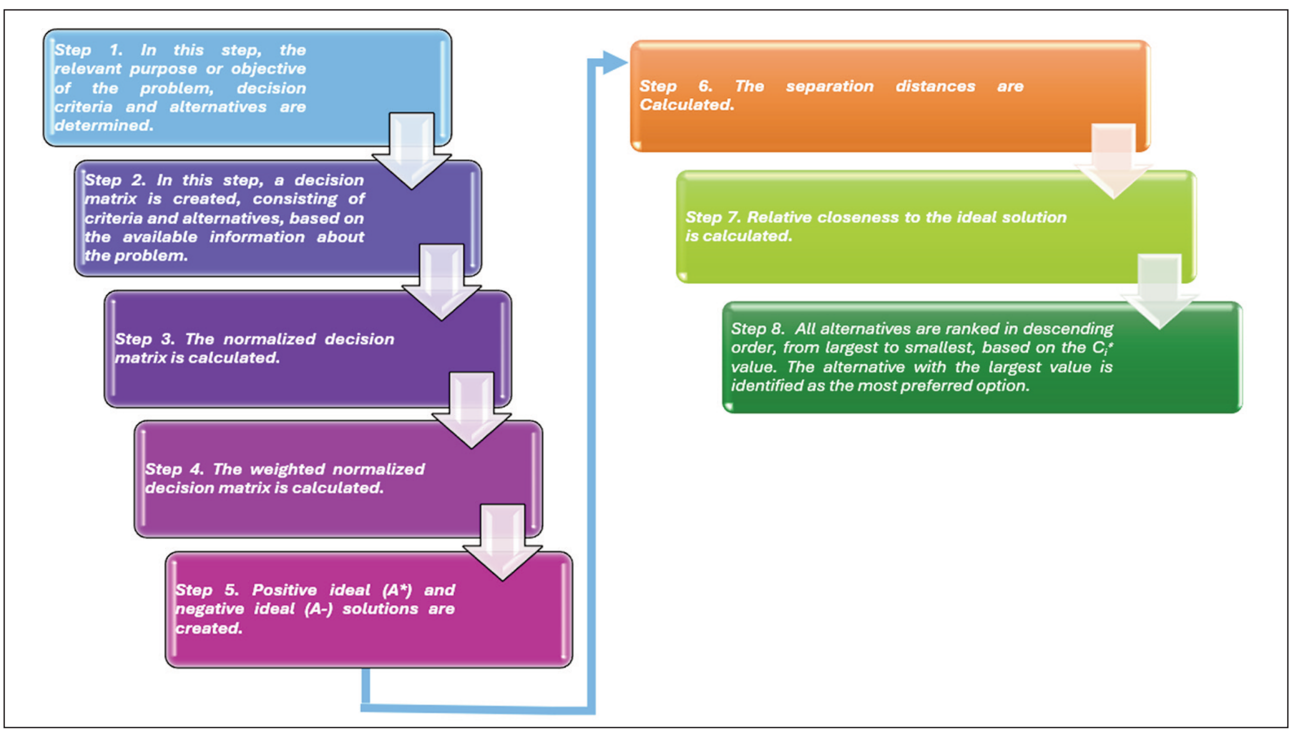


Fig. 1. TOPSIS application steps

Table 2

EQUATIONS USED IN TOPSIS APPLICATION STEPS		
Steps	**Equations**	**Equation No**
Step 1	Decision criteria and alternatives are determined.	
Step 2	$D_{MN} = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1N} \\ a_{21} & a_{22} & \dots & a_{2N} \\ \dots & \dots & \dots & \dots \\ a_{M1} & a_{M2} & \dots & a_{MN} \end{bmatrix}$	(1)
Step 3	$r_{ij} = x_{ij} \Big/ \sqrt{\sum_{i-1}^{m} x_{ij}^2} \quad i = 1, 2, \dots, m \text{ and } j = 1, 2, \dots, n$	(2)
Step 4	$V_{ij} = r_{ij} \times W_j \quad i = 1, 2, \dots, m \text{ and } j = 1, 2, \dots, n$	(3)
Step 5	$A^* = \{(\max_i v_{ij} \mid j \in J), (\min_i v_{ij} \mid j \in J')\}$	(4)
	$A^- = \{(\min_i v_{ij} \mid j \in J), (\max_i v_{ij} \mid j \in J')\}$	(5)
Step 6	$S_i^* = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^*)^2}$	(6)
	$S_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2}$	(7)
Step 7	$C_i^* = \dfrac{S_i^-}{S_i^- + S_i^*}$	(8)
Step 8	All alternatives are ranked in descending order from largest to smallest according to the C_i^* value.	

RESULTS AND DISCUSSION

The TOPSIS optimisation method was applied step by step, as shown in the tables below (tables 3–7). First, the criteria were weighted according to their importance, the decision matrix was created, and the normalised matrix was calculated. Finally, the alternatives were ranked from 1 to 6. In table 7, steps 6–8, the ranking is presented based on the weights assigned to the first group.

Step 1. Criteria, alternatives and selected weights used in the study.

Table 3

THE CRITERIA DETERMINED FOR THE TOPSIS METHOD AND THE WEIGHTS SELECTED ACCORDING TO THE IMPORTANCE PRIORITY OF THE CRITERIA					
Criteria	4	Thermal Conductivity Coefficient Test (W/mK)	Sound Transmission Loss Test (dB)	Cost ($\$/m^2$)	Lightness (g/m^2)
Weights	Weight of the 1st group (W1)	0.4	0.4	0.1	0.1
	Weight of the 2nd group (W2)	0.5	0.1	0.3	0.1
	Weight of the 3rd group (W3)	0.1	0.5	0.3	0.1

Step 2. Creating the decision matrix.

Table 4

DECISION MATRIX CREATED FOR TOPSIS OPTIMIZATION TECHNIQUE				
Alternatives	**Criteria**			
	Thermal Conductivity Coefficient Test (W/mK)	**Sound Transmission Loss Test (dB)**	**Cost ($\$/m^2$)***	**Lightness (g/m^2)**
CAB	33.31	16	108.96	857.2
ACB	17.69	12	108.96	857.2
ABC	19	11	108.96	857.2
AB	12.63	9	73.09	571.4
BC	16.81	11	49.54	571.4
CA	22.38	8	95.20	571.4

** 1$ = 34,6 TL in November 2024.*

Step 3. Normalise the decision matrix.

Table 5

THE REINFORCEMENT MATERIAL TYPES USED IN HAND LAY-UP AND RTM SAMPLES

Alternatives	Criteria											
	Thermal Conductivity Coefficient Test (W/mK)			**Sound Transmission Loss Test (dB)**			**Cost ($/m^2)**			**Lightness (g/m^2)**		
	Weights			**Weights**			**Weights**			**Weights**		
	0.4	**0.5**	**0.1**	**0.4**	**0.1**	**0.5**	**0.1**	**0.3**	**0.3**	**0.1**	**0.1**	**0.1**
CAB	0.64	0.64	0.64	0.57	0.57	0.57	0.48	0.48	0.48	0.48	0.48	0.48
ACB	0.34	0.34	0.34	0.43	0.43	0.43	0.48	0.48	0.48	0.48	0.48	0.48
ABC	0.36	0.36	0.36	0.39	0.39	0.39	0.48	0.48	0.48	0.48	0.48	0.48
AB	0.24	0.24	0.24	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32
BC	0.32	0.32	0.32	0.39	0.39	0.39	0.22	0.22	0.22	0.32	0.32	0.32
CA	0.43	0.43	0.43	0.29	0.29	0.29	0.42	0.42	0.42	0.32	0.32	0.32

Step 4 and Step 5. Weighting and finding positive and negative ideal values.

Table 6

WEIGHTED DECISION MATRIX AND POSITIVE IDEAL (A*) AND NEGATIVE IDEAL (A$^-$) VALUES

Alternatives	Criteria											
	Thermal Conductivity Coefficient Test (W/mK)			**Sound Transmission Loss Test (dB)**			**Cost ($/m^2)**			**Lightness (g/m^2)**		
	Weights			**Weights**			**Weights**			**Weights**		
	0.4	**0.5**	**0.1**	**0.4**	**0.1**	**0.5**	**0.1**	**0.3**	**0.3**	**0.1**	**0.1**	**0.1**
CAB	0.255	0.319	0.064	0.228	0.057	0.285	0.048	0.143	0.143	0.048	0.048	0.048
ACB	0.136	0.169	0.034	0.171	0.043	0.214	0.048	0.143	0.143	0.048	0.048	0.048
ABC	0.146	0.182	0.036	0.157	0.039	0.196	0.048	0.143	0.143	0.048	0.048	0.048
AB	0.097	0.121	0.024	0.128	0.032	0.160	0.032	0.096	0.096	0.032	0.032	0.032
BC	0.129	0.161	0.032	0.157	0.039	0.196	0.022	0.065	0.065	0.032	0.032	0.032
CA	0.171	0.214	0.043	0.114	0.029	0.143	0.042	0.125	0.125	0.032	0.032	0.032
A*	0.255	0.319	0.064	0.228	0.057	0.285	0.048	0.143	0.143	0.048	0.048	0.048
A$^-$	0.097	0.121	0.024	0.114	0.029	0.143	0.022	0.065	0.065	0.032	0.032	0.032

Step 6-8. Discrimination from the positive ideal solution, discrimination from the negative ideal solution and ranking.

Table 7

THE VALUES OF SEPARATION FROM THE POSITIVE IDEAL SOLUTION (S_i^*) AND SEPARATION FROM THE NEGATIVE IDEAL SOLUTION (S_i^-), C_i AND RANKING

Alternatives	S_i^*			S_i^-			C_i			**Ranking**		
	Weights			**Weights**			**Weights**			**Weights**		
	W1	**W2**	**W3**	**W1**	**W2**	**W3**	**W1**	**W2**	**W3**	**W1**	**W2**	**W3**
CAB	0.0005	0.0003	0.0004	0.1974	0.2151	0.1676	1.00	1.00	1.00	**1**	**1**	**1**
BC	0.0533	0.0413	0.0537	0.2066	0.1808	0.2114	0.79	0.81	0.80	2	2	2
CA	0.2125	0.2516	0.1968	0.2125	0.2516	0.1968	0.50	0.50	0.50	3	3	5
ACB	0.1325	0.1502	0.0772	0.0752	0.0939	0.1068	0.36	0.38	0.58	4	5	3
ABC	0.1307	0.1382	0.0931	0.0714	0.1006	0.0962	0.35	0.42	0.51	5	4	4
AB	0.1885	0.2057	0.1399	0.0174	0.0309	0.0353	0.08	0.13	0.20	6	6	6

According to table 7, it is seen that the Carbon/Aramid/Basalt alternative, which ranks 1st in all weighting options, has the highest CC_i value. Accordingly, the most suitable layer layout sequence will be alternative 1. In all weight combinations, the alternative with the lowest CC_i value is the Aramid/Basalt composite plate. Other rankings vary according to weighting choices.

CONCLUSION

In composite materials, determining the properties suitable for the area of use is of great importance. In the design process of the composite, the selection parameters that determine these properties play a decisive role. In this study, thermal insulation, sound insulation, cost and lightness parameters were determined as selection criteria in layered fabric reinforced epoxy composite plates. A total of 6 composite plates were produced: three with three layers and three with two layers, with three different weighting combinations applied to the criteria. Accordingly, in the 1st combination, the thermal and sound insulation criteria are of equal importance, in the 2nd combination, the thermal insulation and cost criteria are more important than the other criteria, and in the 3rd combination, the sound insulation and cost criteria are more important than the other criteria. The application of optimisation techniques not only identified the most suitable solution but also ranked the alternatives according to their suitability. In this study, the TOPSIS method was applied as the optimisation technique.

According to the 3 different combination weights selected, it was seen that the most suitable composite plate for each combination was the Carbon/Aramid/Basalt layered composite (1st Alternative, CAB, 3-layered). For each weighting combination, the appropriate alternatives are varied 3rd, 4th and 5th in ranking. Ranking the most suitable option in the 6t^{h} was found to be Aramid/Basalt layered composite in all weightings. In this study, unlike other studies, determining the first alternative with the TOPSIS method by giving importance weights to the selected properties of composites obtained from basalt, aramid, and carbon fabric is an innovative approach for its use in the textile industry.

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