Original Research

Expert System Optimizing Model of Filament Winding Process for Improved Automated Composite Manufacturing Structure

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Abstract

Various strategies have been adopted to enhance the qualities of composite manufacturing processes to develop achieving composite materials with precise geometry without discounting productivity. Filament winding process is considered an important method for producing composite materials for various industrial applications. Several mandrel materials are usually considered before setting the suitable type in filament winding process to ensure satisfying the desired specifications of the design requirements. This work investigated a wide range of materials that could be utilized as alternatives for the filament winding mandrels in one hand, and classified materials based upon various simultaneous conflicted technical and economic standpoints on the other. Properly optimizing and determining the most appropriate material type according to certain desired specifications via building an informative multi-criteria decision-making model would enhance both productivity and benefit for the composite manufacturing system. The built model was capable of systematically selecting the most appropriate mandrel material type for the filament winding process with very limited or marginal personal selection errors. Twelve simultaneous evaluation criteria were considered. Sensitivity analysis, moreover, was conducted to reveal the reliability of the drawn conclusions.

Keywords - Composite materials; Expert system; Filament winding; Manufacturing processes; Optimization

1. INTRODUCTION

Designing with composite materials has nowadays gained outstanding significance because of their main role in various engineering technologies and applications. Therefore, a diverse range of composite materials has been utilized in a variety of designs and manufacturing processes to satisfy different design requirements including structural composites, functionally graded composites as well as other smart engineering devices (Almagableh et al., 2017; AL-Oqla et al., 2017; AL-Oqla and Hayajneh, 2007; Alves et al., 2010; Siwal et al., 2021; Jawarneh et al., 2021; Al-Oqla, 2021a). Noteworthy efforts have been made for developing the alternatives of composite manufacturing processes to enhance achieving composite materials with precise geometry without discounting productivity (Alaaeddin et al., 2019; Beluns et al., 2021; Hayajneh et al., 2021a). In fact, wide research was performed regarding optimizing the manufacturing characteristics including material handling, material removal rate, strength, dimensional accuracy, and surface finish (Barbero, 2010; Hambali et al., 2009; Fares et al., 2019; Al-Oqla and Al-Jarrah, 2021a; Rana et al., 2021;

AL-Oqla, 2021b; AL-Oqla and Thakur, 2021). This was achieved via selecting the optimal values of the input process parameters. However, to properly find the optimal values of such input parameters, models as well as relationships correlating the manufacturing characteristics and the inputs have to be developed where physics based models have to be expressed through analyzing the mechanism behind the manufacturing process or to develop models based on given statistical data using statistical methods and experts feedback (AL-Oqla et al., 2014a; Al-Oqla and Omar, 2012; AL-Oqla and El-Shekeil, 2019; Rababah and AL-Oqla, 2020). Never the less, such models may induce uncertainty in the obtained solutions and make the whole matter a case of multi-criteria decision making problem where appropriate decisions have to be made in an optimized manner(Al-Oqla and Omar, 2015; AL-Oqla et al., 2018a; AL-Oqla et al., 2015a; AL-Oqla and Salit, 2017a; Al-Oqla, 2021c).

One of the major manufacturing processes of composite materials is filament winding process. It depends upon mandrels as a main part to achieve the processing technique and obtain the desired product shape. In such manufacturing processes, a major parameter involving in optimizing the manufacturing characteristics for proper design is the mandrel. Its material and geometry are the most important issues. In fact, several mandrel materials are considered before setting the suitable type and after looking at and making hundreds of processes, to ensure satisfying the desired specifications of the design (AL-Oqla, 2017; AL-Oqla and Salit, 2017b, c; AL-Oqla and Sapuan, 2018; Voicu and Thakur, 2021; Hayajneh et al., 2021b). Mandrels, in fact, should be made from materials that satisfy wide diverse characteristic according to different manufacturing and design parameters including usage, geometry, motion, rotation, and removal nature (Quanjin et al., 2018). Using a mandrel made from proper material is vital for the reliability and efficiency of the manufacturing process and can affect the overall life of the mandrel and thus the manufacturing productivity and quality.

On the other hand, several functional mandrel types are required according the manufacturing environment and design requirements. Therefore, mandrel types can be distinguished in heated mandrels, non-heated mandrels, dissolvable cores and liners. They can also be classified as removable or non-removable(Zu et al., 2019; Dun et al., 2019). Removable mandrels are classified according to the removal techniques as: entirely removed, collapsible, and breakable or soluble depending upon the part size and complexity, size of openings, resin system, curing, and the number of components to be fabricated. Moreover, there are several requirements for a mandrel to be considered including the necessity to be stiff and strong enough to support its own weight and the weight of the applied composite while resisting the fiber tension pressure from winding and curing(Zu et al., 2019). It has also to be dimensionally stable and should have thermal coefficient of expansion greater than the transverse coefficient of the composite structure.

Persistent mandrels are acceptable for some industrial applications where light-weight mandrels can be left in the final product. Usually, these ‘persistent’ mandrels are made of structural or non-structural foam cores. In either case, the mandrel needs to be of a closed cell material and resistant to the resin as well as the process parameters (heat and temperature) to prevent the resin from filling up the inner cavities of the part. Moreover, mandrels and curing ovens are an integrated part of a filament winding production line (Du et al., 2018; Zu et al., 2018). Thus, an optimal mandrel design is absolutely essential for successful filament winding production. Polished steel mandrels are commonly used. Large components are also made on collapsible mandrels, whereas pressure vessels are normally wound directly on a thin thermoplastic or metallic liner (Du et al., 2018; Zu et al., 2018). The oven/heat source, component, and mandrel should all reach and remain above the minimum cure temperature throughout the cure cycle.

Additionally, in a filament winding process, the filament is applied on a mandrel. Thus, using a heated or non-heated mandrel, the quality of the mandrel surface is an important factor due to the fact that the finally wound component must be stripped (pulled or pushed) over the surface (Du et al., 2018). By using a liner or a dissolvable core the surface quality is not so relevant, due to the fact that the liner remains in the product and the dissolvable core is removed after the winding process.

For dissolvable materials the following are practically used: sand (soluble, water soluble), plaster (soluble, breakout), salt (meltable, eutectic) and alloy (with a low melting temperature). All dissolvable cores are non-heated mandrels. Liners on the other hand, can be made, for example, of polymer, aluminum alloy or steel. Also, like the dissolvable core, the liner cannot be temperature controlled. Besides, it was reported that for huge winding applications, the usage of one complete (fully) mandrel is not useful, based on the weight and costs (Zu et al., 2018). The mandrel for winding applications with large diameters consists of different components. The inner part is a hollow framework construction and only the surface of the mandrel is closed with wood, aluminum alloys, steel or a similar material. Moreover, the selection of such mandrel materials is very hard to be performed manually; as it will take very long time with many human mistakes included. In general, wide aspects, criteria, and requirements are needed to be considered during the mandrels’ material selection process including strength, impact resistance, temperature resistance, technical aspects like manufacturing cost, reparability, degree of solubility and durability.

Therefore, this work aims to build a hierarchy optimizing model of filament winding mandrel type to enhance and improve the composite production system via studying wide range of feasible alternative materials for the filament winding mandrels. The work also aims to classify these materials based upon various simultaneous conflicting criteria and specifications to properly optimize and determine the most appropriate material type according to certain desired specifications. To attain this, the work develops an informative hierarchy expert based model capable of systematically determining the most appropriate mandrel material type for the filament winding process with very limited bias or marginal personal decision errors.

2. The Expert System Model

Thousands of material choices are available to engineers to assist in right material selection. This reveals the need for an expert system for the selection of alternative materials for a given application. Few expert systems are being developed for composite material selection. However it was utilized in other various fields (Nourian et al., 2019; Ghasemi et al., 2013; Sadr Dadras et al., 2014; Shokuhfar et al., 2008) In an expert system, the user feeds in the service condition requirements (e.g., operating temperature range, chemical resistance, fluid exposure, percent elongation, fracture toughness, strength, etc.) and based on the available material database, the expert system provides materials that are suitable for the application. Unlike metals, a large database for the performance of composite materials for various conditions is not available. Raw material suppliers provide designers and fabricators with a list of basic material properties (Jawarneh et al., 2021; Alaaeddin et al., 2019; AL-Oqla et al., 2018b; AL-Oqla et al., 2015b; Aridi et al., 2016; AL-Oqla et al., 2016; AL-Oqla et al., 2021; AL-Oqla et al., 2021; AL-Oqla and Hayajneh, 2020). The datasheet is typically generated by testing standard coupons manufactured in their laboratory. These datasheets are useful for initial screening of materials but not for final selections (Hayajneh et al., 2021a; Al-Oqla, 2021c; Mazumdar, 2001; AL-Oqla et al., 2014b; AL-Oqla and Al-Jarrah, 2021b; AL-Oqla, 2020).

Based on the requirements of an application, possible materials and manufacturing processes that meet the minimum or the maximum requirements of the application are determined. Once a list of materials based on the above guidelines is created, the next task is to determine the candidate materials best suited for the application. After selecting the candidate materials for the various types of feasible manufacturing processes, usually prototype parts are made and then tested to validate the design.

3. Analytical Hierarchy Process (AHP): Model and Criteria

A model utilizing the Analytical Hierarchy Process to select the proper material for filament winding mandrel is established here. AHP is considered in various engineering problems as it is a reliable decision making tool that can lead to consistent decisions (Al-Widyan and Al-Oqla, 2014; Dalalah et al., 2010; Deng et al., 2014; Taylan et al., 2014; Al-Widyan and Al-Oqla, 2011). Step by step illustrations of utilizing the AHP model are illustrated herein.

Determining the requirements and criteria of the applied model are of paramount importance for proper selection of the filament winding process. The twelve considered criteria after performing expert feedback questionnaire are tabulated in Table 1. Moreover, applying these criteria for the Expert Choice© software utilizing the analytical hierarchy process for the current problem is demonstrated utilizing the general analytical hierarchy model in Figure1.

TABLE 1
CRITERIA AND REQUIREMENTS FOR SELECTING THE MATERIAL OF THE FILAMENT WINDING MANDREL

Material Cost	Adhesive Properties
Manufacturing Cost	Heat Resistance
Reparability	Degree of Solubility
Durability	Melting Point
Reliability	Strength
Time to Produce	Weight

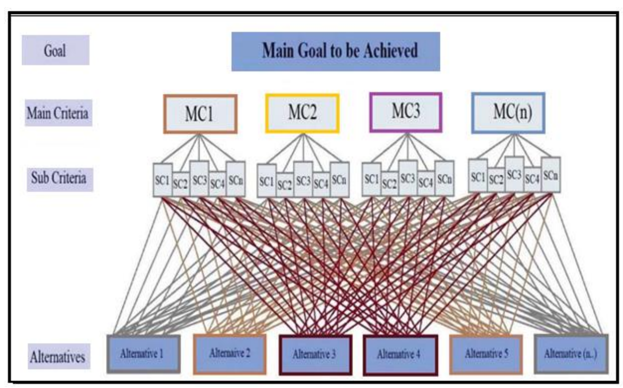

FIGURE 1
THE GENERAL ANALYTICAL HIERARCHY MODEL

After that, the determination of the relative importance of each criterion in the selection model has to be determined utilizing a pairwise comparison manner via filling out a comparison matrix as demonstrated in Table 2. Note that the upper part of such matrix has to be filled with a one-based diagonal as each criterion has the same weight of importance when compared to itself. The lower part of such comparison matrix should have the reciprocals of each corresponding element in the upper part of the matrix. This in order would reveal the importance of each considered criterion in the selection model for the proper mandrel design.

TABLE 2
THE REQUIRED PAIRWISE COMPARISON JUDGMENT MATRIX TO BE FILLED FOR THE UPPER PART

	A	C	E	G	I	K	B	D	F	H	J	L
A	1	a	b	c	d	e	f	j	h	i	j	k
C		1	a	b	c	d	e	f	j	h	i	j
E			1	a	b	c	d	e	f	j	h	i
G				1	a	b	c	d	e	f	j	h
I					1	a	b	c	d	e	f	j
K						1	a	b	c	d	e	f
B							1	a	b	c	d	e
D								1	a	b	c	d
F									1	a	b	c
H										1	a	b
J											1	a
L												1

Such judgment matrix also demonstrates the need for utilizing software-based model to facilitate the selection process with a minimum human bias and computational errors. The relative scores in a certain level results in a matrix of scores a(i, j) with judgment of the pair-wise comparisons. However, it should be consistent for further considerations. For that reason, a test for confirming such consistency must be done to confirm the expert knowledge. The pair-wise comparison matrices can also be represented as:

$$A=\begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \vdots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix}=\begin{bmatrix} w_1/w_1 & \cdots & w_1/w_n \\ \vdots & \vdots & \vdots \\ w_n/w_1 & \cdots & w_n/w_n \end{bmatrix} \tag{1}$$

A consistent matrix can be shown to satisfy that:

$$A\cdot w=nw \tag{2}$$

Where A is the evaluation matrix, **w** is the eigenvector, n is the size of the matrix. The rank vector ($\overline{P}$) for the given matrix A can be calculated using the mean geometric values and normalized as in equations 3 and 4. The overall geometric consistency, eigenvector, means relative error and mean geometric method flowchart are illustrated in Figure 2.

$$P=\begin{pmatrix} p_1=\sqrt[n]{\prod_{j=1}^{n} a_{1j}} \\ p_2=\sqrt[n]{\prod_{j=1}^{n} a_{2j}} \\ \cdots \\ p_n=\sqrt[n]{\prod_{j=1}^{n} a_{nj}} \end{pmatrix} \tag{3}$$

$$\overline{P}=\begin{pmatrix} \overline{p_1}=p_1/\sum_{i=1}^{n} p_i \\ \overline{p_2}=p_2/\sum_{i=1}^{n} p_i \\ \cdots \\ \overline{p_n}=p_n/\sum_{i=1}^{n} p_i \end{pmatrix} \tag{4}$$

4. Results and Discussions

One of the experts' feedback filled matrix on the Expert Choice© software is demonstrated in Figure 3, with marginal inconsistency value of 0.09, which is acceptable for such selection model. It was noted that the value with red color means reciprocals of that value. i.e, (4) in red color means (0.25).

The overall weights of the considered criteria were then generated and normalized utilizing the software to be as demonstrated in Figure 4. It can be demonstrated that the criterion material cost has the highest importance regarding selecting the mandrel's material followed by the strength of the material. However, the degree of solubility as well as reliability criteria were the least important evaluation criteria in the selection model according to the experts' feedback with a consistency ratio (CR) equals to 0.09, so the comparison is acceptable as it is less than 0.1.

On the other hand, the possible alternative materials for the filament winding mandrels are illustrated in Table 3. They have wide range of properties from traditional materials like steel to alloy materials to ensure various characteristics of the potential materials.

TABLE 3
THE POSSIBLE ALTERNATIVES FOR THE SELECTION MODEL

Steel	Aluminum
Wood	Polymer
Sand	Salt
Plaster	Alloy

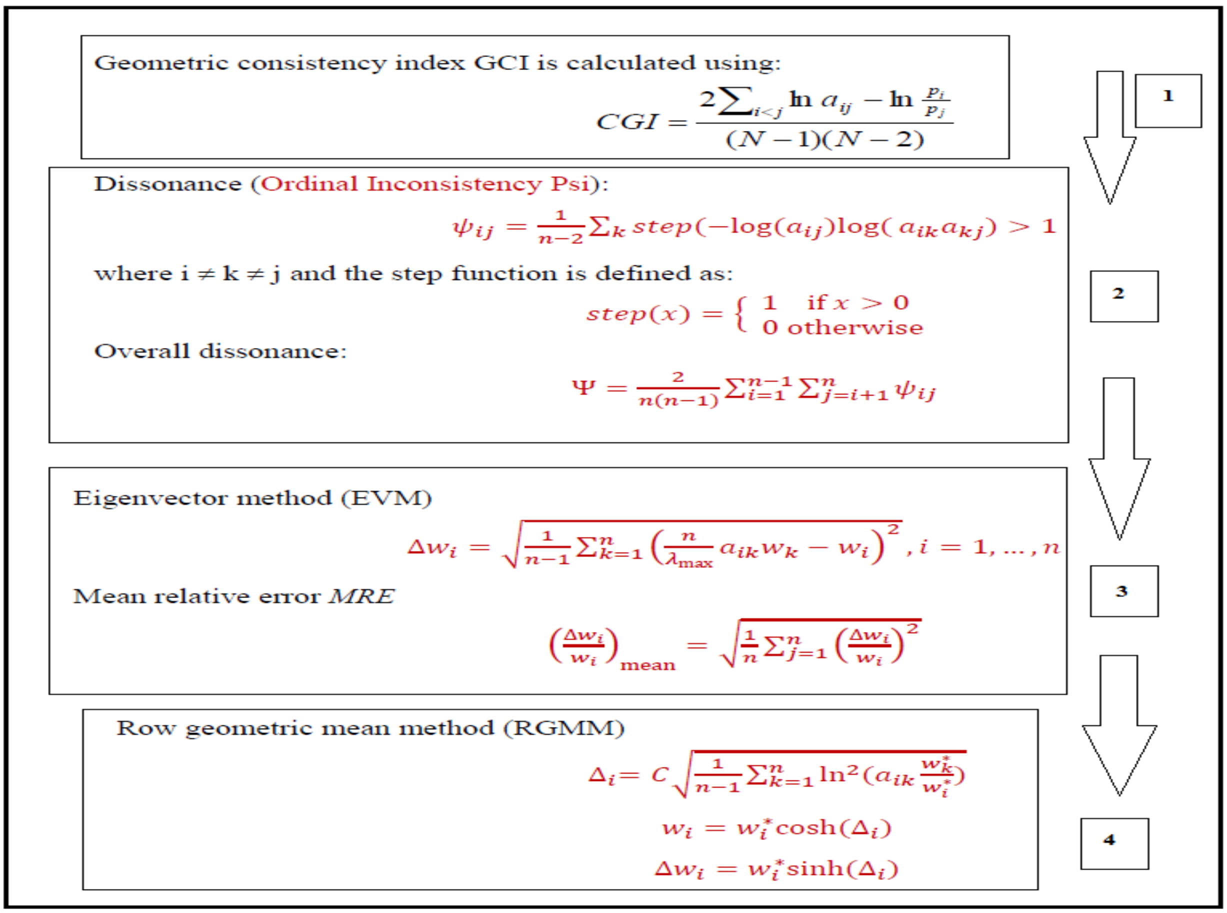

FIGURE 2: FLOW CHART OF FINDING GEOMETRIC CONSISTENCY, EIGENVECTOR, MEAN RELATIVE ERROR AND GEOMETRIC MEAN METHOD

	Material Cc	Manufactur	Reparabilit	Durability	Reliability	Time to Prc	Adhesive P	Heat Resist	Degree of :	Melting Poi	Strength	Weight
Materi		4.0	4.0	2.0	4.0	4.0	3.0	2.0	5.0	2.0	2.0	2.0
Manufa			2.0	3.0	3.0	3.0	5.0	3.0	4.0	2.0	2.0	2.0
Repara				3.0	3.0	3.0	3.0	4.0	2.0	3.0	3.0	2.0
Durabi					2.0	2.0	2.0	3.0	3.0	2.0	3.0	2.0
Reliabi						2.0	3.0	4.0	2.0	2.0	3.0	3.0
Time t							3.0	2.0	3.0	3.0	2.0	3.0
Adhesi								3.0	3.0	4.0	3.0	4.0
Heat R									2.0	1.0	2.0	2.0
Degree										4.0	4.0	4.0
Melting											2.0	2.0
Streng												1.0
Weight	Incon: 0.09											

FIGURE 3: A FILLED JUDGMENT MATRIX

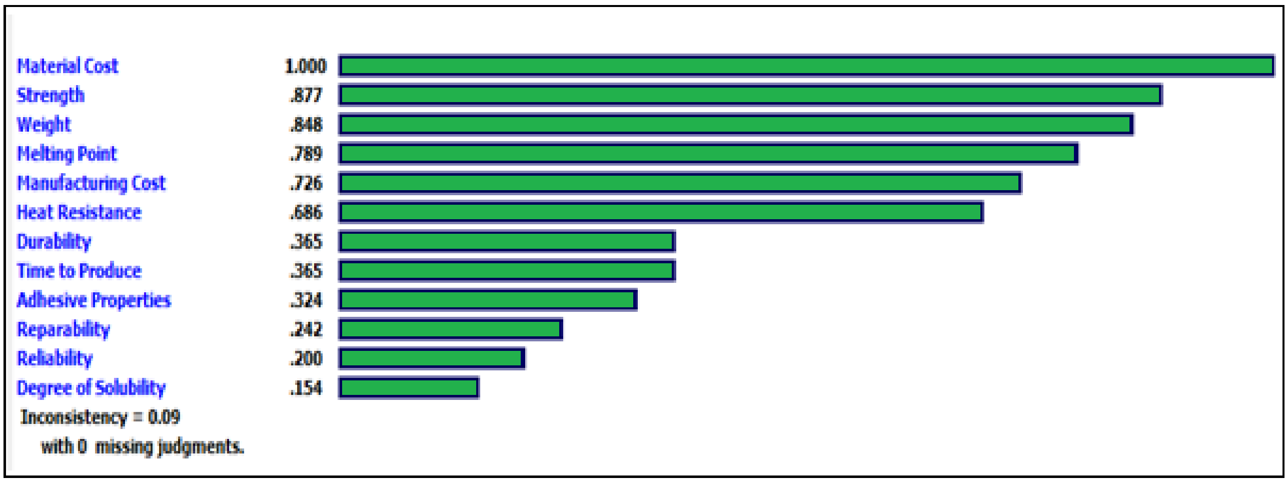

FIGURE 4: WEIGHTS OF THE CONSIDERED CRITERIA

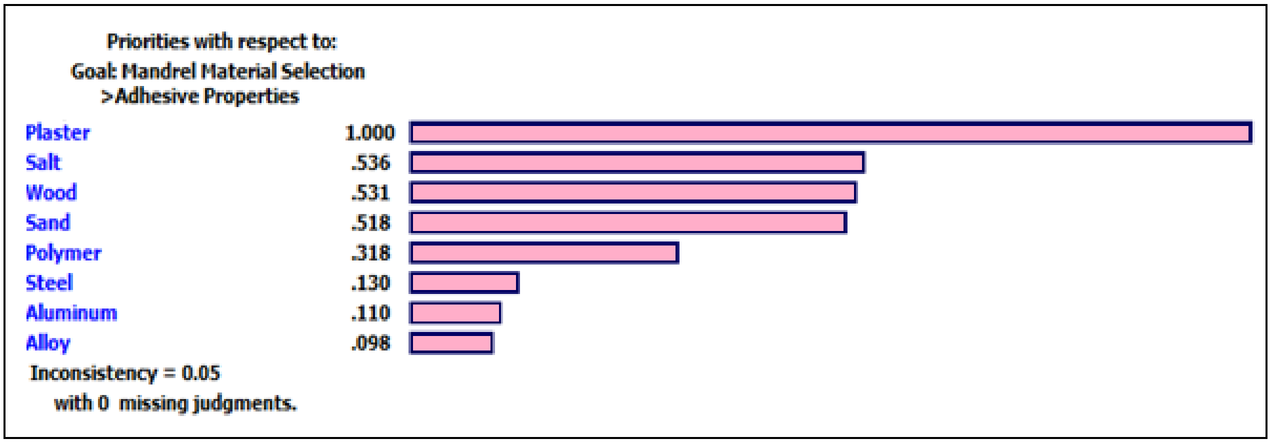

FIGURE 5: PRIORITIES OF ALTERNATIVES WITH RESPECT TO THE ADHESIVE PROPERTIES CRITERION

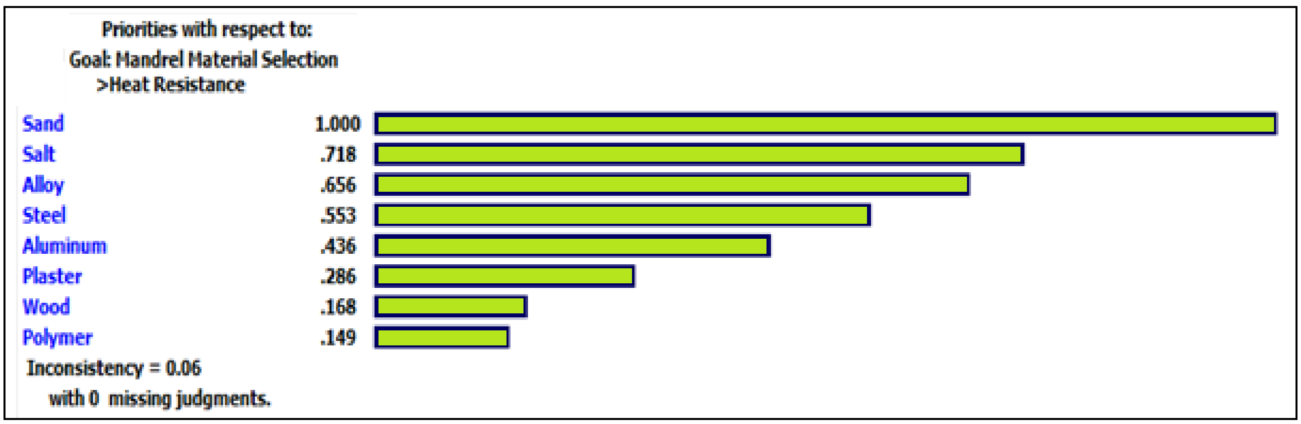

FIGURE 6: PRIORITIES OF ALTERNATIVES WITH RESPECT TO HEAT RESISTANCE CRITERION

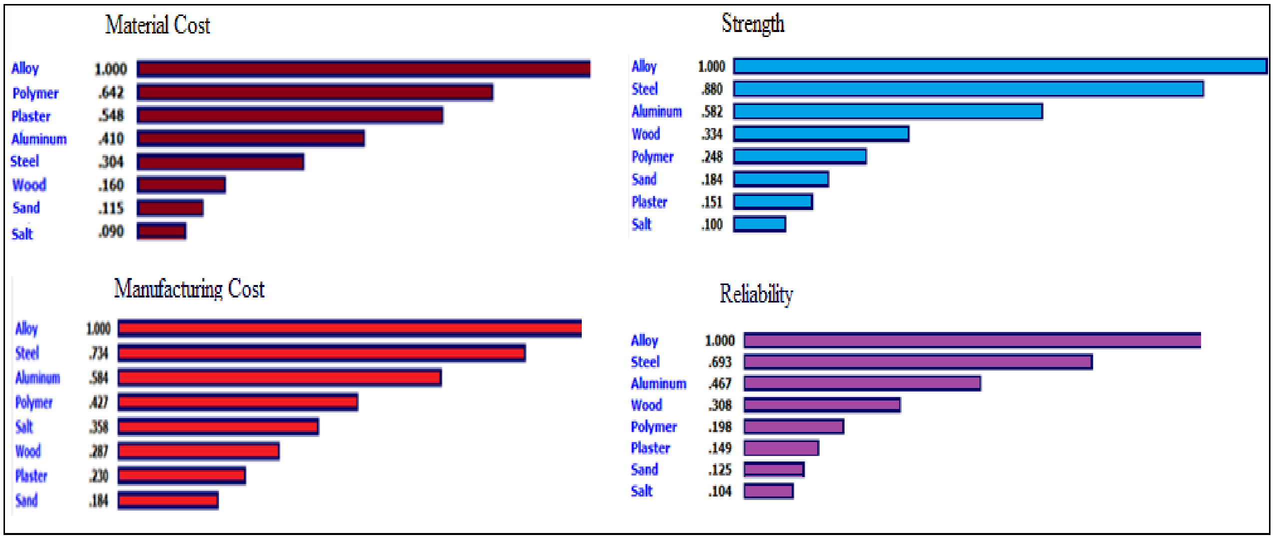

FIGURE 7: PRIORITIES OF ALTERNATIVES WITH RESPECT TO MATERIAL COST, STRENGTH, MANUFACTURING COST, AND RELIABILITY CRITERIA

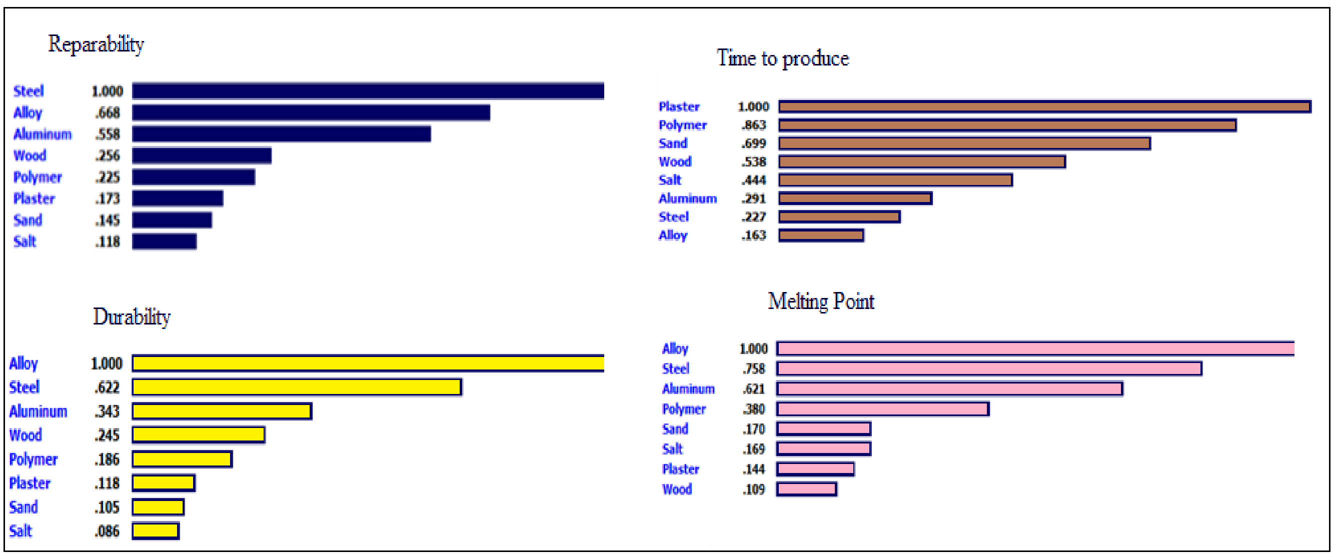

FIGURE 8: PRIORITIES OF ALTERNATIVES WITH RESPECT TO REPARABILITY, TIME TO PRODUCE, DURABILITY, AND MELTING POINT CRITERIA

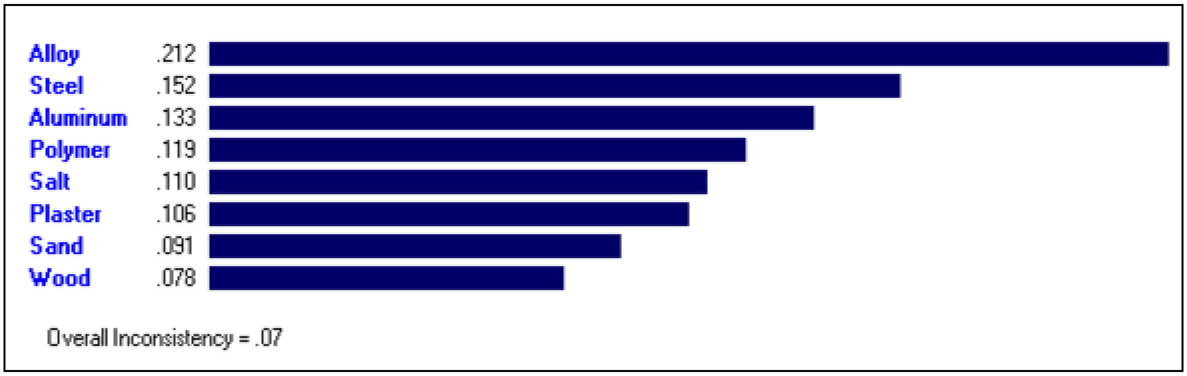

FIGURE 9: ALTERNATIVES OVERALL PRIORITIES OF THE EVALUATION MODEL

The alternatives priorities according to each single considered criterion in the model are then generated to demonstrate their importance according to each criterion independently. The priorities of alternatives with respect to the adhesive properties criterion for instant are demonstrated in Figure 5. It can be demonstrated that plaster mandrel type can be the best according to the time to produce criterion, whereas mandrel type from alloy is the worst according to this particular criterion with an inconsistency value of 0.05; which is considered very acceptable and the judgment matrix that leaded to such priorities were consistent. Moreover, the priorities of alternatives with respect to heat resistance criterion are demonstrated in Figure 6. It can be demonstrated that sand mandrel type is the most preferable according to this criterion; whereas polymer-based mandrel type is the last choice with respect to the heat resistance criterion. Such judgment is considered acceptable as the inconsistence criterion is 0.06. Similarly, the rest of alternative priorities with respect to other considered criteria in the model are demonstrated in Figures 7 and 8.

On the other hand, determination of candidate materials can be generated utilizing the overall priorities of the alternatives considering the entire evaluation criteria simultaneously. This is revealed in Figure 9. It can be demonstrated that alloy based mandrel is the best type as it has the most overall priority in the evaluation model with 21.2% followed by the steel type with a priority of 15.2%. However, the least preferred type is the wood with only 7.8% priority. The closeness of priorities of the considered material types, moreover, clearly indicates that selecting the most appropriate material type is very difficult without considering such appropriate decision making model to reduce the human biased decisions and to facilitate calculation error.

In addition, the reliability of the considered model can be demonstrated via appropriate sensitivity study, which usually clarifies the effect of changing weights of the considered criteria. This is demonstrated in Figure 10. A scenario of changing the weights of some criteria in the model and its corresponding selection weights of the materials alternatives are demonstrated in Figures 11 and Figure 12 respectively. It can be demonstrated that changing weights from the current situation (Figure 11) to other unexpected new weights (Figure 12) would not significantly affect the selection of the first preferable alternative (alloy type). It can be also noticed that although other alternatives priorities may be changed, the first priority was not altered as an indicator of the robustness of the decisions made from the current selection model and its reliability is verified.

5. Conclusions

A multi-criteria expert hierarchy optimizing model for evaluating and determining the most appropriate material type for the mandrel of filament winding process was constructed. It was capable of properly evaluating and selecting the best mandrel material type considering various conflict evaluation criteria simultaneously. The selection of such mandrel materials was very hard to be performed manually; as it would take very long time with many human mistakes included. It was revealed that alloy-based mandrel was the best type with the most overall priority in the evaluation model with 21.2% followed by the steel type with a priority of 15.2%. However, the least preferred type is the wood with only 7.8% priority. Sensitivity analysis was also conducted to reveal the reliability of the drawn conclusions. The closeness of priorities of the considered material types, moreover, clearly indicates that selecting the most appropriate material type would be very difficult without considering such appropriate decision making model to reduce the human biased decisions in the selection process.

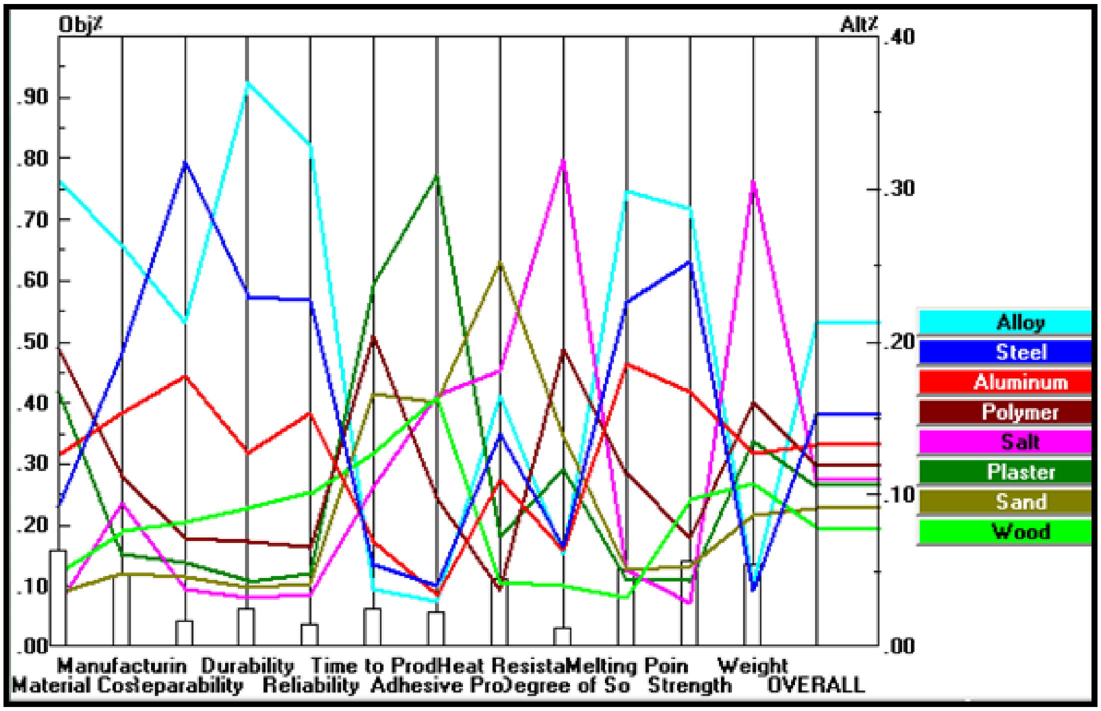

FIGURE 10: THE SENSITIVITY ANALYSIS OF THE SELECTION DECISIONS OF THE CONSIDERED MODEL

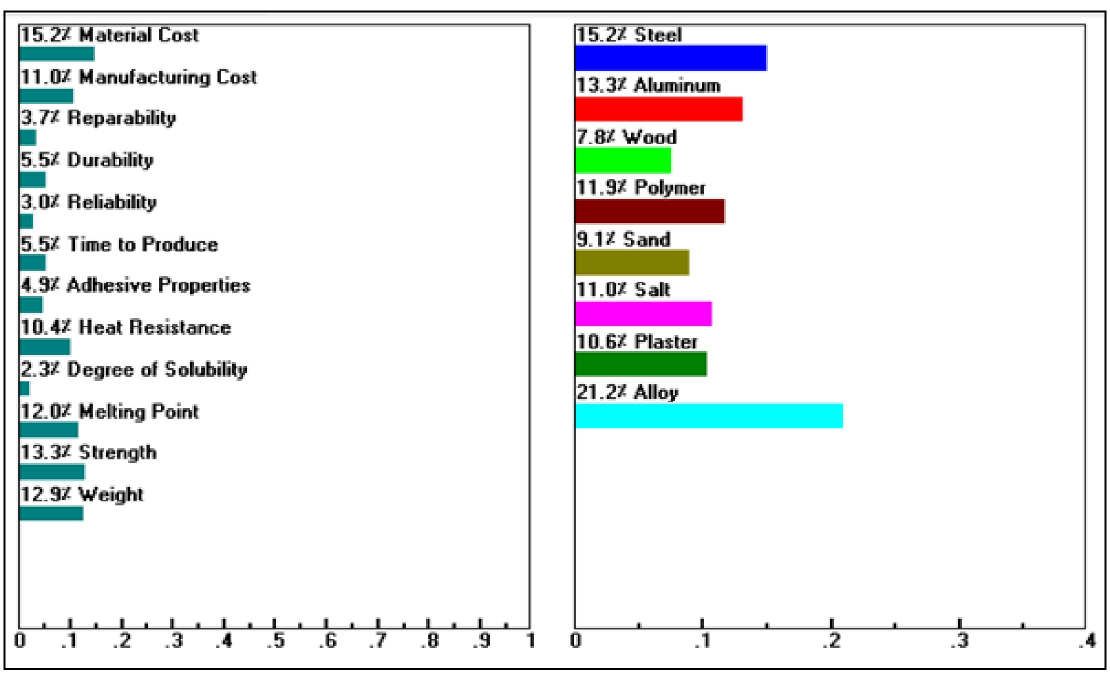

FIGURE 11: THE CURRENT WEIGHTS OF THE EVALUATION CRITERIA

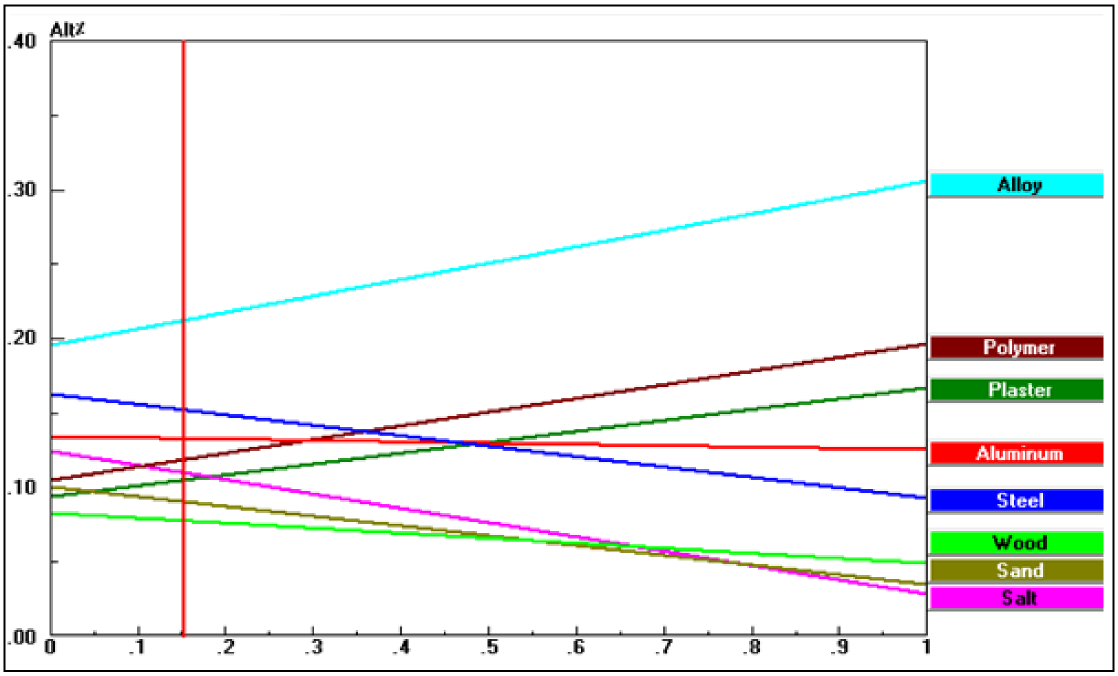

FIGURE 12: THE NEW ALTERNATIVES RANKING AFTER CHANGING THE WEIGHTS OF THE EVALUATION CRITERIA

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