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ORIGINAL PAPER

Application of analytical hierarchy process for the determination of green polymeric-based composite manufacturing process

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Abstract

Design for manufacturing is essential before launching the manufacturing processes for bio-products, where various issues must be considered in advance. Manufacturing green composites involvs several technical issues that have to be considered. Such issues include; the uniformity of the fiber distributed inside the composites, the water absorption of both fiber and matrix, the thermal degradations and the weathering effect of fiber and matrix, the wettability of resin impregnated into the spaces between fibrils, and the breakage of fibers during the mixing stages within the manufacturing processes. Therefore, the final desired properties of the green composites in relation to the selections of right materials, pre-processing methods, and manufacturing processes are distinguishably important for developing more functional green products. Thus, this work addresses a multi-criteria decision-making model to determine the appropriate green polymeric-based composite manufacturing process properly. The model was built based upon the Analytical Hierarchy Process (AHP) involving eleven (11) technical-economic conflicting evaluation criteria. The manufacturing alternatives for green composites were simultaneously evaluated regarding all the considered evaluations. The results have revealed that selecting the best manufacturing process is challenging to perform without a particular bias toward a specific method. However, the selection was straightforward using the presented model as most of the manufacturing methods were of high priority regarding a specific evaluation criterion, but with low priorities regarding others. The compression molding process is determined as the best choice based on the overall considered evaluation criteria. However, it was not regarding production characteristics and material type criteria. Resin transfer molding and filament winding were found close in their priorities regarding the model's evaluation criteria. It was shown that both compression molding and filament winding were the best processes regarding the cost considerations with overall priorities of 14.2% and 8.5%, respectively. The robustness of the results for the constructed model was verified via sensitivity analysis to validate its reliability. It was revealed that no manufacturing alternative was dominant while an exaggerated deviation in the weights of the primary evaluation criteria has occurred.

Keywords Green composites · Manufacturing processes · Decision model · AHP · Filament winding · Vacuum bagging

1 Introduction

Over the past years, composite materials gained a growing attention due to their desired characteristics. However, green composites have recently become of paramount importance due to their environmental features. Their applications are spread over many fields including; automotive, construction, aerospace, and furniture industries [1–4]. Design for manufacturing is essential before any manufacturing process, as many issues have to be considered in advance, such as; cost, marketing, maintenance, environmental impacts, and recycling. Optimizing the outcomes of these preceding issues in the early stages will have a direct influence over the downstream activities [3, 5, 6]. Design for manufacturing includes; to design a robust part of any product, manufacture it efficiently, achieve the desired function and define the standard manufacturing process. It is a set of design guidelines that attempt to ensure the product's manufacturability. Design for manufacturing prevents the quality issues and eliminates the manufacturing waste. It eliminates the risks in the

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new product development by preventing the costly scenario of learning about the manufacturability issues when you're about to launch. Thus, the goal of design for manufacturing is to design product's components to be manufactured as efficiently as possible. It integrates with the design model as it contains several stages and steps that the designers should follow to build satisfactory designs, and eventually, robust products. These steps include the consumers' needs, the market study, the design concept, the design specifications, the manufacturing issues, and the sales. However, for the design of green products made from green composites, several characteristics, including thermal stability, have to be considered.

Most of the manufacturing processes used for conventional composites can be adopted for the natural fiber composites, such as; compression molding, injection molding, vacuum infusion molding, resin transfer molding, as well as hot press processes [7–11]. Conventional green polymeric composite manufacturing processes are illustrated in Fig. 1.

An accelerating interest in developing more substantial fiber-reinforced composite materials was very noticeable over the last few decades. Biological observations inspired such an interest. For example, the human bones revealed a unique mechanical performance due to the protein fibers reinforcing the soft tissues [12, 13]. Many conventional polymer-based composites reinforced by glass, carbon, or aramid fibers are currently used in many sectors. Among these artificial fibers, glass fibers are the reinforcement commonly used for plastics. This is due to their comparative prices, excellent mechanical performances, and high stability during fabrication. However, glass fibers have high density, and they require high energy during processing. Moreover, they are non-biodegradable and reveal health hazards.

In general, there are several issues in selecting the proper manufacturing techniques for the green composites. The manufacturing techniques generally used for conventional fiber composites can be employed for the natural fiber composites (NFCs); these include compression molding, injection molding, vacuum infusion molding, resin transfer molding as well as hot press processes [9, 14, 15]. These manufacturing techniques are considered productive for the NFCs production. However, their suitability for natural fiber reinforced polymer composites is still unsure due to the geometrical, mechanical, thermal, and structural properties of the natural fibers. The green composites are somehow different from both synthetic fibers and petroleum-based plastics. Chemical treatments on the fiber surface are normally required to enhance the compatability and the bonding between the hydrophilic fiber and the hydrophobic matrix. Other technical issues also make the selection of the manufacturing process for the green composites of a paramount importance. Such issues include the uniformity of the fiber distributed inside the composites, the water absorption of both fiber and matrix, the thermal degradation and the weathering effect of fiber and matrix, the wettability of resin impregnated into the spaces between fibrils, and the breakage of fibers during mechanical stirring/mixing stages. Therefore, the the final desired properties of the green composites in relation to the selections of right materials, pre-processing methods, and manufacturing processes are distinguishably important for developing more functional green products [16–18].

The total design model introduced by (Stuart Pugh, 1991) has met worldwide acceptance as a powerful tool in design for manufacturing [19]. It includes several stages and steps that the designer should follow to build satisfactory designs, and eventually, good products. These steps include the consumers' needs, the market study, the design concept, the design specifications, the manufacturing issues, and the sales. Pugh model has been widely accepted as one of the best models for design and evaluation. Therefore, it is considered as an important design tool for manufacturing [20]. However, for designing green products made from green composites, several characteristics, including thermal stability, have to be considered [21–23]. One of the essential characteristics of the NFCs that should be considered is the thermal degradation of the natural fibers. For example, lignocellulosic fibers undergo noticeable changes in their characteristics at elevated temperatures of 100–250 °C [24–26].

Different from conventional polymer composites, processing of green composites is governed by the thermal instability of composites during manufacturing, the water absorption capability, the wide morphological differences in fibers as well as the changes in the rheological behavior [18, 27, 28]. Hence, understanding the composites' characteristics is essential in controlling the fabrication processes and their composites. For example, the flow characteristics of the natural fibers and the bio-polymers are significantly altered due to the viscoelastic behavior exhibited during processing. However, only limited studies explored the flow behavior of the natural fiber composites during fabrication. These studies found an increase in the composite viscosity, substantially a reduction in the composite processability, with the increase in the natural fiber contents [11, 29]. Furthermore, some biopolymers such as PLA also revealed undesired flow properties [11, 30]. In addition, the natural fiber's dispersion and its sticking effect with the polymer matrix are both reduced due to the hydrophilic nature, adding a challenge to the fabrication process [31, 32]. Another challenge is the wide span of the fiber types and the fiber qualities regarding their chemical composition and their morphology [17, 33–38].

Accordingly, it is essential to select the most appropriate natural fiber composite manufacturing process, where designers have to consider it at the initial stages of the bio-product design. Thus, this work aimed to build a multi-criteria decision-support model capable of determining the most

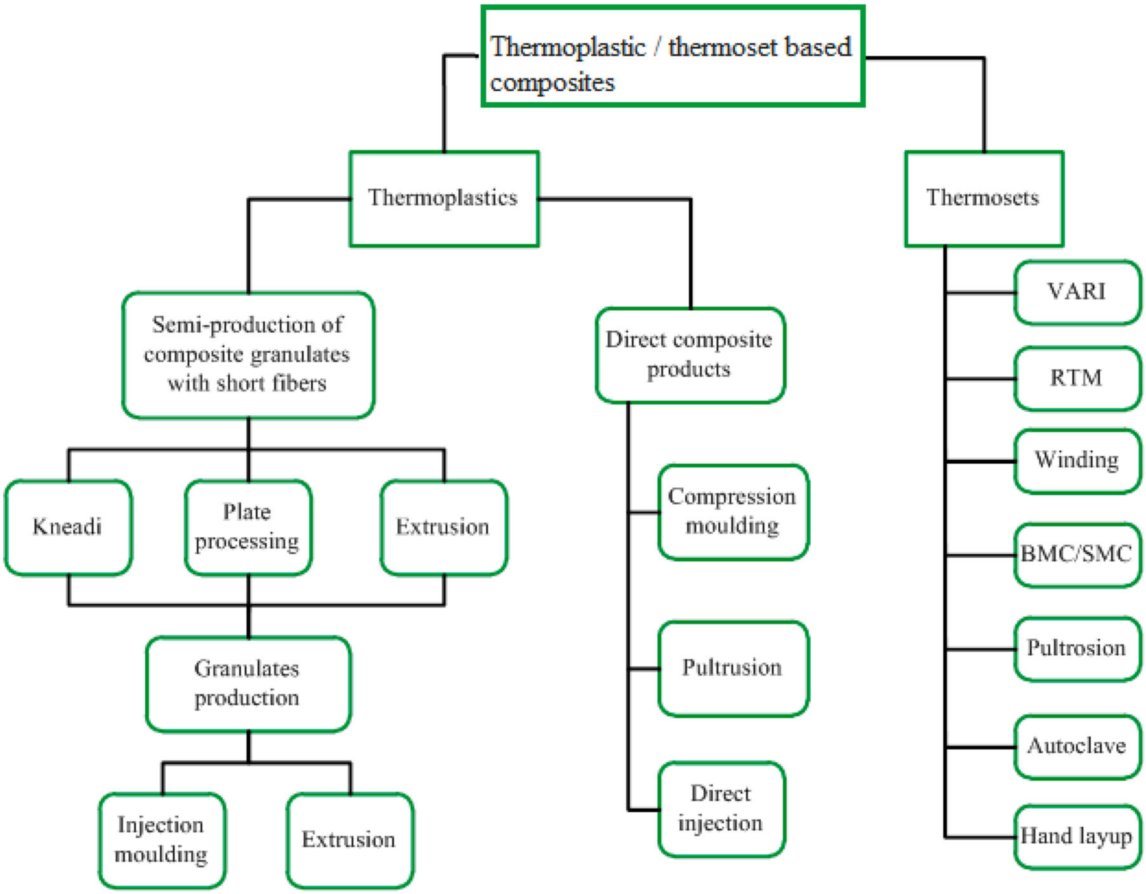


Fig. 1 Conventional green polymeric composite manufacturing processes

suitable manufacturing process for green composites considering various available alternatives as well as simultaneous conflicting evaluation criteria. This would enhance the reliability of the considered manufacturing processes and develop better-predicted characteristics for the produced bio-products based on the technical–economic and environmental evaluation criteria.

The research article comprises four sections. The first section has already presented the literature review and the research problem. The second section explains the adopted research methodology. The third section describes the results, and the final section concludes the research outcomes.

2 Methodology

Multi-criteria decision-making (MCDM) tools are utilized for optimizing and selecting an appropriate alternative from wide available candidates for various fields. The Analytical Hierarchy Process (AHP) is such a tool that uses a particular weight for each factor of the many factors influencing the decision-making process. The weight of each factor is calculated based on scientific expertise to ensure satisfactory conclusions. AHP can provide the possibility of incorporating verbal judgments that enhance the precision of findings. It also allows better ratio and scale priorities. The method offers the benefit of minimizing the bias in decision-making by allowing the capture of both subjective and objective evaluations, and the possibility of checking the consistency of the evaluations and the alternatives. Unlike other methods—the fuzzy-AHP method, TOPSIS, and others—AHP shows a good consistency in a pair-wise decision and figures out any potential bias [39–41]. As a result, AHP is considered as one of the best standard and reliable multi-criteria decision-making methods. Its simplicity and efficiency encouraged its wide use for various applications of materials selections, energy planning strategies, renewable energy, and many others [40, 42–52].

2.1 The analytical hierarchy process (AHP)

The main and critical step in the MCDM process is to divide the primary goal into sub-goals (objectives). Hence, the process goes through three levels. These are the primary goal, criteria, and alternatives. However, each criterion can be divided into sub-criteria with less importance in the decision-making process. In AHP model, the primary goal comes at the highest level, the alternatives at the lowest, and the objectives lie in between.

The second step is to assign a proper relative weight to each objective or criterion in the corresponding level. Besides the local priority, each criterion has a global priority that shows the alternatives' relative importance. The sum of the relative weights for all sub-criteria for a given objective or criteria must be unity. Once the weighted factors are assigned to the criteria, the relative scores are computed for each choice on a relational basis by comparing the choices to each other. The scores are then resolved through the hierarchy leading to a relative score for each choice at every layer, and to an overall score. A matrix $\mathbf{A}(i, j)$ of relative scores is established within each level, indicating the judgment on a pair-wise basis.

To construct a matrix consistent, it should be compatible with the transitivity and reciprocity rules as mentioned in Eqs. (1) and (2).

$$a_{i,j} = a_{i,k} \cdot a_{k,j} \tag{1}$$

$$a_{i,j} = \frac{1}{a_{j,i}} \tag{2}$$

where i, j, and k are the elements in a matrix. The pair-wise judgment matrices can be stated as:

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \vdots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} = \begin{bmatrix} w_1/w_1 & \cdots & w_1/w_n \\ \vdots & \vdots & \vdots \\ w_n/w_1 & \cdots & w_n/w_n \end{bmatrix} \tag{3}$$

The construction of a consistent matrix can be represented as:

$$\begin{bmatrix} w_1/w_1 & \cdots & w_1/w_n \\ \vdots & \vdots & \vdots \\ w_n/w_1 & \cdots & w_n/w_n \end{bmatrix} \begin{bmatrix} w_1 \\ \vdots \\ w_n \end{bmatrix} = n \begin{bmatrix} w_1 \\ \vdots \\ w_n \end{bmatrix} \tag{4}$$

Expressing Eq. (4) in a matrix form gives:

$$\mathbf{A} \cdot \mathbf{w} = n\mathbf{w} \tag{5}$$

where **A, w,** and n are the pair-wise comparison matrix, the eigenvector, and the matrix dimension, respectively.

A quantitative measure of consistency was introduced by Saaty et al. [53, 54] to provide a mathematical value to the deviation of consistency. This measure is called the Consistency Index. An inconsistency test is applied to evaluate the expert knowledge and robustness. The inconsistency ratio should be less than 0.1 for validating the process judgment. For ratio greater than 0.1, overall re-assessment should be carried on the subjective judgment [55–61].

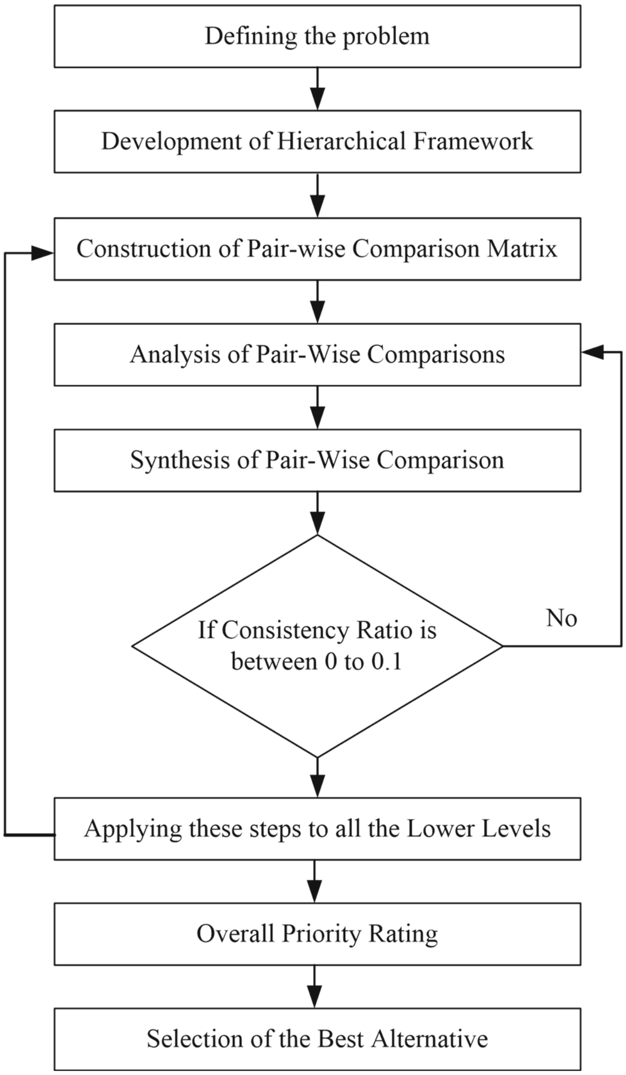


Fig. 2 Analytical hierarchy process (AHP)

The procedural steps of the analytical heirarchy process are provided in Fig. 2. Further information on the AHP are detailed in a research by Saaty [53]. A typical AHP model structure is illustrated in Fig. 3. Level I of the AHP model defines the name of the model, level II contains the main criteria, which are production characteristic (PC), cost consideration (CS), material type (MT), and geometry of design (GD). The considered alternatives for the manufacturing processes are Resin Transfer Molding (RTM), Compression Molding (CM), Vacuum Bag Molding (VBM), and Filament Winding (FW). The sub-criteria in level III are production quantity (PQ), rate of production (RP), processing time (PT), shape of design (SD), size (SZ), weight (WG), complex of design (CD), tolerance and surface finish (TF), tooling cost (TC), equipment cost (EC), and ease of maintenance (EM).

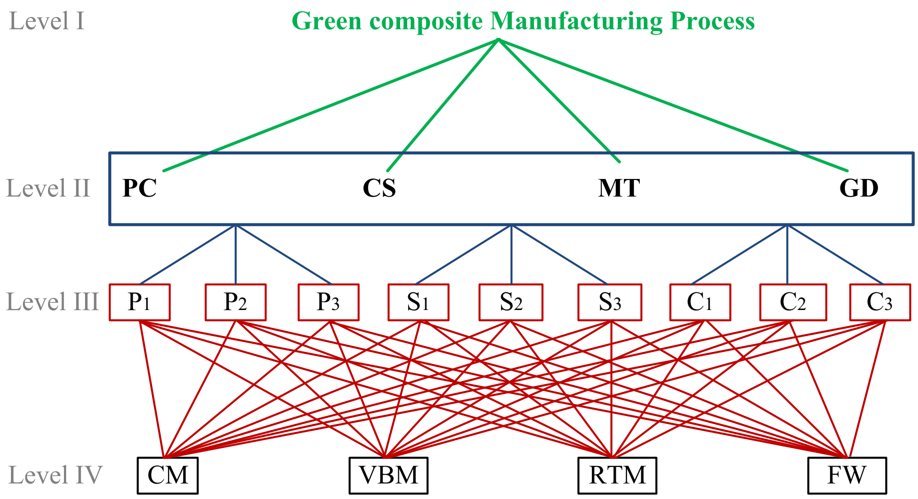


Fig. 3 Typical AHP model structure

Table 1 The model main and sub-evaluation criteria as well as the manufacturing alternatives

Main criteria	Sub-criteria	Manufacturing alternatives
Production characteristic (PC)	Production quantity (PQ)	Compression molding (CM)
	Rate of production (RP)	
	Processing time (PT)	Vacuum bag molding (VBM)
Geometry of design (GD)	Shape of design (SD)	
	Size (SZ)	Filament winding (FW)
	Weight (WG)	
	Complex of design (CD)	Resin transfer molding (RTM)
	Tolerance and surface finish (TF)	
Cost consideration (CS)	Tooling cost (TC)	
	Equipment cost (EC)	
Material type (MT)	Ease of maintenance (EM)	

2.2 Application of AHP model

Expert Choice™ software version 11 was adopted to select the most proper green composite manufacturing process according to several parameters. As a result, AHP can provide the decision-makers with many material and process alternatives for optimal economic and technical results. Various criteria influencing the decision-making of determining the most appropriate process were carefully proposed. These criteria and their sub-criteria were intentionally considered for the AHP after intensive literature review [62–69]. The overall model with main and sub criteria as well as manufacturing alternatives with their relationships are illustrated in Table 1.

3 Discussion

3.1 Pair-wise comparison

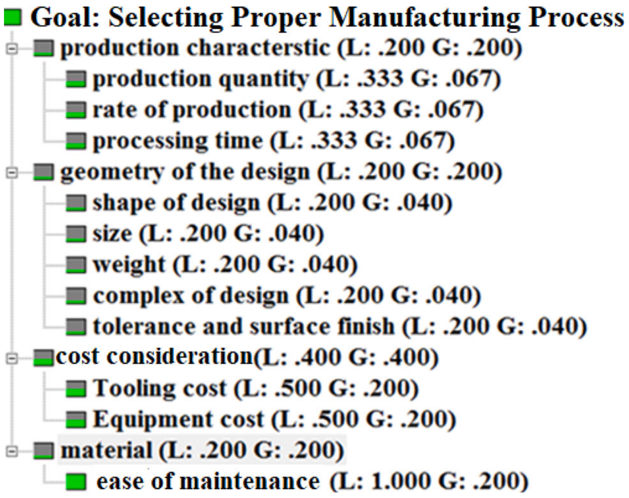
The comparison was performed in pairs of the main factors that are branched from the primary goal. Relative importance for these pairs was assigned. The number of the paired comparisons is expressed as

$$\text{No. of comparisons} = \frac{n(n-1)}{2} \tag{6}$$

To elaborate more, consider the production characteristic factors shown in Fig. 4, under which three questions are developed to be answered. Therefore, the sample of questions from the production characteristics standpoint can be as follow:

- How much is the production quantity more important relative to the rate of production?
- How much is the production quantity more important relative to the processing time?
- How much is the rate of production more important relative to the processing time?

The data that was intended for evaluating the comparability of the criteria selected for this study was collected via a



Goal: Selecting Proper Manufacturing Process
- production characterstic (L: .200 G: .200)
  - production quantity (L: .333 G: .067)
  - rate of production (L: .333 G: .067)
  - processing time (L: .333 G: .067)
- geometry of the design (L: .200 G: .200)
  - shape of design (L: .200 G: .040)
  - size (L: .200 G: .040)
  - weight (L: .200 G: .040)
  - complex of design (L: .200 G: .040)
  - tolerance and surface finish (L: .200 G: .040)
- cost consideration(L: .400 G: .400)
  - Tooling cost (L: .500 G: .200)
  - Equipment cost (L: .500 G: .200)
- material (L: .200 G: .200)
  - ease of maintenance (L: 1.000 G: .200)

Fig. 4 Overall importance of factors and sub-factors in the model

questionnaire that was sent out to thirteen highly regarded experts in the green composite manufacturing in different locations of the world including both academics and professional experts. Eight responses were returned, they were checked for consistency. Seven of these responses were found consistent and were deemed adequate for the sake of the study according to the AHP method [54, 55]. The experts answered the survey following the descriptive scale of verbal assessments having choice 5 = Extremely, 4 = Very strongly, 3 = Strongly, 2 = Moderately, 1 = Equaly. The corresponding reciprocal scale of importance was developed by Saaty [53]. Cronbach Alpha is applied to assess the reliability of the responses. A value of 0.84 is obtained demonestrating the reliability of the responses. The three questions mentioned provide sufficient information to fill the matrix. The judgment matrix columns (that captured the relative importance) were then normalized and the matrix rows were averaged and revealed the results. This was performed for each judgment matrix for each expert's feedback. The geometrical mean value was then performed for the consistent judgments to get the overall priorities. It was performed using the Expert Choice™ software package. The overall importance results of the primary factors related to the primary goal, and the relative weights of the sub-factors with each main criterion are illustrated in Fig. 4, where L is a local priority and G is a global priority.

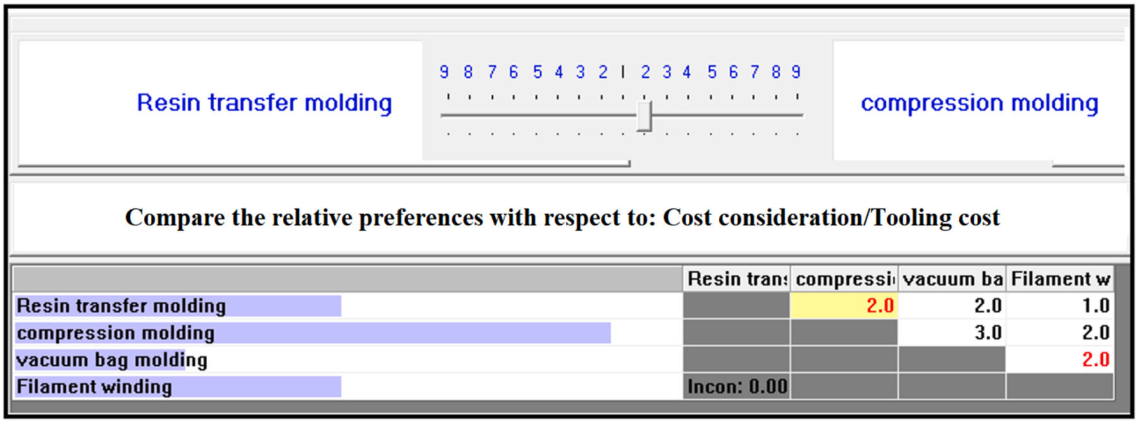
3.2 Pair-wise comparison for alternatives

The same comparison procedure was followed as already discussed for the factors and the sub-factors involved regarding the alternatives. The survey data for the alternatives regarding the sub-factor "tooling cost" when considering the main criterion "cost consideration" is shown in Fig. 5. It can be seen that six weights have to be assigned to complete the judgment, where values with red colors represent their reciprocals. That is, the value of (2) in red color means (1/2). The level of consistency was found to be 0. It implies that the judgment was performed with a high level of consistency and the judgment is highly accepted for this particular step in the model.

Similarly, the weights of the alternatives related to the main criteria are illustrated in Fig. 6. It can be shown that the importance and the relative weights of the alternatives differ for each main criterion in the model. It is clear that selecting a particular manufacturing process for green composites is sometimes contradictory when conflicting criteria are considered, making it difficult for humans to judge without a certain bias. The overall weights of the considered alternatives with the considered criteria in the model are illustrated in Table 2.

Moreover, the overall priority of the manufacturing processes regarding the criteria in the model is illustrated in Fig. 7. It can be revealed that both compression molding and filament winding are the best processes regarding the cost considerations with overall priorities of 14.2% and 8.5%, respectively. However, the compression molding was not the best process regarding other criteria. On the other hand, vacuum molding was the worst process regarding the cost criterion with a priority of only 3.6%. However, it was the best choice regarding the material type criterion with a priority of 7.1%. Moreover, the risen transfer manufacturing process was the best regarding the geometry of the design criterion with a priority of 7.0%. Thus, it clarifies that the conventional selection of the best manufacturing process for green composites is not an easy task for the designers without an appropriate decision-making scheme.

Accordingly, the overall priorities of the green manufacturing process alternatives are illustrated in Fig. 8. It can be demonstrated that the most appropriate manufacturing process was the compression molding, taking into consideration the overall conflicting criteria simultaneously with a priority value of 30%. The second-best alternatives were the resin transfer and the filament winding processes with 25.9% and 25.5% priority values, respectively. However, vacuumed bag molding was the worst alternative, with a priority of only 18.8%. This reveals the need for such decision-making models to consider the most appropriate manufacturing process for green composites when various conflicting criteria are reasonably optimized. Thus, the Analytical Hierarchy Process can be utilized to decompose sophisticated problems with conflicting evaluation criteria into sum of small pairwise problems to end up with a consistent non-biased decision. Thus, according to the overall evaluation criteria, both compression molding and resin transfer molding scored the highest priority values and were selected as the most appropriate manufacturing processes for the composite as



Compare the relative preferences with respect to: Cost consideration/Tooling cost

	Resin tran:	compressi	vacuum ba	Filament w
Resin transfer molding		2.0	2.0	1.0
compression molding			3.0	2.0
vacuum bag molding				2.0
Filament winding	Incon: 0.00			

Fig. 5 Judgment matrix for the alternatives related to the tooling cost sub-criterion

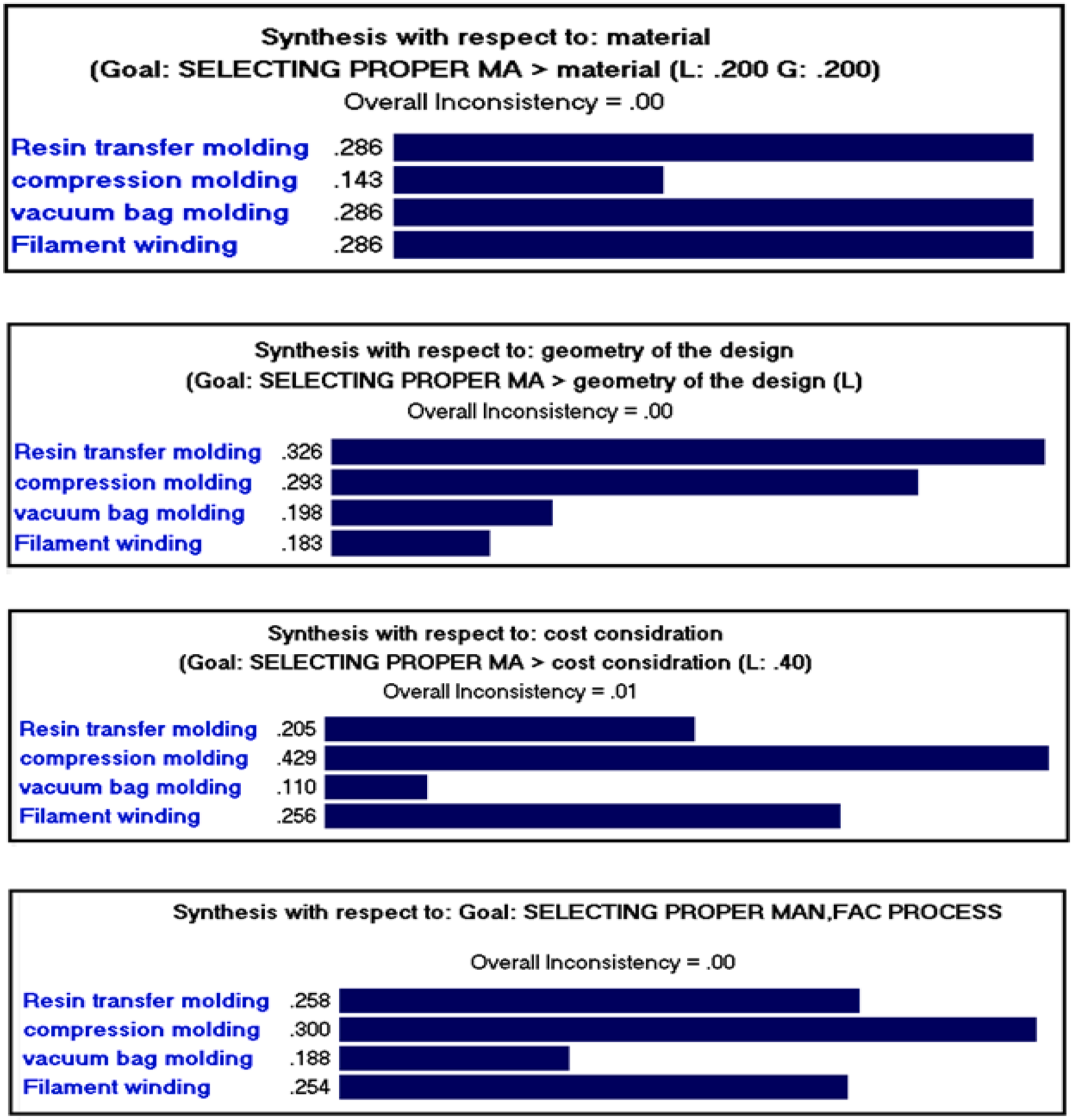


Fig. 6 Relative significance of the alternatives related to the main criteria in the model

Table 2 Relative weights of the alternatives related to the model's criteria

Sum of Priority		Alternatives				
Level I	Level II	Compression molding	Filament winding	Resin transfer	Vacuum bag molding	Grand total
Cost Consideration	Equipment cost	0.071	0.047	0.03	0.016	0.164
	Tooling cost	0.071	0.038	0.038	0.02	0.167
Cost consideration total		0.142	0.085	0.068	0.036	0.331
Geometry of the design	Complex of design	0.014	0.007	0.014	0.007	0.042
	Shape of design	0.014	0.004	0.014	0.008	0.04
	Size	0.014	0.014	0.014	0.014	0.056
	Tolerance and Surface finish	0.014	0.007	0.014	0.007	0.042
	Weight	0.007	0.007	0.014	0.007	0.035
Geometry of the design total		0.063	0.039	0.07	0.043	0.215
Material	Ease of maintenance	0.035	0.071	0.071	0.071	0.248
Material total		0.035	0.071	0.071	0.071	0.248
Production characteristic	Processing time	0.024	0.024	0.013	0.007	0.068
	Production quantity	0.012	0.012	0.024	0.024	0.072
	Rate of production	0.024	0.024	0.013	0.007	0.068
Production characteristic total		0.06	0.06	0.05	0.038	0.208
Grand total		0.3	0.255	0.259	0.188	1.002

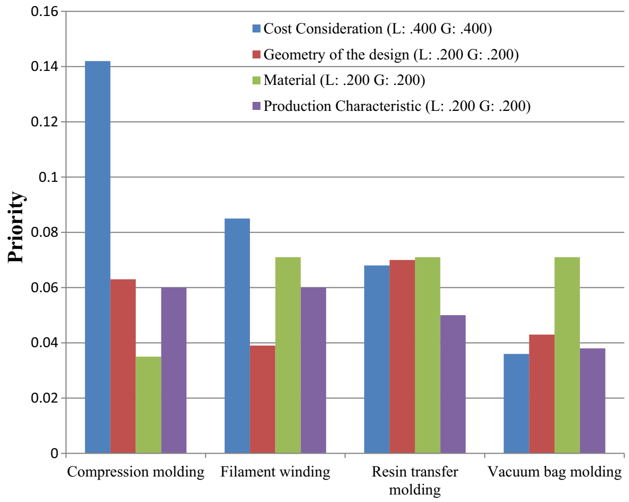


Fig. 7 The overall priority of the manufacturing processes related to the criteria

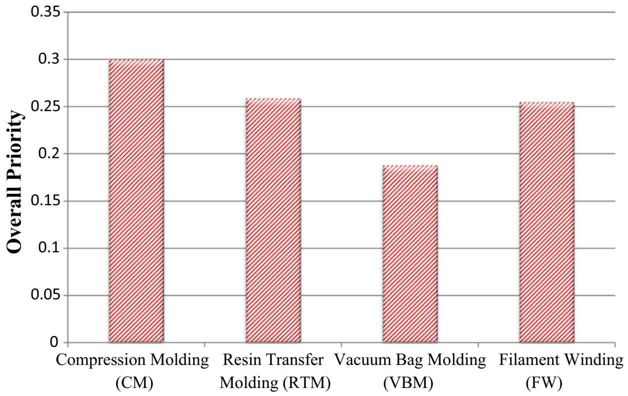


Fig. 8 The overall priority of the manufacturing processes

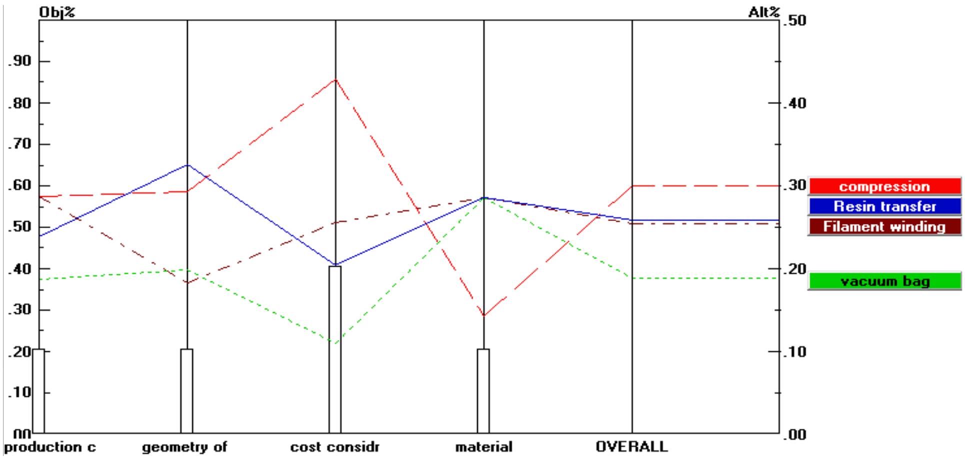
they were highly preferred for most of the influential criteria in the model as illustrated using the AHP methodology.

The relative weights of the alternatives are pretty noticeable, it shows that there are no significant alternatives in the current model. It reflects the great difficulties for the decision-makers when selecting the best alternative process for optimal green composite manufacturing. Thus, such model and methodology can help designers and decision-makers in determining the proper manufacturing processes for green composites consistently, and reducing the bias during decisions.

3.3 Sensitivity analysis of the model

The sensitivity analysis was carried to measure the significance of changing any parameter in the model. As the pair-wise comparisons between the alternatives have already been established, it was shown that the highest priority was in favor of compression molding. The question that arises is,

Fig. 9 Performance pattern sensitivity with respect to the goal



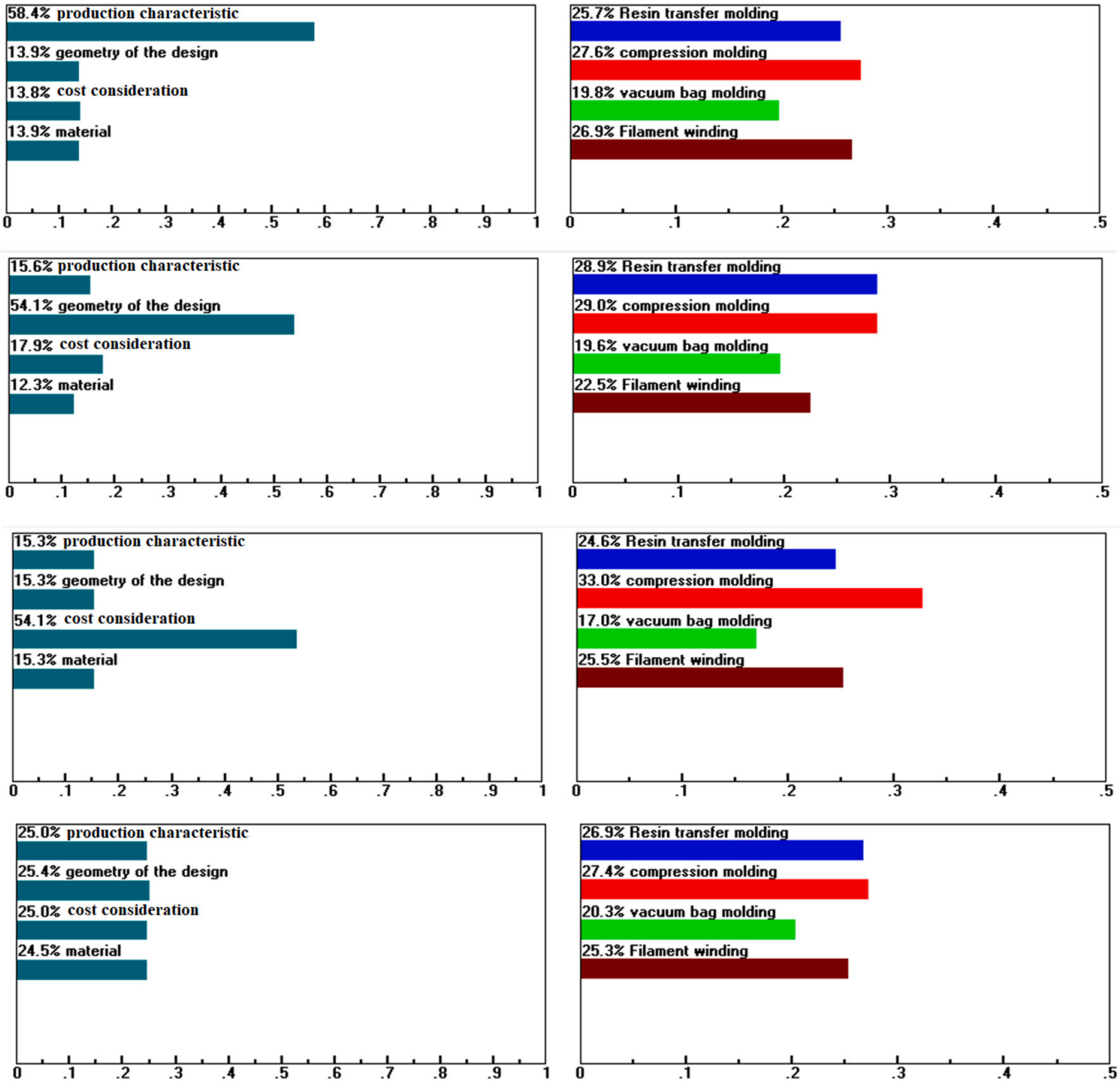


Fig. 10 Dynamic sensitivity with respect to the goal

what will be the impact of the weight variations of these alternatives on the main goal? The impact of the weight variations of the most involved factors in the current model is shown in Fig. 9 which represents the performance pattern sensitivity with respect to the goal. Figure 10 represents the dynamic sensitivity with respect to the goal. There are no dominant criteria nor dominant manufacturing processes in the model as shown in Fig. 9. Therefore, the sensitivity analysis is required to illustrate the model's reliability and robustness in presenting a dominant alternative manufacturing process if a dominant factor exists. To do so, first, assume the "production characteristics" as the dominant factor in the model with an exaggerated value of more than 50% of the main goal and less than 40% for the remaining factors in the model. The proper alternative is still unchanged (compression molding) with a relative weight of 27.6%. This assumption means that regardless of the exaggerated increase in the "production characteristics" factor, none of the alternatives became dominant in the model. This assumption revealed that the results of the current study are not sensitive to minor variations in the weight of the "production characteristics" factor. Similarly, it is found that "compression molding" is still the best alternative regarding the manufacturing process attribute factor when changing factors to be dominant in the model.

The sensitivity analysis was applied for all the factors in the model. It was observed that, while changing the main factors, none of the manufacturing process alternatives has significant influence on the model. Therefore, the analysis revealed this conclusion even if all of the criteria have the same importance (almost equal weights), see Fig. 10. This analysis provides confidence on the decision made and its consistency. Therefore, the alternatives "compression molding" and "resin transfer" are still considered the best green composite manufacturing processes. This conclusion is now quantitatively measured and justified through the consistent judgments of the pair-wise comparisons and the child factors of the parent goal.

It is evident that none of the alternatives is dominating the model. In other words, none of the alternatives possess weight higher than 50%. However, among all other alternatives proposed in this work, "compression molding" and "risen transfer" obtained the highest scores as the best two processes to be adopted for green composite manufacturing, considering eleven evaluating and conflicting criteria. The study results were very reliable under the variations of the factors and the sub-factors with reasonable amounts.

4 Conclusions

Unlike the conventional polymer composites, processing of green composites is governed by the thermal instability of composites during processing, the water absorption capability, and the wide morphological differences in fibers, and the changes in the rheological behavior. Thus, the direct selection of the best manufacturing process for green composites is not an easy task for the designers without an appropriate decision-making scheme. The compression molding was found to be the best process among the other considered manufacturing processes for green composites, considering the overall conflicting criteria simultaneously. The second preferable alternative was the resin transfer molding followed by the filament winding. These two processes were found to be with almost the same priority considering the overall criteria. However, vacuumed bag molding was the worst from the overall aggregate evaluation criteria. All the considered alternative manufacturing processes were found preferable regarding some criteria but undesired regarding others. Therefore, no dominant process was found in the model. It means that no manufacturing process can be considered directly to be the best for green composites regarding all the evaluation criteria. It reveals the need for such decision-making models in order to consider the most appropriate manufacturing process for green composites when various conflicting criteria are reasonably optimized.

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