Fibers and Polymers 2015, Vol.16, No.1, 153-163
DOI 10.1007/s12221-015-0153-3
ISSN 1229-9197 (print version)
ISSN 1875-0052 (electronic version)

Decision Making Model for Optimal Reinforcement Condition of Natural Fiber Composites

Faris M. AL-Oqla[1]*, S. M. Sapuan[1,2], M. R. Ishak[3], and Nuraini A. A.[1]

[1]*Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor, Malaysia*
[2]*Laboratory of Bio-Composite Technology, Institute of Tropical Forestry and Forest Products, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor, Malaysia*
[3]*Department of Aerospace Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor, Malaysia*

(Received July 2, 2014; Revised August 14, 2014; Accepted August 25, 2014)

Abstract: Natural fiber reinforced polymer composites (NFCs) have recently received much attention as eco-friendly materials due to their desired characteristics such as the high specific properties, low cost, and recyclability features. Achieving an optimal reinforcement condition in NFCs to obtain desired properties is still challenging for both designers and industry. Selecting an appropriate reinforcement condition for natural fiber composites can dramatically enhance achieving better low-cost sustainable design possibilities. Several factors affect acquiring such reinforcement conditions, which make it a matter of multi-criteria decision making (MCDM) problem. This work was able to build and implement DM models in the field of NFCs to optimize the reinforcement conditions for the first time. Here, both Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) methods were utilized to achieve the optimal reinforcement condition of the date palm/epoxy composite to maximize its overall tensile property considering combined evaluation criteria. Eleven potential reinforcement conditions were evaluated regarding Maximum Tensile Strength (MTS), Maximum Shear Stress (MSS) and Elongation to Break (EL) criteria simultaneously. Experts' feedback was surveyed to determine both the appropriateness of the evaluation criteria as well as their corresponding weights. MSS has the most contribution in the evaluation process with a weight of 39.0 %, whereas MTS and EL have weights of 31.0 % and 29.0 % respectively. The harmony between AHP and TOPSIS methods in determining the optimal reinforcement condition considering the whole desired evaluation criteria increased its reliability. This work presents a guide and roadmap for implementing proper decision making models in the field of natural fiber composites to optimize their desired characteristics as it is implemented here for the first time.

Keywords: Polymer-matrix composites, Mechanical properties, Sustainable products, Decision making model, Date palm fibers

Introduction

It is necessary to select the proper material type for engineering applications to contribute achieving successful low cost design to enhance both sustainability and customer satisfaction attributes [1,2]. Decisions related to significant environmental impact like implementing a given green product in a particular market have received much attention in recent economic planning to maximize the benefit as well as attaining the industrial sustainability. Nowadays, the product environmental attribute criterion has become one of the most important factors that dramatically influence customers' purchase decisions in today's consumer market [3,4]. Usually, green products have higher prices than others. Such price increases with higher compatibility between the product's characteristics and its environmental performance [2]. Part of this high cost indeed, is due to marketing arguments whereas other major portions are related to the costly research and development (R&D) investments as well as the high cost of green input items and technologies [3]. Therefore, there is a need to develop and assist producing such green products with lower prices to be able to widen their usage in order to achieve real sustainable societies.

Implementing a specific material type in a particular industry is restricted by several criteria and constrains [2,5,6], where different performance parameters have to be investigated to ensure the suitability of such material for a particular application. Therefore, the selection of the most appropriate material type for a particular application is deemed as a multi criteria decision making (MCDM) problem where accurate and keen decisions have to be taken to ensure the technical suitability of such material utilizing appropriate decision making tools [5,7].

Due to the tremendous need of achieving more sustainable societies in one hand, and in light of the high petroleum prices on the other, NFCs became highly valuable type of materials. Such type of materials utilizes the available natural fibers (like jute, hemp, date palm, kenaf, etc.) as fillers to reinforce polymers to make new eco-friendly alternative materials for different industrial applications. Such applications include construction, furniture, packaging, and automotive industries [1,2,8-10]. There are several available

*Corresponding author: farisv9@yahoo.com

natural fiber types that can be used in NFCs. However, the main extensively used types in industrial applications are cotton, jute, flax, coir, sisal and hemp [2,11,12]. Natural fibers usually classified according to their origin. They are categorized into Seed Fibers like cotton. Leaf Fibers like sisal, banana and date palm. Bast Fibers (stem fibers or skin fibers) like hemp, date palm, flax, jute and kenaf. Fruit Fibers like coconut (coir), and oil palm. Stalk Fibers (grass fibers) like bagasse, rice, bamboo and grass. Root Fibers like broom root [11,12]. Such materials can offer a good economic opportunity for automotive industry to reduce the weight of the produced vehicles, which would reduce both fuel consumptions and CO_2 emissions. Consequently, implementing NFCs in industry can contribute to the productivity, sustainability as well as the environmental performance. Such implementation would also enhance better utilization of the available resources and wastes to solve environmental waste problem issues as well as reducing pollution [2,8]. NFCs have been raised as an alternative to the glass/carbon reinforced polymer composites due to their major desired advantages over the later. Such advantages include good acoustical and thermal insulation properties, energy recovery, low cost, CO_2 sequestration enhanced, reduced dermal and respiratory irritation, and availability [1,9,10].

Technically speaking, NFCs performance and properties strongly depend on the characteristics of their individual constituencies as well as the polymer/filler interfacial adhesion [13-15]. That is; the overall NFCs attributes and capabilities depend on the physical, mechanical and chemical composition of the inherent material where technical aspects such as fiber length, fiber diameter, and fiber treatment are crucial in determining the final composite tensile properties as well as other mechanical ones [13,14,16,17]. AL-Oqla and Sapuan [2] introduced extensive criteria that have to be taken into consideration to select the appropriate NFC materials for a specific application. Authors discussed these criteria and classified them into distinguished levels according to the NFCs constituents (fiber and matrix) as well as the features of the final composite itself, in addition to both general and specific composite performance levels to enhance evaluating the technical aspects of the produced NFCs in a fairly optimized manner. Accordingly, one of the most potential natural fiber types that can be utilized in different industrial applications are the date palm ones [2,10]. It is considered as the best regarding several criteria like cost, availability, specific modulus and strength to cost ratio criteria [2]. On the other hand, one of the most suitable date palm/polymer matrix composites is the date palm/epoxy one, where good tensile and mechanical properties can be achieved [18,19]. Unfortunately, the tensile properties of the date palm/ Epoxy (like any other natural fiber/polymer matrix) are dramatically affected by the reinforcement conditions such as fiber diameter, fiber length, and fiber surface treatment [16,18,19].

Several studies had investigated this type of composites to enhance its mechanical properties to be suitable for wider applications [17-20]. It was demonstrated that there was no particular distinguished reinforcement condition that can maximize the whole individual aspects of tensile properties of this composite. That is; some specific reinforcement conditions may be able to increase the maximum tensile strength in one hand, but lead to a decrease in the shear stress and/or the ductility on the other, and vice versa. Therefore, it seems desirable to optimize the whole reinforcement conditions of the date palm/epoxy composite and to select the most suitable reinforcement conditions to achieve the best overall tensile properties and performance of this composite. Consequently, decision making models have to be utilized and implemented to select the best reinforcement conditions of such composite considering combined evaluation criteria simultaneously which can contribute to its role in different industrial applications to get more economical benefits. Comprehensive analysis of the published results regarding date palm/epoxy composites as well as keen experts' feedback can help capturing the trends and effects of the reinforcement conditions on the composite properties.

Several researches had implemented different MCDM tools regarding to the material selection process itself, but no work utilized such tools or models to optimize the reinforcement conditions of the natural fiber composites. Such utilized tools include technique for order preference by similarity to ideal solution (TOPSIS), the analytic hierarchy process (AHP), Vise Kriterijumska Optimizacija Kompromisno Resenje (VIKOR) method, Fuzzy AHP technique, graph theory, simple additive weighted (SAW) method, weighted product method (WPM) and others [7,21-23]. Dweiri and Al-Oqla [5] utilized the AHP method for material selection and increased the choice confidence by applying the sensitivity analysis. Sapuan *et al.* [21] also enhanced the selection of the natural fiber reinforced polymer composites materials using the AHP method. Moreover, Dağdeviren *et al.* [24] developed an evaluation model to select weapons based on the analytic AHP and TOPSIS methods. In contrast, little studies were found considering decision models for selecting the quality fibers for particular applications [25-27].

Although, there is no absolute distinguished superiority of one MCDM tool over the others, and it is difficult to determine the best decision making method for a given problem [28-30], the analytical hierarchy process has some potential advantages like its popularity, simplicity and the ability to capture both quantitative and qualitative attributes in a simple manner [30,31]. Moreover the capability of AHP was validated in numerous examples where priorities close to the corresponding real life answers were generated [5,32]. In addition, the AHP method is preferable over the fuzzy AHP or any combination of fuzzy-MCDM tool particularly when the data is precisely known (i.e. when no subjectivity involved in the problem). That is; converting the crisp data into fuzzy format will increase both complexity and computational requirements in one hand, and rob the simple original data of their elegance on the other, which often leads to less desirable outcomes [28].

In light of the above, where no previous work had utilized MCDM tools or models to optimize the reinforcement conditions of NFCs, the intention of the present work is to build suitable decision making models for evaluating the reinforcement conditions in such materials. More precisely, to build decision making models utilizing both AHP and TOPSIS methods to assess and achieve the optimal refinement condition of the date palm/epoxy composite considering combined evaluation criteria. The evaluation process will consider the composite tensile properties. That is; to determine the most appropriate reinforcement condition to achieve the maximum tensile properties considering multiple evaluation criteria. This in order can enhance better selection of NFCs, expand the usage of such composites in different industrial applications, and assist implementing such techniques to evaluate different natural fiber composites to maximize their desired characteristics.

Methods

Here, both the AHP and TOPSIS were used in determining the optimal refinement condition of the date palm/epoxy composite to achieve maximum tensile properties. The AHP

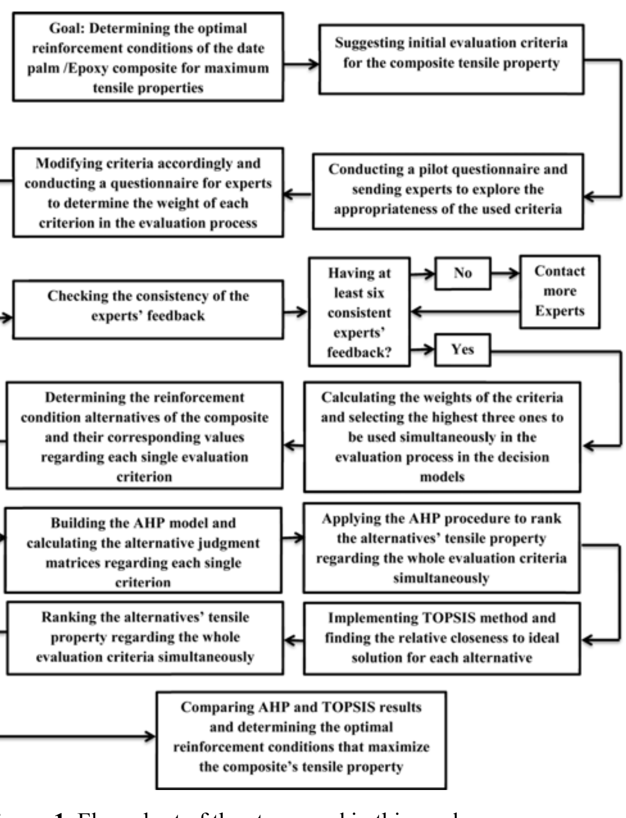


Figure 1. Flow chart of the steps used in this work.

is one of the most powerful, popular and flexible decision making methods that can achieve best decisions considering both tangible and intangible aspects and attributes [5,7,22,33]. As mentioned previously, AHP method is preferable over the fuzzy-AHP or any combination of fuzzy-MCDM tool particularly when the data is precisely known and when no subjectivity involved in the problem [28,31]. Furthermore, the AHP was capable to deal with real life complex and uncertain environment more efficiently than fuzzy judgment [34,35]. That is; the fuzzy AHP has recently a criticism that its arithmetic operation violates the AHP reciprocal and continuity axioms as well as the operational rule of consistency, which make it questionable for decision making problems [35]. TOPSIS is one popular multiple criteria technique that can be used to identify solutions among finite set of alternatives. It has both rational and understandable logic. Moreover, it gains a solution that is closest to the hypothetically best and simultaneously farthest from the hypothetically worst. In the present study, the AHP method was used to assist TOPSIS in evaluating the relative importance of different criteria with respect to the objective. Therefore, both AHP and TOPSIS methods were employed and integrated to achieve the performance ranking of the possible reinforcement condition alternatives. A flow chart of the steps used in this work is demonstrated in Figure 1.

Analytical Hierarchy Process

The AHP, unlike conventional approaches, utilizes both pair-wise comparisons and verbal judgments to promote the precision of findings, and thus enhances better ratio and scale priorities. It also provides the advantage of minimizing the decision making bias by allowing capturing subjective and objective evaluations as well as the possibility of checking the consistency of the evaluations and alternatives. Therefore, it was implemented in numerous domains including material selection [5,7,21], energy planning and corrective actions [36-38], in addition to other industrial and applications [32,33,39-42].

The AHP method was developed by Saaty [43] as a multi-criteria decision making method to solve complex problems by dividing them into sub problems utilizing the tree leaves structure. The AHP method can be mainly differentiated into three steps as follows:

Step 1: Forming the complex decision problem in a hierarchical structure. Here, the complex MCDM problem has to be decomposed into sub-problems with goal, criteria, sub- criteria and decision alternatives. The main goal or objective has to be at the top level, the multiple criteria of the problem at the second level, the sub-criteria at the third level, and the decision alternatives have to be at the final or lower level [5,32].

Step 2: Conducting the pairwise comparisons of both alternatives and the criteria. Once the hierarchy is constructed, the next step starts determining the relative importance of

Table 1. The AHP intensity of importance scale

For any pair of objectives *i*, *j*	
Score	Relative importance
1	Objectives *i* and *j* are of equal importance.
3	Objective *i* is weakly more important than *j*.
5	Objective *i* is strongly more important than *j*.
7	Objective *i* is very strongly more important than *j*.
9	Objective *i* is absolutely more important than *j*.

Note: 2, 4, 6, 8 are intermediate values.

each criterion within each specific level. That is; pairwise comparisons of criteria are conducted to compare them according to their levels of contribution or effects based on the specified main criterion in the higher level.

To find out the importance of each factor or criterion relative to others with respect to the objective (weights) in the AHP method, multiple pair-wise comparisons utilizing Saaty's comparison scale (Table 1) have to be performed, where the value of 1 is always assigned to any criterion compared with itself [5,24,39]. This in order, yields to a square matrix with all elements in its diagonal are equal to 1.

This pair-wise comparison process on n criteria can be summarized in an $(n\times n)$ judgment matrix A with elements of $a(i, j)$. Such matrix can be expressed as in equation (1). After that, computations commence normalizing and finding the relative weights of each individual matrix. The relative normalized weight (Wi) of each criterion can be obtained utilizing finding the geometric mean of the ith row, $i \in [1, \ldots, n]$ as in equation (2) and then normalizing these obtained geometric means of all rows in the judgment matrix. The relative normalized weight as a column vector ($\boldsymbol{W}$) (eigen vector) can be obtained utilizing equation (3).

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

$$GM_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}} \quad (2)$$

$$W = \begin{pmatrix} W_1 = GM_1/\sum_{i=1}^{n} GM_i \\ W_2 = GM_2/\sum_{i=1}^{n} GM_i \\ \cdots \\ W_n = GM_n/\sum_{i=1}^{n} GM_i \end{pmatrix} \quad (3)$$

For a consistent matrix equation (4) can be satisfied:

$$\begin{bmatrix} w_1/w_1 & \cdots & w_1/w_n \\ \vdots & \vdots & \vdots \\ w_n/w_1 & \cdots & w_n/w_n \end{bmatrix} \times \begin{bmatrix} w_1 \\ \vdots \\ w_n \end{bmatrix} = n \begin{bmatrix} w_1 \\ \vdots \\ w_n \end{bmatrix} \quad (4)$$

In a matrix form

$$\mathbf{A} \cdot \mathbf{w} = n\mathbf{w} \quad (5)$$

where **A** is the judgment matrix, **w** is the Eigen vector and n is the matrix dimension. Equation (5) is an eigenvalue problem. For a consistent matrix, the largest eigenvalue equals the number of comparisons i.e.; $\lambda_{max}=n$.

After that, the consistency index (CI) has to be calculated. To do so, the largest eigen value λ_{max} has to be calculated as the average of the consistency values. Then apply equation (6) to find the consistency index.

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (6)$$

It is worthy to note here that the smaller the value of CI the more consistent the judgment is. That is; the judgment should be strictly constant in order to be used in the AHP analysis, otherwise, the judgment is rejected as it is inconsistent and has to be revised until a conditional consistency level is obtained. Thus, a random consistency index was proposed as in Table 2 [32] to compare the achieved judgment consistency with this random one in a consistency ratio (CR) as in equation (7).

$$CR = \frac{CI}{RI} \quad (7)$$

If the value of this CR is smaller or equal to 10 %, the inconsistency is acceptable. Otherwise judgments should be revised.

Step 3: Performing consistency check to ensure that all captured judgments are acceptable and then ranking the alternatives regarding the considered criteria in the model [22,24].

TOPSIS Method

Several authors reported technique for order preference by similarity to ideal solution (TOPSIS) as a multi criteria decision making way to identify solutions from a finite set of alternatives. According to this method, the best alternative would be the closest one to the positive ideal solution and the farthest simultaneously from the negative ideal one [24,27,44,45]. The main principle of this method is to suggest a solution which has the shortest distance from the hypothetical one in the Euclidean space [41,44]. The suggested

Table 2. The modified average random consistency index (RI)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

solution can sometimes have the minimum Euclidean distance from both the ideal and negative ideal (worst) solution comparing to other alternatives. TOPSIS technique in order tries to find solutions that are close to the ideal solution but far from the worst one. If a multi-criteria decision making problem are supposed to have n alternatives (A_1, A_2, A_3, ..., A_n) and m criteria (C_1, C_2, C_3, ..., C_m). The evaluation values of each alternative regarding each criterion can be arranged in a matrix as $A(a_{ij})_{n\times m}$. Let the vector of criteria to be W= (w_1, w_2, w_3, ..., w_m) and satisfies $\sum_{j=1}^{m} w_j = 1$. Thus, the judgment matrix for the ranking can be illustrated as

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix} \quad i = 1, \ldots, m, j = 1, \ldots, n \tag{8}$$

Then the main steps of TOPSIS can be summarized as:

Step 1: Constructing of the normalized judgment matrix. The normalized score r_{ij} is calculated as:

$$r_{ij} = \frac{X_{ij}}{\sum_i (X_{ij}^2)^{1/2}} \quad i = 1, \ldots, m, j = 1, \ldots, n \tag{9}$$

Step 2: Calculating the weighted normalized judgment matrix. This can be obtained utilizing the AHP technique (i.e. AHP can be integrated with TOPSIS in this step). The weighted normalized score V_{ij} is expressed as:

$$V_{ij} = W_j \cdot r_{ij} \tag{10}$$

Step 3: Determining both positive ideal (V^+) and negative ideal (V^-) solutions. The ideal and negative ideal solutions can be calculated as:

$$V^+ = \{V_1^+, \ldots, V_n^+\} \text{ Where } V_j^+ = \{\max_i(v_{ij}) \text{ if } j \in J; \min_i(v_{ij}) \text{ if } j \in J'\} \tag{11}$$

$$V^- = \{V_1^-, \ldots, V_n^-\} \text{ Where } V_j^- = \{\min_i(v_{ij}) \text{ if } j \in J; \max_i(v_{ij}) \text{ if } j \in J'\} \tag{12}$$

where J=(j=1, 2, ..., n)/j is set of beneficial factors and J'=(j=1, 2, ..., n)/j is set of non-beneficial factors.

Step 4: Finding the separation measures for each alternative utilizing the n-dimensional Euclidean distance. The separation from the ideal alternative is:

$$S_i^+ = [\sum_j (V_j^+ - V_{ij})^2]^{1/2}; \quad i = 1, \ldots, m \tag{13}$$

$$S_i^- = [\sum_j (V_j^- - V_{ij})^2]^{1/2}; \quad i = 1, \ldots, m \tag{14}$$

Step 5: Finding the relative closeness to ideal solution (C_i^*) and the corresponding rank of the candidate. That is; selecting the alternative with maximum C_i^*. Such relative closeness of the alternative Aij can be defined as:

$$C_i^* = \frac{S_i^-}{S_i^+ + S_i^-}, \quad 0 < C_i^* < 1, \; S_i^- \geq 0, \; S_i^+ \geq 0 \tag{15}$$

Results and Discussion

The Determination of the Alternatives and Criteria

In order to reach the reasonable optimal reinforcement condition of the date palm/epoxy that give reasonable high tensile properties, eleven potential reinforcement conditions

Table 3. Decision matrix for candidate date palm fiber/epoxy composite materials

Candidate composite specification	Composite name	Material selection criteria		
		MTS[a] (MPa)	MSS[b] (MPa)	EL[c] (%)
DPF/epoxy with 5 (mm) FL[d], 0.2 (mm) FD[e] via 9 % NaOH[f]	C1	115	3.1	5
DPF/epoxy with 15 (mm) FL, 0.2 (mm) FD via 6 % NaOH	C2	320	4.2	16
DPF/epoxy with 20 (mm) FL, 0.2 (mm) FD via 6 % NaOH	C3	270	3.8	18
DPF/epoxy with 40 (mm) FL, 0.3 (mm) FD, via 0 % NaOH (Untreated Fiber)	C4	115	10	8
DPF/epoxy with 40 (mm) FL, 0.3 (mm) FD via 3 % NaOH	C5	150	10	16
DPF/epoxy with 40 (mm) FL, 0.3 (mm) FD via 6 % NaOH	C6	145	10	15
DPF/epoxy with 40 (mm) FL, 0.3 (mm) FD via 9 % NaOH	C7	135	10	10
DPF/epoxy with 40 (mm) FL, 0.5 (mm) FD via 3 % NaOH	C8	130	6	12
DPF/epoxy with 40 (mm) FL, 0.5 (mm) FD via 6 % NaOH	C9	120	6	10
DPF/epoxy with 40 (mm) FL, 0.7 (mm) FD via 3 % NaOH	C10	120	5	9
DPF/epoxy with 40 (mm) FL, 0.7 (mm) FD via 6 % NaOH	C11	85	4	14

[a]MTS: maximum tensile strength, [b]MSS: maximum shear stress, [c]EL: elongation to break, [d]FL: fiber length, [e]FD: fiber diameter, [f]date palm fiber/epoxy composite with 5 mm fiber length, 0.2 mm fiber diameter, treated with 9 % NaOH solution.

that have potential tensile properties were considered. These alternatives are combinations of different levels of fiber diameters, fiber lengths, and different NaOH concentration treatments. The NaOH treatments solution was selected because it was reported as one of the most suitable solution types for date palm fiber to enhance its mechanical properties [18,20]. The eleven candidate alternatives with respect to the whole evaluation criteria are tabulated in Table 3.

The appropriateness of the evaluation criteria used in the present study were surveyed by a type of pilot questionnaire sent to twelve worldwide experts in the field of natural fiber composites. Responses of eight experts' feedback were analyzed to determine the evaluation criteria for the date palm/epoxy composites. Initially, the number of suggested evaluation criteria was five. After experts' feedback they were reduced into four. After determining the weights of these evaluation criteria (Details are illustrated in section Estimating The Criteria's Weights Utilizing AHP) another reduction was performed to end up with reasonable three criteria based upon the experts' point of view. Consequently, the main combined evaluation criteria were the maximum tensile strength, maximum shear stress and the elongation to break. These criteria can dramatically affect the selection of maximum tensile properties of the date palm/epoxy composite. That is; the tensile strength can determine the appropriateness and capability of the matrix to withstand loads while being stretched before breaking. The shear stress criterion on the other hand, can represent the interfacial bonding between the fiber and the matrix, and higher shear stress lead to higher mechanical performance of the composite. Moreover, elongation to break can demonstrate the capability of the natural fiber composite to resist changes in its shape while loading without being cracked, which can enhance the composite tensile properties particularly in withstanding the impact load behavior. The values of the considered criteria used in evaluation were deduced from extensive literature considering single fiber pull out technique with similar experimental conditions. There were obvious variations of the measured values in all criteria used in evaluation due to the non-uniform specimen states. One example of such variations is shown in Figure 2, where three different stress-strain curves of a single date palm/epoxy fiber pull out were achieved for three different trials. Because only one value has to be reported for each alternative, an average value for each tested criteria was taken. It is worthy note that the considered evaluation criteria (maximum tensile strength, maximum shear stress and the elongation to break) are beneficial ones, where higher values are desired. The raw data of the alternatives behavior were adopted from [18,19], and the considered average values were produced and tabulated in Table 3.

Every single considered candidate alternative demonstrates different behavior regarding each of the considered evaluation criteria. This increases the complexity of determining the best overall tensile property of the date palm/epoxy composites without using a proper decision making model. Such variations are clearly illustrated in Table 3. For instance, candidate number 4 (C4) has relatively small values in both maximum tensile strength (MTS) and elongation to break (EL %), but at the same time has a relative high value of the maximum shear stress (MSS). This obviously demonstrates that there is no specific reinforcement condition that can maximize the whole evaluation criteria of the tensile properties simultaneously. Therefore, there is a necessary need for a decision making technique to determine the optimal reinforcement conditions to increase the desired overall tensile property which can enhance the economic benefit of such composites as well as contribute to the industrial sustainability by facilitating the production and implementing such low-cost ecofriendly type of materials.

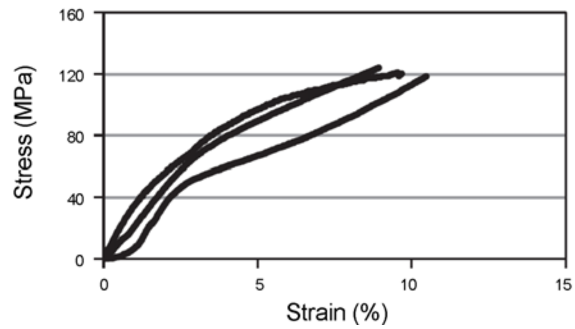


Figure 2. Variations in the tensile testing stress-strain curves of (40 mm L, 0.5 mm D) single date palm/epoxy fiber pull out treated with 6 % NaOH concentration. Adopted from [18].

Estimating The Criteria's Weights Utilizing AHP

After forming the considered problem in a hierarchy structure, the AHP method was used to determine the weights of the criteria. In this particular stage, another type of questionnaire was constructed and sent to another group of twelve experts worldwide. Such typical questionnaire for seeking expert's feedback in determining the relative weights of the main evaluation criteria is shown in Figure 3.

Feedbacks of ten filled responses were received. After performing the consistency check, only nine responses were consistent and thus considered for determining the weights of the evaluation criteria by achieving the pair wise comparison matrix utilizing the scale shown in Table 1. The final aggregated assignments were finally gained. Based on AHP method, the weights captured from experts were analyzed utilizing equations (1) through (5) to get the contribution (normalized weights) of each criterion in evaluating the composite tensile properties. These contributions are presented in Figure 4. It can be seen that the maximum shear stress has the most contribution in determining the maximum tensile properties of the composite with a weight of 39 %. Elongation to break criterion has the least contribution of 29 % whereas

Compare the relative importance with respect to: Goal: Selection of an optimal reinforcement condition to achieve maximum tensile properties of Date Palm Fiber /Epoxy composite
Circle one number per row below using the scale:
1 = Equal 3 = Moderate 5 = Strong 7 = Very strong 9 = Extreme

1	Maximum Tensile Strength	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Maximum Shear Stress
2	Maximum Tensile Strength	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Elongation to Break
3	Maximum Shear Stress	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Elongation to Break

Figure 3. Typical questionnaire for determining the relative weights of the main evaluation criteria.

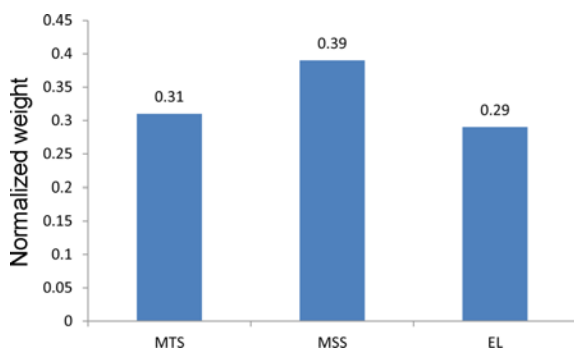


Figure 4. Results of contributions of each criterion to the main goal.

the maximum tensile stress has relatively moderate contribution among the previous two with a value of 31.0 %. Such determination of the weights and importance of the used evaluation criteria was an added value step of this work by surveying experts' feedback to distinguish such importance of each single criterion. That is; there is usually an inherent integrated behavior between these criteria for the natural fiber composites which make it not easy to determine the appropriate weight for each of them to evaluate a natural fiber reinforced polymer composite. Experts' feedback considered that the maximum shear stress criterion should be taken into consideration with a slightly higher weight than others because it can represent the interfacial bonding between the fiber and the matrix, which is crustal in evaluating the composite for general loading application.

Assessment of Alternatives

Assessment of Alternatives Using AHP

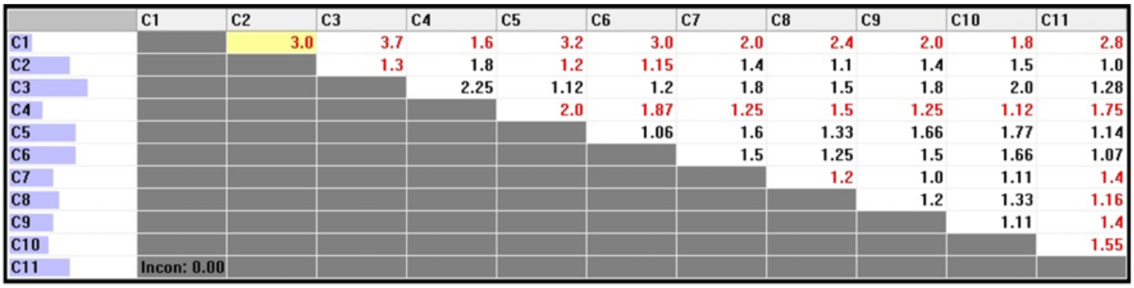
According to AHP, the relative priorities of the whole candidate alternatives with respect to each criterion were calculated utilizing the weights tabulated in Table 3 to build up the judgment matrices for all evaluation criteria as in equation (1). The detailed calculations of these matrices are shown in Figure 5, 6 and 7 where only the upper part of each judgment matrix is shown and the lower part is the

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
C1		2.78	2.34	1.0	1.3	1.26	1.17	1.13	1.04	1.04	1.35
C2			1.18	2.78	2.13	2.2	2.37	2.46	2.66	2.66	3.76
C3				2.34	1.8	1.86	2.0	2.07	2.25	2.25	3.17
C4					1.3	1.26	1.17	1.13	1.04	1.04	1.35
C5						1.03	1.11	1.15	1.25	1.25	1.76
C6							1.07	1.11	1.2	1.2	1.7
C7								1.03	1.12	1.12	1.58
C8									1.08	1.08	1.52
C9										1.0	1.41
C10											1.41
C11	Incon: 0.00										

Figure 5. The detailed judgment matrix of the alternatives regarding maximum tensile strength.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
C1		1.35	1.22	3.22	3.22	3.22	3.22	1.93	1.93	1.61	1.29
C2			1.1	2.38	2.38	2.38	2.38	1.42	1.42	1.19	1.05
C3				2.85	2.85	2.85	2.85	1.57	1.57	1.31	1.05
C4					1.0	1.1	1.0	1.66	1.66	2.0	2.5
C5						1.1	1.0	1.66	1.66	2.0	2.5
C6							1.1	1.66	1.66	2.0	2.5
C7								1.66	1.66	2.0	2.5
C8									1.0	1.2	1.5
C9										1.2	1.5
C10											1.25
C11	Incon: 0.00										

Figure 6. The detailed judgment matrix of the alternatives regarding maximum shear strength.



	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
C1		3.0	3.7	1.6	3.2	3.0	2.0	2.4	2.0	1.8	2.8
C2			1.3	1.8	1.2	1.15	1.4	1.1	1.4	1.5	1.0
C3				2.25	1.12	1.2	1.8	1.5	1.8	2.0	1.28
C4					2.0	1.87	1.25	1.5	1.25	1.12	1.75
C5						1.06	1.6	1.33	1.66	1.77	1.14
C6							1.5	1.25	1.5	1.66	1.07
C7								1.2	1.0	1.11	1.4
C8									1.2	1.33	1.16
C9										1.11	1.4
C10											1.55
C11	Incon: 0.00										

Figure 7. The detailed judgment matrix of the alternatives regarding elongation to break.

Table 4. The relative priorities of the alternatives with respect to the desired evaluation criteria

Criteria / Alternative	MTS	MSS	EL
C1	0.068	0.043	0.038
C2	0.187	0.058	0.106
C3	0.158	0.052	0.138
C4	0.068	0.138	0.061
C5	0.088	0.138	0.123
C6	0.085	0.143	0.115
C7	0.079	0.138	0.076
C8	0.076	0.083	0.092
C9	0.07	0.083	0.076
C10	0.07	0.069	0.069
C11	0.05	0.055	0.107

reciprocal of that upper one (red values in figures are reciprocals of the values, i.e. the value of 1.3 in red color means 0.7692). Applying equations (2) through equation (5) to each judgment matrix leaded to results illustrated in Table 4. It is a worthy note here that the consistency ratios of the whole judgment matrices were below 0.1 which are acceptable values according to AHP method. That is; the judgment matrices were consistent.

Similarly, the final priorities of all candidate alternatives to the main goal (with respect to the whole criteria that maximize the tensile properties of the desired composite simultaneously) are illustrated in Figure 8. The closeness of some alternatives in the final priorities demonstrates that determining the optimal alternative without using a decision making tool is very difficult task. Consequently the final ranking of the candidate alternatives that maximize the tensile properties is shown in Table 5. It can be seen here, that despite of having high values of maximum tensile stress for C2 and C3, the best alternative was C5 which has much lower tensile stress value. This clearly demonstrate the benefit of using both combined evaluation criteria and decision making tools in determining the best reinforcement conditions in natural fiber composite field where human errors and bias

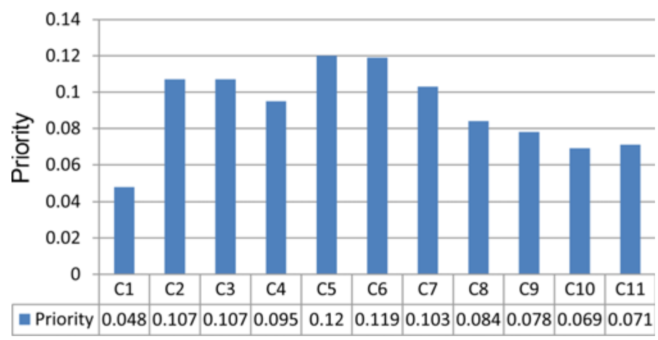


Figure 8. Priorities of all candidate reinforcement conditions with respect to the whole evaluation criteria simultaneously.

Table 5. Final desired ranking of the alternatives that maximize the composite tensile properties using AHP method

Rank	Alternative	
1	DPF/epoxy with 40 (mm) FL, 0.3 (mm) FD via 3 % NaOH	C5
2	DPF/epoxy with 40 (mm) FL, 0.3 (mm) FD via 6 % NaOH	C6
3	DPF/epoxy with 15 (mm) FL, 0.2 (mm) FD via 6 % NaOH	C2
4	DPF/epoxy with 20 (mm) FL, 0.2 (mm) FD via 6 % NaOH	C3
5	DPF/epoxy with 40 (mm) FL, 0.3 (mm) FD via 9 % NaOH	C7
6	DPF/epoxy with 40 (mm) FL, 0.3 (mm) FD, via 0 % NaOH (Untreated Fiber)	C4
7	DPF/epoxy with 40 (mm) FL, 0.5 (mm) FD via 3 % NaOH	C8
8	DPF/epoxy with 40 (mm) FL, 0.5 (mm) FD via 6 % NaOH	C9
9	DPF/epoxy with 40 (mm) FL, 0.7 (mm) FD via 6% NaOH	C11
10	DPF/epoxy with 40 (mm) FL, 0.7 (mm) FD via 3% NaOH	C10
11	DPF/epoxy with 5 (mm) FL, 0.2 (mm) FD via 9% NaOH	C1

in decisions can be reduced.

Moreover, the untreated date palm fiber with suitable diameter and length can be utilized to achieve better overall tensile strength than other treated reinforcement conditions. That is; most of the fiber NaOH treatment processes with unsuitable reinforcement conditions are not beneficial for the overall tensile properties of the natural fiber composite (even if the treatments are properly used within the recommended concentrations). Therefore, fiber treatment with unsuitable reinforcement conditions has to be avoided where time, cost and effort may be saved. On the other hand, although some tensile properties may be enhanced by fiber chemical treatment, the overall tensile properties of the composite may not dramatically promoted if not suitable reinforcement conditions and evaluation criteria were carefully selected.

Assessment of Alternatives Using TOPSIS Method

TOPSIS analysis was performed using a decision matrix from data tabulated in Table 3. According to the TOPSIS procedure, all judgment matrix constituent elements must be normalized using equation (9). The normalized weights of the decision matrix in TOPSIS analysis is shown in Table 6. After that, the weights of the criteria estimated by the AHP technique were utilized to form the TOPSIS weighted decision matrix. This was performed based on TOPSIS method and utilizing steps 2-4. As a result, the rank of the alternatives was obtained. The analysis results are summarized in Table 7. Consequently, a rank to each alternative was given according to its relative closeness to the ideal solution (C_i^*). Finally, the candidate alternative reinforcement conditions were arranged in descending order as in Table 8.

It can be clearly shown that the final ranking of the whole alternatives are not the same using AHP and TOPSIS methods. This is can be frequently found in works that used more than one decision making tools. That is; different decision making tools usually ends up with different alternatives' ranking [23,24]. The main point here, is that the best alternative (C5) was achieved by both techniques which can be confidently concluded that the reinforcement condition designated as (DPF/epoxy with 40 (mm) FL, 0.3 (mm) FD via 3 % NaOH) has the highest overall tensile property considering the whole desired combined evaluation criteria simultaneously. Moreover, both AHP and TOPSIS methods evaluate the alternative C5, C6, C2 and C3 as the first four

Table 6. The weighted normalized judgment matrix for TOPSIS analysis

Alternative	MTS	MSS	EL
C1	0.20	0.13	0.12
C2	0.57	0.18	0.38
C3	0.48	0.16	0.43
C4	0.20	0.42	0.19
C5	0.27	0.42	0.38
C6	0.26	0.44	0.36
C7	0.24	0.42	0.24
C8	0.23	0.25	0.29
C9	0.21	0.25	0.24
C10	0.21	0.21	0.21
C11	0.15	0.17	0.33
Weight	0.31	0.39	0.29

Table 7. Results of TOPSIS analysis method

Alternative	MTS	MSS	EL	S_i^+	S_i^-	C_i^*
C1	0.063	0.051	0.035	0.181	0.016	0.084
C2	0.176	0.070	0.110	0.096	0.151	0.610
C3	0.148	0.061	0.117	0.108	0.131	0.549
C4	0.063	0.166	0.055	0.129	0.117	0.477
C5	0.085	0.166	0.117	0.091	0.146	0.617
C6	0.080	0.166	0.103	0.097	0.138	0.586
C7	0.074	0.166	0.069	0.113	0.123	0.521
C8	0.072	0.099	0.083	0.128	0.072	0.361
C9	0.066	0.099	0.069	0.137	0.062	0.312
C10	0.066	0.083	0.062	0.148	0.046	0.237
C11	0.047	0.066	0.097	0.164	0.064	0.280
V_j^+	0.176	0.166	0.117			
V_j^-	0.047	0.051	0.035			

Table 8. The final desired ranking of the alternatives that maximize the composite tensile properties using TOPSIS method

Rank	Alternative
1	C5
2	C2
3	C6
4	C3
5	C7
6	C4
7	C8
8	C9
9	C11
10	C10
11	C1

Figure 9. The trend in alternative ranking in both AHP and TOPSIS methods.

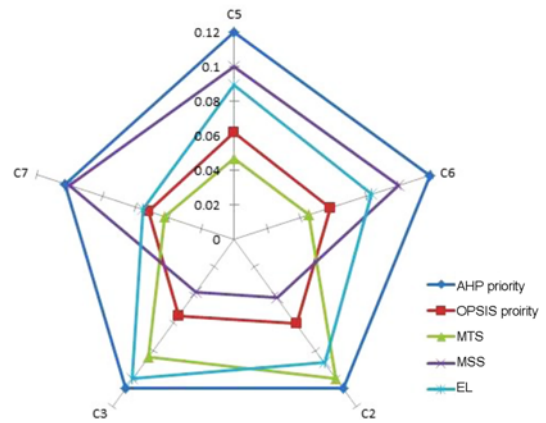


Figure 10. The relative performance and priorities of first five potential alternatives.

potential reinforcement conditions which can obviously increase the reliability of the decision making regarding determining the optimal reinforcement condition of the date palm/epoxy composite. A comparison of the alternatives' ranking trend in both AHP and TOPSIS methods is demonstrated in Figure 9 where an obvious similarity of ranking the considered alternatives in both techniques is demonstrated. This can demonstrate that the drawn results are unbiased and reliable ones. The relative performance and priorities of the first five potential alternatives (C5, C6, C2, C3 and C7) are demonstrated with appropriate scales in Figure 10. It can be shown that the first potential alternative in both AHP and TOPSIS methods (C5) doesn't have the largest value neither in MTS nor EL. On the other hand, the alternative C7 comes in the fifth position although it has a large value of MSS (like that of C5). This can obviously demonstrate that the combined evaluation criteria leads to better evaluation of the natural fiber composites and can enhance determining the optimal reinforcement condition rather than single evaluation criterion. Moreover, it is a worthy note here that the alternatives' performance variation regarding the combined evaluation criteria (as in Figure 10) can increase the complexity in determining the most appropriate reinforcing condition of the natural fiber composite without using a proper decision making tool. In addition, the reliability of the using TOPSIS method is demonstrated in Figure 11 where the normalized values of the alternatives regarding all the evaluation criteria are distributed within the limits of the positive ideal solution and the negative ideal one.

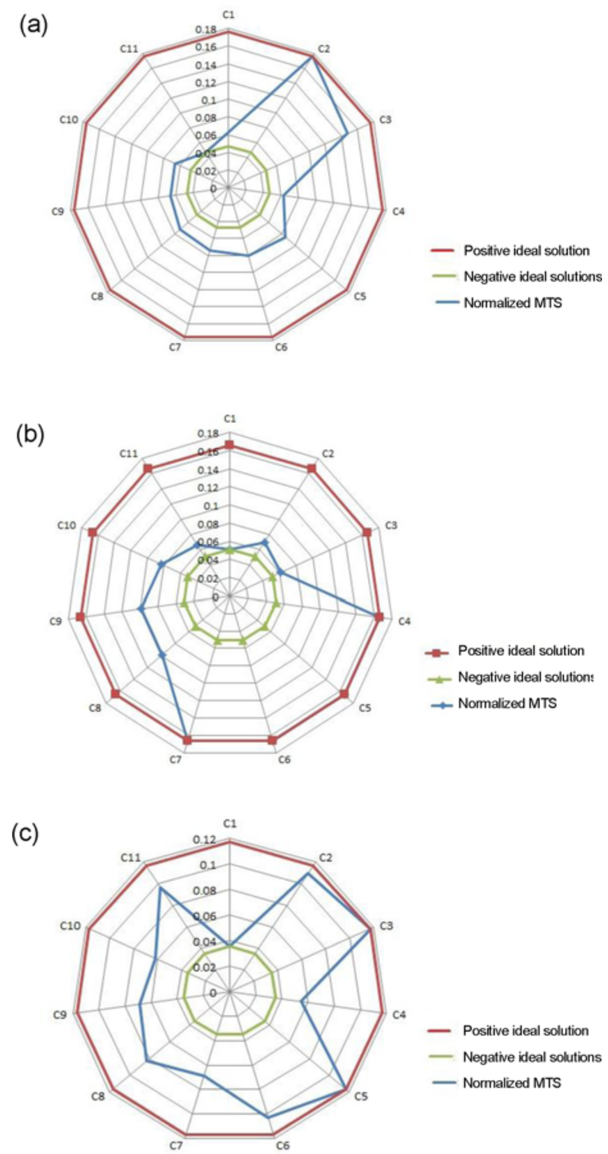


Figure 11. The distribution of the evaluation criteria within the ideal positive and ideal negative solutions in TOPSIS method; (a) MTS, (b) MSS, and (c) EL.

Conclusion

This study was able to build MCDM models to determine the most appropriate reinforcement conditions of the date palm/epoxy composite to achieve the best recommended tensile properties. Utilizing DM techniques to select the optimal reinforcement conditions of natural fiber composites was successfully presented here for the first time. This work can assist implementing such techniques for different natural fiber composites to maximize their desired characteristics and hence promote achieving better low-cost sustainable design possibilities. The potential alternatives of the reinforcement conditions were ranked and evaluated regarding different simultaneous evaluation criteria to enhance better evaluation and selection of the NFCs. Expert's feedback was an added value step to consider the combined evaluation criteria and their weights. The closeness in the alternatives final priorities demonstrates that determining the optimal alternative without using such decision making tools is a very difficult task where human errors and bias in decisions may appear.

Acknowledgments

The authors would like to acknowledge the Universiti Putra Malaysia for supporting this work through an international graduate research fellowship (IGRF).

References

1. M. P. Dicker, P. F. Duckworth, A. B. Baker, G. Francois, M. K. Hazzard, and P. M. Weaver, *Compos. Pt. A-Appl. Sci. Manuf.*, **56**, 280 (2014).
2. F. M. AL-Oqla and S. M. Sapuan, *J. Clean Prod.*, **66**, 347 (2014).
3. I. A. Ahmed, A. W. K. Ahmed, and R. K. Robinson, *Food Chem.*, **54**, 305 (1995).
4. K. Mathiyazhagan, K. Govindan, and A. Noorul Haq, *Int. J. Prod. Res.*, **52**, 188 (2014).
5. F. Dweiri and F. M. Al-Oqla, *Int. J. Comput. Appl. Technol.*, **26**, 182 (2006).
6. J. L. Toupe, A. Trokourey, and D. Rodrigue, *Polym. Compos.*, **35**, 730 (2014).
7. R. Rao and B. Patel, *Mater. Des.*, **31**, 4738 (2010).
8. C. J. C. Jabbour, A. B. L. D. S. Jabbour, K. Govindan, A. A. Teixeira, and W. R. D. S. Freitas, *J. Clean Prod.*, **47**, 129 (2013).
9. M. C. Symington, W. M. Banks, O. D. West, and R. Pethrick, *J. Compos. Mater.*, **43**, 1083 (2009).
10. F. M. AL-Oqla, S. M. Sapuan, M. R. Ishak, and N. A. Aziz, *BioResources*, **9**, 4608 (2014).
11. M. Jawaid and H. Abdul Khalil, *Carbohydr. Polym.*, **86**, 1 (2011).
12. O. Faruk, A. K. Bledzki, H.-P. Fink, and M. Sain, *Prog. Polym. Sci.*, **37**, 1552 (2012).
13. S. Ojha, G. Raghavendra, and S. Acharya, *Polym. Compos.*, **35**, 180 (2014).
14. S. M. Sapuan, F.-L. Pua, Y. El-Shekeil, and F. M. AL-Oqla, *Mater. Des.*, **50**, 467 (2013).
15. D. Nurwaha, W. Han, and X. Wang, *J. Text. Inst.*, **104**, 419 (2013).
16. A. Alawar, A. M. Hamed, and K. Al-Kaabi, *Compos. Pt. B-Eng.*, **40**, 601 (2009).
17. H. Kaddami, A. Dufresne, B. Khelifi, A. Bendahou, M. Taourirte, M. Raihane, N. Issartel, H. Sautereau, J.-F. Gerard, and N. Sami, *Compos. Pt. A-Appl. Sci. Manuf.*, **37**, 1413 (2006).
18. A. Shalwan and B. Yousif, *Mater. Des.*, **53**, 928 (2014).
19. T. Alsaeed, B. Yousif, and H. Ku, *Mater. Des.*, **43**, 177 (2012).
20. A. Abdal-hay, N. P. G. Suardana, D. Y. Jung, K.-S. Choi, and J. K. Lim, *Int. J. Precis. Eng. Manuf.*, **13**, 1199 (2012).
21. S. M. Sapuan, J. Kho, E. Zainudin, Z. Leman, B. Ali, and A. Hambali, *Indian J. Eng. Mat. Sci.*, **18**, 255 (2011).
22. M. K. Rathod and H. V. Kanzaria, *Mater. Des.*, **32**, 3578 (2011).
23. S. Opricovic and G.-H. Tzeng, *Eur. J. Oper. Res.*, **156**, 445 (2004).
24. M. Dağdeviren, S. Yavuz, and N. Kılınç, *Expert Syst. Appl.*, **36**, 8143 (2009).
25. A. Majumdar, *Fiber. Polym.*, **11**, 121 (2010).
26. A. Majumdar, B. Sarkar, and P. K. Majumdar, *Fiber. Polym.*, **5**, 297 (2004).
27. A. Majumdar, B. Sarkar, and P. Majumdar, *J. Text. Inst.*, **96**, 303 (2005).
28. R. V. Rao, "Decision Making in the Manufacturing Environment: Using Graph Theory and Fuzzy Multiple Attribute Decision Making Methods", Springer, 2013.
29. K. Mela, T. Tiainen, and M. Heinisuo, *Adv. Eng. Inform.*, **26**, 716 (2012).
30. W. Ho, X. Xu, and P. K. Dey, *Eur. J. Oper. Res.*, **202**, 16 (2010).
31. T. L. Saaty and J. S. Shang, *Eur. J. Oper. Res.*, **214**, 703 (2011).
32. T. L. Saaty and L. G. Vargas, "Models, Methods, Concepts & Applications of the Analytic Hierarchy Process", Springer, US, 2012.
33. M. A. Almomani, A. Abdelhadi, A. Mumani, A. Momani, and M. Aladeemy, *Int. J. Adv. Manuf. Technol.*, **72**, 161 (2014).
34. T. L. Saaty and L. T. Tran, *Math. Comput. Model.*, **46**, 962 (2007).
35. K. Zhü, *Eur. J. Oper. Res.*, **236**, 209 (2014).
36. M. I. Al-Widyan and F. M. Al-Oqla, *Build. Simul.*, **7**, 537 (2014).
37. A. Mattiussi, M. Rosano, and P. Simeoni, *Decis. Support Syst.*, **57**, 150 (2014).
38. M. I. Al-Widyan and F. M. Al-Oqla, *IJERA*, **1**, 1610 (2011).
39. F. M. Al-Oqla and A. A. Omar, *Prog. Electromagn. Res. Pier C*, **25**, 249 (2012).
40. Z. Ayağ, *J. Intell. Manuf.* In press, DOI: 10.1007/s10845-014-0930-7.
41. M. Tavana and A. Hatami-Marbini, *Expert Syst. Appl.*, **38**, 13588 (2011).
42. F. M. AL-Oqla and M. T. Hayajneh, "A Design Decision-making Support Model for Selecting Suitable Product Color to Increase Probability", Amman, Jordan, 2007.
43. T. Saaty, "The Analytic Hierarchy Process", McGrawHill, New York, 1980.
44. T.-C. Wang and T.-H. Chang, *Expert Syst. Appl.*, **33**, 870 (2007).
45. A. Moghassem, *Fiber. Polym.*, **11**, 669 (2010).