A COMPARATIVE STUDY ON MATERIAL SELECTION OF AEROSPACE COMPONENTS FOR FUSED FILAMENT FABRICATION

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1 INTRODUCTION

Manufacturing of many aerospace structures from advanced composite materials has led to lighter and more fuel-efficient aircraft which has boosted profits of companies in this sector [1]. Lack of toughness, low shelf life as well as multi-step processing are among the reasons why thermoset composites are less preferred than thermoplastic composites for replacement of the load-bearing components in which superior toughness and damage tolerance are required [2]. An example of such improvements is structural components of aircraft like the clips used to attach fuselage panels to its frame in the Airbus A350 XWB, which were reproduced in carbon fibre reinforced thermoplastic composites [3]. The thermoplastic polymers introduce manufacturing flexibility due to their melt processability and enable the production of highly integrated structures thanks to their fusion weldability [4]. Moreover, the variety of processing methods available for this type of material allows for choosing the manufacturing process which works best considering the production rate and component size. That is one of the reasons why aerospace companies have been moving toward using the additive manufacturing technologies to decrease the production costs of low-production-rate parts [5]. However, selection of the most suitable material among the numerous polymers available is a challenge that one should tackle each time a component is going to be designed or upgraded. This is a crucial design aspect since minor errors in material selection of sensitive applications like aerospace could cause structural issues which puts the safety and reliability of the aircraft in danger.
To meet the processing and performance requirements, a robust approach is required to balance all the interrelated and sometimes conflicting attributes of a component that is going to be reproduced out of composite. One can take advantage of multi-criterion decision-making (MCDM) methods to systematically evaluate and rank the alternatives based on the relative importance of the criteria. A comprehensive review on the application of MCDM methods in material selection was conducted in diverse fields and it was shown that the hybrid methods (a combination of two or more MCDM methods) are the most common techniques for material selection studies [6]. For instance, Alaaeddin *et al.* [7] applied analytical hierarchy process (AHP) method to prioritize different polymers for fabrication of short sugar palm composites and integrated it with technique for order preference by similarity to ideal solution (TOPSIS) and elimination and choice expressing reality (ELECTRE) ranking methods to find the most suitable polymeric matrix for their application. In another study, Mansor *et al.* [8] used the same combination of methods to select the thermoplastic polymer matrix for hybrid natural fibre composites formulation to develop a structural automotive component. Another example is a study reported by Rao [9] that integrated AHP method with "vIse kriterijumska optimizacija kompromisno resenja" (VIKOR) compromise ranking method to find the best material for designing a component operating at high-temperature environment. One can realize that in the majority of the studies, AHP method is used to assign the relative importance of attributes, especially for the methods like TOPSIS and VIKOR which are incapable of determining decision criteria weights. AHP reflects the designer's preferences on

the material ranking and it could potentially result in bias towards the final ranking result depending on the designer's knowledge [10]. Moreover, the distribution of data and the potential interdependency between the decision criteria, which are usually disregarded in decision-making problems, play significant roles in determination of the criteria weights. Jahan *et al.* [11] proposed a weighting framework consisting of subjective, objective and correlation (SOC) weights which can cover those shortcomings in the material selection approaches.

In this work, we aim to compare the performance of two weighting frameworks of AHP and SOC in conjunction with TOPSIS and VIKOR methods to rank a set of polymeric alternatives that can be used for manufacturing of a filament for fused filament fabrication (FFF) of an aerospace component. This provides an insight about the effect of personal judgment and interdependency of decision criteria on the final decision. The motivation behind choosing TOPSIS and VIKOR ranking methods is the easy and efficient computational approaches for relatively high number of alternatives and criteria in comparison to other MCDM methods. Although they share similarities in functioning based on the measure of 'closeness to the ideal solution', they use different normalizations (linear normalization for VIKOR and vector normalization for TOPSIS). On the other hand, TOPSIS best solution is the alternative that has the shortest Euclidean distance from the ideal solution and farthest distance from the worst solution simultaneously while VIKOR best solution is the one that is the closest to the ideal solution [12]. This comparison signifies the importance of suitability of methodology and precision that should be determined considering the nature of the material selection problem.

2 MATERIAL SELECTION ALTERNATIVES AND CRITERIA

The filaments used in FFF 3D-printing require a specific diameter, printability, and certain other mechanical, physical, and chemical properties depending on the application of the final 3D-printed part. Much research has been devoted to developing new composite feedstock materials with optimized properties to widen the material portfolio for FFF manufacturing by the incorporation of fibres into the pure polymers [13]. The materials for aerospace applications need to meet strict requirements in terms of safety and reliability in addition to their application properties. The goal of this material selection study is to find the most suitable matrix systems for developing an FFF filament that will demonstrate good processability and provide high mechanical properties while meeting the aerospace requirements like flammability. A list of the important criteria and associated explanations to select those criteria for this study are provided in Table 1.

The number of criteria has been kept low enough (less than 15 criteria) to avoid the unnecessary complications while addressing as many material characteristics as possible. Moreover, an effort was made to choose the criteria from the quantitative attributes of materials for the sake of simplicity since qualitative criteria need an additional step for quantification [14]. For the goal of this study, the thermoplastic polymers were considered as candidates that demonstrated the potential of meeting aerospace requirements in the literature. This includes eight high temperature thermoplastics such as polyether ether ketone (PEEK), polyetherketoneketone (PEKK), polyimide (PI), polysulfones (PSU), polyphenylene sulfide (PPS), polyether sulfone (PESU), polyphenyl sulfone (PPSU), and polyetherimide (PEI), as well as polycarbonate (PC) which is an engineering polymer but has performed as an aerospace-grade material for manufacturing of many aircraft components [15]. The data for material properties are the average value and were collected from online databases [16], [17].

Table 1. The list of material selection criteria and the associated reasoning behind their selection.

Attribute	**Unit**	**Explanation**
Density (ρ)	g/cm^3	It is important for light-weighting purposes.
Glass Transition Temperature (T_g)	˚C	High glass transition temperatures are preferred and is a measure of service temperature of the material.
Processing Temperature (T_p)	˚C	Lower processing temperature reduces manufacturing costs.
Coefficient of Thermal Expansion (*CTE*)	µm/m.˚C	Low CTE prevents the printed part from warpage.
Thermal Conductivity (*K*)	W/m.˚C	High thermal conductivity facilitates redistribution heat for polymer sintering.
Specific Heat (C_p)	J/kg.˚C	Higher specific heat is preferred since more heat can be added in the system when extruding.
Young's Modulus (*E*)	GPa	High modulus of the filament can result in components with high modulus.
Tensile Strength at Yield (*TS*)	MPa	High strength of the filament can result in components with high tensile strength.
Shrinkage (*S*)	%	Low shrinkage from melt prevents warpage and result in dimensional stability.
Moisture Absorption (*MA*)	w.t.%	Moisture content should be low enough to maintain the quality and performance.
Limiting Oxygen Index (*LOI*)	%O_2	Low LOI is a measure of high flammability of materials.
Cost (*C*)	$/kg	The lower the material cost, the lower the final component's cost.

3 MATHEMATICAL APPROACHES

The material selection was performed using two different multi-criterion decision-making methods of TOPSIS and VIKOR. The selection criteria are required to be weighted based on a rational and comprehensive approach in order to be incorporated in the decision-making methods. As stated previously, two different weighting approaches of AHP and SOC are applied in order to strengthen the comparison.

3.1 Weighting Methods

3.1.1 Analytical Hierarchy Process (AHP)

AHP is a pair-wise comparison of decision criterion in which the designer judges the attributes by assigning a value of 1, 3, 5, 7, or 9 corresponding to the verbal judgments of "equal importance", "moderate importance", "strong importance", "very strong importance", and "absolute importance", with values of 2, 4, 6, and 8 for compromising between the previous values. This gives a square matrix of $A_{n\times n}$ (Eq. 1) where a_{ij} denotes the comparative importance of attribute *i* with respect to attribute *j*. In this matrix, $a_{ij}=1$ when $i=j$ and $a_{ji}=1/a_{ij}$. Here *n* is the number attributes.

$$A_{n\times n} = \left[\begin{array}{c|ccccc} Attributes & 1 & 2 & 3 & \cdots & n \\ \hline 1 & a_{11} & a_{12} & a_{13} & \cdots & a_{1n} \\ 2 & a_{21} & a_{22} & a_{23} & \cdots & a_{2n} \\ 3 & a_{31} & a_{32} & a_{33} & \cdots & a_{3n} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ n & a_{n1} & a_{n2} & a_{n3} & \cdots & a_{nn} \end{array}\right] = \begin{bmatrix} 1 & a_{12} & a_{13} & \cdots & a_{1n} \\ 1/a_{12} & 1 & a_{23} & \cdots & a_{2n} \\ 1/a_{13} & 1/a_{23} & 1 & \cdots & a_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{2n} & 1/a_{3n} & \cdots & 1 \end{bmatrix} \tag{1}$$

The relative normalized weight of each criterion can be obtained by calculating the geometric mean of each row and normalizing them in the comparison matrix following the equation below [18]:

$$w_j^s = \frac{\left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}}}{\sum_{i=1}^{n}\left(\prod_{j=1}^{n} a_{ij}\right)^{\frac{1}{n}}} \tag{2}$$

The inconsistency in judgments of the analyst about the problem can be evaluated by calculation of consistency ratio (*CR*) according to Eq. 3. The consistency index (*CI*) in this equation is defined based on the maximum eigen value (λ_{max}) of comparison matrix as in Eq. 4. Also, random index (*RI*) is defined for every number of attributes [19]. A *CR* of 0.1 or less is considered as acceptable and it reflects an informed judgment that could be attributed to the knowledge of the analyst about the problem under study.

$$CR = \frac{CI}{RI} \tag{3}$$

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{4}$$

3.1.2 SOC Weighting Framework

This weighting framework proposed by Jahan *et al.* [14] consists of different objectives, subjective and inter-criterion correlation weights. These weights are obtained using entropy method, AHP, and standard deviation methods, respectively, after identifying the selection attributes for the application. The entropy method determines the weights of the *m* attributes for *n* alternatives through the equation below:

$$w_j^o = \frac{1-E_j}{\sum_{j=1}^{n}(1-E_j)} \qquad i=1,\ldots,m;\ j=1,\ldots,n \tag{5}$$

where,

$$E_j = -\frac{1}{\ln(m)}\left(\sum_{i=1}^{m}\frac{x_{ij}}{\sum_{i=1}^{m}x_{ij}}\ln\left(\frac{x_{ij}}{\sum_{i=1}^{m}x_{ij}}\right)\right) \tag{6}$$

Here x_{ij} represents elements of the decision matrix and *i* and *j* indicate the number of alternatives and criteria, respectively. In this method, the attributes with performance ratings that are very different from each other have higher importance for the problem due to their higher influence on the ranking outcomes.

In order to calculate the effect of the correlation among criteria, correlation (*R*) is calculated according to Eq. 7 and is applied in Eq. 8 to obtain the corresponding weights for *m* alternatives. A value of *R* near 0 indicates little correlation between criteria, while a value near 1 or −1 indicates a high level of correlation.

$$R_{jk}=\begin{cases}\dfrac{\sum_{i=1}^{m}\left(x_{ij}-\bar{x}_j\right)\left(x_{ik}-\bar{x}_k\right)}{\sqrt{\sum_{i=1}^{m}\left(x_{ij}-\bar{x}_j\right)^2\sum_{i=1}^{m}\left(x_{ik}-\bar{x}_k\right)^2}} & \text{If objectives of criteria } j \text{ and } k \text{ are same} \\ & j \text{ and } k=1,\ldots,\mathrm{n} \\ -\dfrac{\sum_{i=1}^{m}\left(x_{ij}-\bar{x}_j\right)\left(x_{ik}-\bar{x}_k\right)}{\sqrt{\sum_{i=1}^{m}\left(x_{ij}-\bar{x}_j\right)^2\sum_{i=1}^{m}\left(x_{ik}-\bar{x}_k\right)^2}} & \text{If objectives of criteria } j \text{ and } k \text{ are different}\end{cases} \tag{7}$$

$$w_j^c=\frac{\sum_{k=1}^{n}\left(1-R_{jk}\right)}{\sum_{j=1}^{n}\left(\sum_{k=1}^{n}\left(1-R_{jk}\right)\right)} \tag{8}$$

The subjective weights in this framework are obtained based on the AHP method which was elaborated in section 3.1.1. The final weights of criteria are obtained using Eq. 9 which will be used in ranking procedures as explained in the next section.

$$W_j=\frac{\left(w_j^o w_j^s w_j^c\right)^{\frac{1}{3}}}{\sum_{j=1}^{n}\left(w_j^o w_j^s w_j^c\right)^{\frac{1}{3}}} \tag{9}$$

3.2 Multi-Criteria Decision-Making Methods

3.2.1 TOPSIS Approach

The TOPSIS method is a powerful tool for dealing with high number of decision criteria and alternative materials involved in the decision-making process. This method requires reasonable quantitative weights for the attributes to maintain the correct trade-offs among the objectives. The first step in this method is to normalize the decision matrix ($X_{m\times n}$) after determination of the criteria weights. Consequently, the weighted normalized matrix can be obtained according to the equation below which shows vector normalization for all *n* criteria:

$$V_{ij}=M_{ij}W_j \tag{10}$$

where,

$$M_{ij}=\frac{x_{ij}}{\sqrt{\sum_{j=1}^{n}x_{ij}^2}} \tag{11}$$

In this equation, x_{ij} are the elements of $X_{m\times n}$ design matrix and are referring to the value of each attribute for each alternative. Also, *i* and *j* indicate the number of alternatives (from 1 to *m*) and criteria (from 1 to *n*), respectively. In the next step, the ideal (best) and negative ideal (worst) solution should be determined according to the Eq. 12 and Eq. 13 considering the weighted normalized *V* [18].

$$V^+=\left\{\left(\sum_i^{\max}V_{ij}\ /\ j\in J\right),\left(\sum_i^{\min}V_{ij}\ /\ j\in J'\right)\middle/ i=1,2,\ldots,m\right\}=\left\{V_1^+,V_2^+,\ldots,V_n^+\right\} \tag{12}$$

$$V^{-}=\left\{\left(\sum_{i}^{\min} V_{ij} \,/\, j \in J\right),\left(\sum_{i}^{\max} V_{ij} \,/\, j \in J'\right) \Big/ i=1,2,\ldots,m\right\}=\left\{V_1^{-},V_2^{-},\ldots,V_n^{-}\right\} \tag{13}$$

where in $J=\{j|j\in\{1,2,\ldots,n\}\}$, j is associated with beneficial attributes and in $J'=\{j|j\in\{1,2,\ldots,n\}\}$, j is associated with non-beneficial attributes. Based on these values, the "separation measures" of each alternative (S_i) from the ideal one is achieved by calculation of the Euclidean distance expressed as:

$$S_i^{-}=\left\{\sum_{j=1}^{n}\left(V_{ij}-V_j^{-}\right)^2\right\}^{0.5},\quad i=1,2,\ldots,m \tag{14}$$

$$S_i^{+}=\left\{\sum_{j=1}^{n}\left(V_{ij}-V_j^{+}\right)^2\right\}^{0.5},\quad i=1,2,\ldots,m \tag{15}$$

The final ranking of the alternatives is obtained by calculation of the relative closeness (C) of alternatives to the ideal solution according to Eq. 16. The higher the value of relative closeness of a particular alternative, the higher the ranking of that alternative in the material selection list.

$$C_i=\frac{S_i^{-}}{S_i^{+}+S_i^{-}} \tag{16}$$

3.2.2 VIKOR Approach

The straightforward mathematical procedure and the ease of implementation are among the reasons why VIKOR has been the topic of many studies for decision-making problems. This approach can be considered as an updated version of TOPSIS method in which the best solution is obtained based on the same rule of 'closeness to the ideal solution' but the worst case is not viewed as a reference point. The VIKOR method aims to minimize the individual regret and maximize the group utility for decision makers [6]. The mathematical procedure is explained as follows. As previously indicated, VIKOR approach applies the linear normalization for calculating the weighted normalized index according to the Eq. 17 which is known as the "utility measure". Also, R index is obtained by Eq. 18 which shows the "regret measure".

$$S_i=\sum_{j=1}^{n} w_j \frac{f_j^{*}-f_{ij}}{f_j^{*}-f_j^{-}} \tag{17}$$

$$R_i=\max_j\left[w_j \frac{f_j^{*}-f_{ij}}{f_j^{*}-f_j^{-}}\right] \tag{18}$$

where f_{ij}, f_j^{*} and f_j^{-} are elements of design matrix, best and worst values of f for all criteria, respectively. Also, w_j represents the weights of criteria which is defined as explained in section 3.1. Consequently, the Q indices can be calculated according to the Eq. 19.

$$Q_i=v\frac{S_i-S^{*}}{S^{-}-S^{*}}+(1-v)\frac{R_i-R^{*}}{R^{-}-R^{*}} \tag{19}$$

In this equation, $S^{*}$and R^{*} are the minimum values of S_i and R_i, respectively, over all alternatives. Similarly, $S^{-}$and R^{-} are the maximum values over all values of S_i and R_i, respectively. Here v is known as the weight of the decision-making strategy of ''the maximum group utility''. It is usually considered to be equivalent to 0.5 which means the compromise solution is obtained by consensus. Here the material with the best ranking has the minimum value of Q and in case it meets the following conditions, it can be proposed as the compromise solution; First condition is the acceptable advantage which requires the satisfaction of $Q(A_2)-Q(A_1)\geq 1/(m-1)$ inequality. The second condition is known as the acceptable stability in decision-making and states that the top-ranked alternative should also be ranked first based on R_i *and* S_i values. Here A_1 and A_2 are the alternatives ranked as the first and second solutions. If only the first condition is not met, all the alternatives that follow the inequality of $Q(A_K) - Q(A_1) < 1/(m-1)$ are considered as the compromise solutions for maximum K. On the other hand, if only the second condition is not satisfied, the alternatives with the first and second positions are the solutions [12], [20].

4 RESULTS AND DISCUSSION

For selecting the best thermoplastic polymer in developing an aerospace-grade FFF filament, the design matrix was established by collecting the average value of each of 12 criteria reported in Table 1 for every material, as explained in Section 2. Following the weighting procedures discussed in Section 3.1, the decision matrix was devised according to AHP procedure for calculating the subjective weights. With *RI* being equal to 1.54, the value of *CR* was calculated to be 0.061 which validates the designer's informed judgment. The objective weights were calculated through entropy method and the correlation's weights of criteria were determined following Eq. 7 and 8. All the weighting results are defined in Table 1.

As can be observed in Figure 1, the moisture absorption, cost and shrinkage obtained the highest objective weight factors since the data for these criteria is more scattered than the other criteria in the design matrix [21]. Similarly, the objective weight of density is almost zero since the density of polymeric materials are very close to each other. The most important criteria from the designer's point of view are cost, tensile strength, and Young's modulus. This shows that the designer is interested in an FFF filament that shows good mechanical properties at a low cost. This is to the desire to improve the mechanical properties of 3D-printed parts to replicate the performance of metallic components while keeping them light and affordable. Considering the correlation's weight factors, one can realize that the correlation values are almost equal for all criteria, and attributes are slightly correlated for this set of data. Thus, it can be concluded that the correlation concept is not decisive in this decision-making problem. Finally, the SOC weights are reflecting the effect of all three factors on the final decision and together with AHP weights, are used for material ranking by TOPSIS and VIKOR approaches.

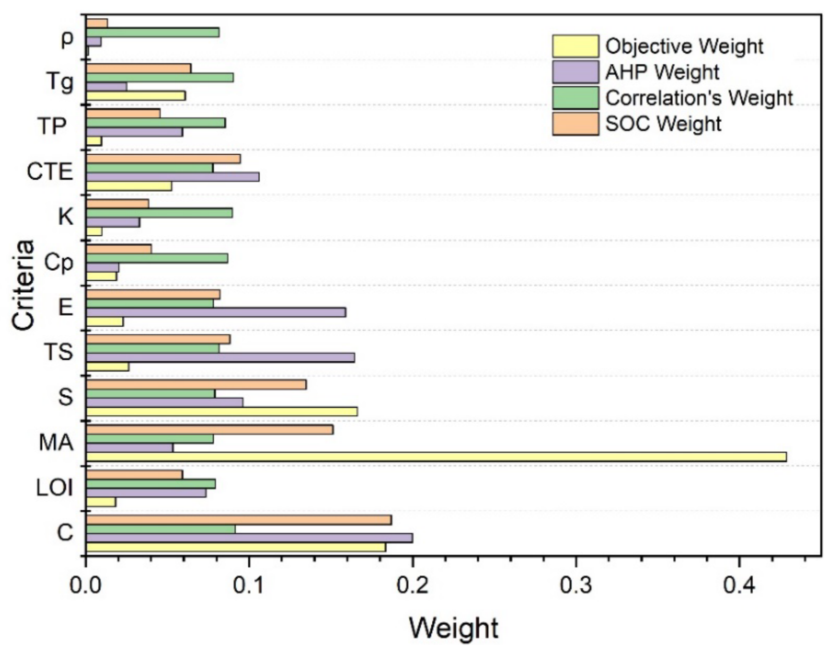

Figure 1. The results of weighting frameworks for different criteria.

The ranking lists obtained by each method are demonstrated in Figure 2. The ranking list of AHP-VIKOR and SOC-VIKOR approaches, reported in Table 2, were obtained having $v = 0.5$ and they both satisfied the conditions explained in Section 3.2.2. Therefore, the results can be considered as the compromise solutions. Looking into the Figure 2, one can observe that the polymers of PEI and PPS achieved the first and second positions in three methods and in the last approach, SOC-TOPSIS, these two are ranked among the top three materials. Thus, it can assertively be concluded that the best material for meeting the objectives of this study is PEI. This is in line with the results of studies existing in the literature that were in pursuit of replacing the metallic components of aircraft with thermoplastic composite materials [22]. For instance, researchers attempted to 3D-print aircraft vanes using a carbon fibre reinforced ULTEM1000 composite filament which is an aerospace grade of PEI [23]. Moreover, we can see that PC appears in the three highest-ranked alternatives in approaches involving TOPSIS method. It can be stated that when being far from the worst condition is important, PC can be a good choice for the application of interest. This means that by choosing PC as the polymeric matrix, we might not achieve the maximum performance, but it is assured that the material stands far enough from the worst-case scenario.

Table 2. Ranking results for different thermoplastic polymers

Materials	**Ranking Methods**					
	AHP-TOPSIS		*AHP-VIKOR*			
	Ci	*Rank*	*Si*	*Ri*	*Qi*	*Rank*
PI	0.4839	7	0.4936	0.1192	0.3786	3
PEEK	0.3100	9	0.5756	0.1668	0.7566	8
PEKK	0.4223	8	0.4134	0.2000	0.5369	4
PSU	0.6232	5	0.5890	0.1346	0.6522	6
PPS	0.6496	2	0.4070	0.1645	0.3754	2
PESU	0.6002	6	0.5550	0.1306	0.5609	5
PPSU	0.6327	4	0.5584	0.1590	0.6863	7
PEI	0.6623	1	0.3967	0.0795	0.0000	1
PC	0.6409	3	0.6236	0.1645	0.8526	9
	SOC-TOPSIS		*SOC-VIKOR*			
	Ci	*Rank*	*Si*	*Ri*	*Qi*	*Rank*
PI	0.3546	9	0.5495	0.1514	0.7387	8
PEEK	0.4404	8	0.5918	0.1559	0.8648	9
PEKK	0.5604	6	0.4073	0.1869	0.5351	7
PSU	0.6331	5	0.5337	0.0723	0.3538	4
PPS	0.6838	3	0.4069	0.0997	0.1536	2
PESU	0.5180	7	0.5335	0.0972	0.4616	6
PPSU	0.6780	4	0.4838	0.0822	0.2709	3
PEI	0.6902	2	0.3933	0.0745	0.0096	1
PC	0.6989	1	0.5211	0.0946	0.4191	5

Other than the difference in normalizations, the different performance of SOC-TOPSIS approach can be related to the effect of weighting results. It can be understood from Figure 1 that cost is among the most significant criteria for all objective, subjective, and correlation weights and it becomes even stronger when they are multiplied to form the final weight in the SOC framework. Knowing that PC is the most affordable material among all the alternatives, it can be realized that PC is a more conservative candidate among all when cost is of great significance.

Moreover, when the weighting framework of AHP is applied, we observe that PI rises to the top three materials. This is due to the high importance of mechanical properties and LOI as well as low importance of T_g from the designer's point of view since PI is known to have high modulus, tensile strength, and LOI with the highest T_g among all the alternatives. Yet, it cannot compete with the overall performance of the PEI and PPS regarding the selection priorities. Lastly, it can be said that there is a good agreement between the methods, however, the weighting framework should be validated before further attempt toward manufacturing of the desired component. This can be pursued by consulting several knowledgeable experts of the field and/or collecting material properties in a more precise manner.

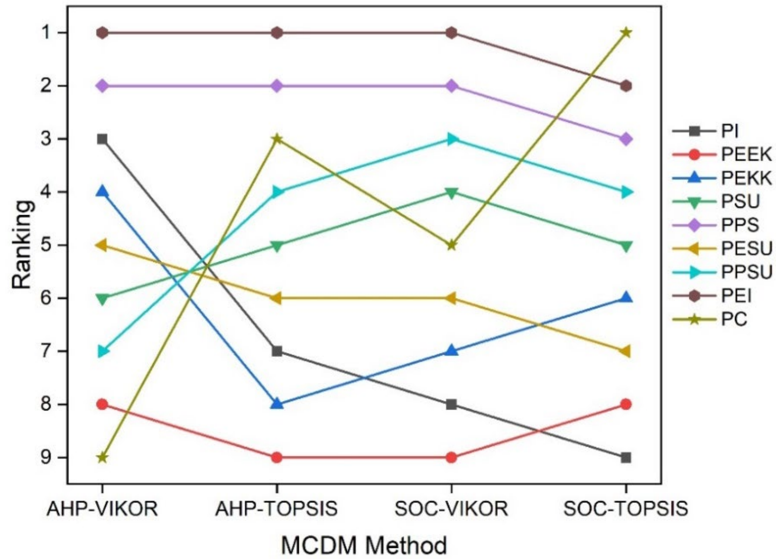

Figure 2. Comparison of the ranking results of the four ranking approaches for material selection.

5 CONCLUSION

In this paper, we sought to find the most suitable thermoplastic polymer to be used for manufacturing of a composite filament for FFF 3D printing of an aerospace component. To solve this material selection problem, nine thermoplastic polymers were chosen as the set of alternative materials which were ranked considering the importance of 12 decision criteria. Their significance was quantified using two different weighting frameworks of (1) AHP that demonstrates the designer's preferences, and (2) SOC which combines the AHP weights with correlation effect of criteria and objectivity of the decision matrix. The weights obtained from these methods were then implemented in two common MCDM methods, namely TOPSIS and VIKOR, to achieve the final ranking lists of materials. Although there are some differences between the performance of the methods, they all agree that PEI is the most suitable material for this application and PPS stands in the second position. However, the SOC-TOPSIS approach gives more priority to PC and ranks it as the best material. This might be due to the strong contribution of the cost criterion as a result of SOC weighting framework together with the nature of TOPSIS approach to provide a solution that not only is it the closest to the ideal solution but also stands far from the worst case. In conclusion, this study provides a good insight about the effect of different weighting methods on the final decision. Objectivity and the effect of correlation among data are not involved in the most of decision-making processes and the introduced methodologies can encourage more robust and reliable decisions, specifically for sensitive applications like aerospace. This study was conducted based on the average property of the materials. The robustness of the ranking results can be improved by using the exact properties of the materials of interest or more precise databases. Also, the results of selection should be verified in a real-case design problem to confirm the better performance of the alternatives suggested by these methods.

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