Experimental Polymeric Nanocomposite Material Selection for Automotive Bumper Beam Using Multi-Criteria Decision Making Methods

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Abstract: *Material selection is a main purpose in design process and plays an important role in desired performance of the products for diverse engineering applications. In order to solve material selection problem, multi criteria decision making (MCDM) methods can be used as an applicable tool. Bumper beam is one of the most important components of bumper system in absorbing energy. Therefore, selecting the best material that has the highest degree of satisfaction is necessary. In the present study, six polymeric nanocomposite materials were injection molded and considered as material alternatives. Criteria weighting was carried out through analytical hierarchy process (AHP) and Entropy methods. Selecting the most appropriate material was applied using technique for order preference by similarity to ideal solution (TOPSIS) and the multi-objective optimization on the basis of ratio analysis (MOORA) methods respect to the considered criteria. Criteria weighting results illustrated that impact and tensile strengths are the most important criteria using AHP and Entropy methods, respectively. Results of ranking alternatives indicated that polycarbonate containing 0.5 wt% nano Al_2O_3 is the most appropriate material for automotive bumper beam due to its high impact and tensile strengths in addition to its low cost of raw material. Also, the sensitivity analysis was performed to verify the selection criteria and the results as well.*

Keywords: *Thermoplastic, Nanocomposite, Bumper beam, Nanoparticle, Mechanical properties*

1. INTRODUCTION

Selecting the best material among different material alternatives is called a typical multi-criteria decision making (MCDM) problem [1]. Decision making is the study of identifying and selecting alternatives according to the values and preferences of the decision maker [2]. Making a decision implies that there are alternative choices to be considered and in such a case, not only as many of these alternatives as possible are identified but also the best one is selected to meet the decision maker's goals, objectives, desires, and values [1, 2].

Polymeric nanocomposites containing functional organic and inorganic nanoparticles, have attracted extensive interest of academic and industrial perspectives due to the unique characteristics of nanoparticles, including their large surface area, high surface reactivity, and relatively low cost [3, 4].

Analytical hierarchy process (AHP) is a technique under MCDM that introduced by Saaty (1980) to rank alternatives or criteria based on inputs from expert's judgments [5]. Mansor et al. [6, 7] applied AHP method for material selection. One of the objective weighting measures which has been proposed by researchers is the Shannon entropy concept. Entropy concept was used in various scientific fields [8].

Shanian [9], Caliskan [10] and Taherian [11] used technique for order preference by similarity to ideal solution (TOPSIS) method for solving material selection problems. The TOPSIS method is based on the concept that the best decision should be the closest to the ideal solution and farthest from the non-ideal solution [1].

Hafezalkotob et al. [12] and Karande [1] applied the multi-objective optimization on the basis of ratio analysis (MOORA) for material selection. The MOORA method is a multi-objective optimization technique that can be successfully applied to solve various types of

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complex decision making problems in the manufacturing environment.

Jahan et al. [13] proposed a new version of VIKOR method for material selection which covers all types of criteria with emphasize on compromise solution that also overcomes the main error of traditional VIKOR by a simpler approach. Rashedi et al. [14] studied multi-objective material selection for wind turbine blade and tower using Ashby's approach. Karande and Chakraborty [1] applied MOORA method to solve some of the common material selection problem. They observed that three methods implemented in their study (MOORA, reference point approach and full multiplicative MOORA) are very simple to understand, easy to implement and provide almost exact ranking to material alternative.

There are very limited reports on materials selection for the polymeric nanocomposite automotive parts. However, several studies investigated the selection of a composite material for automotive bumper beam or other part of automotive systems. For example Hambali et al. [15] studied application of AHP in the design concept selection of automotive composite bumper beam during the conceptual design stage. Davoodi et al. [16] studied mechanical properties of hybrid kenaf/glass reinforced epoxy composite for passenger car bumper beam. Mansor et al. [6] investigated hybrid natural and glass fibers reinforced polymer composites material selecting using AHP for automotive brake lever design. The literature review indicates that researchers have not studied polymeric nanocomposite material selection for automotive bumper beam. In the present study, firstly six alternatives (three polyamide-6 nanocomposites foams containing different weight percentages of multi-walled carbon nanotubes (MWCNTs) and three polycarbonate nanocomposites including different weight percentages of nano alumina) were produced by injection molding process. Then, using four different procedure multi-criteria decision making methods (AHP-TOPSIS, Entropy-TOPSIS, AHP-MOORA and Entropy-MOORA), the most appropriate polymeric nanocomposite material was selected respect to considered criteria (i.e. impact strength, tensile strength, cost and manufacturing process). The sensitivity analysis was performed.Eventually, some beneficial conclusions explained at the end of this article.

2. EXPERIMENTAL PROCEDURE

2. 1. Materials and Equipment

Polyamide 6 (PA-6) with trade name of Tecomide NB40 NL E with the density of 1.13 g/cm3 and polycarbonate (PC) with trade name of HOPELEX PC-1100U with the melt flow index (MFI) of 10g/10min (300°C, 1.2 kg) was used as polymeric matrixes. Industrial grade of multi-walled carbon nanotubes (MWCNTs) with the purity of 90% supplied by US Research Nanomaterials Inc. (USA) was used in experimentations. Inner and outer diameters and length of nanotubes are 5-10 nm, 10-30 nm and 10-30 μm, respectively. Al_2O_3 nanoparticles with the purity of 99% and the particle size of 20 nm supplied by US Research Nanomaterials Inc. (USA) was also used as another reinforcing agent. Poly (styrene-co-maleic anhydride (SMA)) supplied by Sigma-Aldrich (USA) was used as a compatibilizer in PC blends with nano alumina. Azodicarbonamide was usedas the chemical blowing agent of the foaming process of PA-6/MWCNT nanocomposites.

A ZSK-25 (Coperion Werner & Pfleiderer, Germany) twin-screw extruder was used for melt compounding of the composite components and an NBM HXF-128 injection molding machine with L/D=21.1 and D=37mm of screw was also used for injection molding of specimens. A Gotech-AI-7000M tensile test machine was used to calculate tensile strength of samples. Also a Charpy impact test machine with pendulum mass of 2.036 kg and arm length of 39.48 cm was used to determine the impact strength of samples.

2. 2. Preparation of Specimens

Before melt compounding, PA-6, PC and SMA are dried using anoven at 120 °C for 2 hours. PA-6 blend with MWCNT and PC blend with SMA and nano alumina are then extruded in a twin-screw extruder with varying weight percentages

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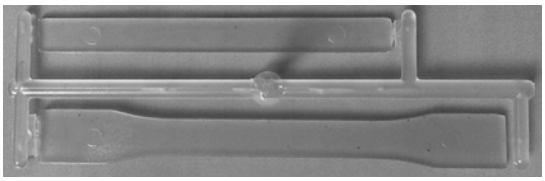
at screw speed of 250 rpm. Obtained nanocomposite granules are dried in the drying unit of injection molding machine at 80 °C for 20 hours. In order to provide foaming conditions, 2 wt% of Azodicarbonamide and 1 wt% of paraffin oil are added to PA-6/ MWCNT nanocomposite granules as the blowing and softening agents, respectively. Later on the mixtures are injected to a mold cavity based on ASTM-D638 and ASTM-D6110 for tensile and impact tests, respectively. Table 1 indicated six considered nanocomposites as alternatives in the present study. Also Fig. 1 shows some of the injected samples of this research work. Likewise Fig. 2 indicates the SEM picture of two samples of PA-6/MWCNT nanocomposite foams with a microcellular structure.

Table 1. The material alternatives

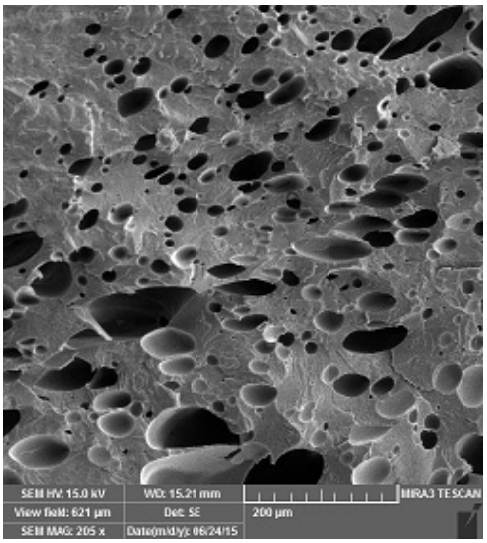
No.	Material
M-1	PA6/0.5 wt% MWCNT (Nanocomposite Foam)
M-2	PA6/1 wt% MWCNT (Nanocomposite Foam)
M-3	PA6/1.5 wt% MWCNT (Nanocomposite Foam)
M-4	PC/0.5 wt% Nano Alumina (Nanocomposite)
M-5	PC/1 wt% Nano Alumina (Nanocomposite)
M-6	PC/1.5 wt% Nano Alumina (Nanocomposite)



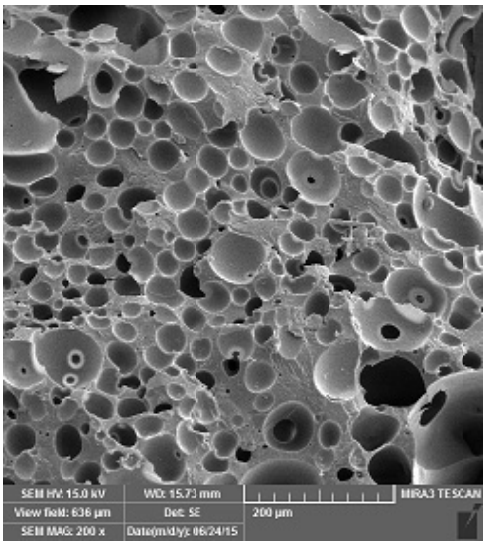
a

b

Fig. 1. a) PC containing 0.5 wt% nano alumina and b) PA-6 containing 0.5 wt% MWCNT



a



b

Fig. 2. SEM picture of nanocomposite foam samples, a) PA-6 containing 1 wt% MWCNT and b) PA-6 containing 1.5 wt% MWCNT

2. 3. Definition of Decision Making Problem

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Composite materials have been widely used in automotive industry in recent years [17, 18] especially in automotive bumper system [19, 20]. One of the most important components of bumper system is the bumper beam that plays an important role in absorbing the bulk of energy in accidents. The selection of the best material for automotive bumper beam depends on many criteria that the most important of them are as follow:

2. 3. 1. Tensile Strength (TS)

One of the most important criteria in material selection for bumper beam is the tensile strength of material. Tensile strength is the maximum tensile stress that a material can tolerate before it undergoes cracking, fracture or plastic deformation.

2. 3. 2. Impact Strength (IS)

The most important criterion in selecting the most appropriate material for bumper beam is the impact strength. Bumper beam is a main structure for absorbing the energy of collisions. The impact strength is the absorbed impact energy by the cross-section area of the material.

2. 3. 3. Cost (Co)

It is obvious that the cost plays a very significant role in determining the most appropriate material for bumper beam. In this research, cost is defined as the raw materials cost including polymeric matrix, nanoparticles, blowing agent, and compatibilizer.

2. 3. 4. Manufacturing Process (MP)

Another important parameter is the difficulty of manufacturing process of material for selection the proper material for the bumper beam. This criterion is according to the author's experience during production the polymeric nanocomposite materials.

3. MULTI-CRITERIA DECISION MAKING (MCDM) METHODS

3. 1. Criteria Weighting

In the present study, weighting of criteria was done using two methods: AHP and Entropy.

3. 1. 1. AHP Method

AHP has been widely used to solve multi-criteria decision making in both academic research and industrial practice. AHP is based on experience and knowledge of the experts or users to determine the factors affecting the decision making process [5]. In AHP approach that is a powerful tool in solving complex decision problems, the decision problem is structured hierarchically at different levels as shown in Fig. 3.

AHP uses pair wise comparison of the same hierarchy elements using a Saaty [21] scale indicating the importance of one element over another element using the Saaty's relative importance 1-9 point scale as represented in Table 2. The judgments are decided based on the experience and knowledge of decision makers or users.

The consistency ratio is calculated based on the following steps:

1. Calculate the eigenvector or relative weights and λ_{max} for each matrix of order n.
2. Compute consistency index (CI) for each

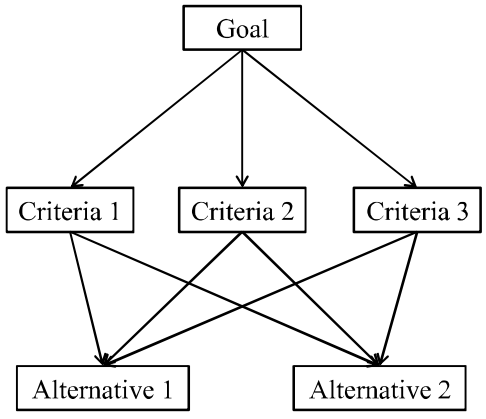

Fig. 3. The structure of AHP

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Table 2. Saaty's relative importance scale [21]

No.	Material
M-1	PA6/0.5 wt% MWCNT (Nanocomposite Foam)
M-2	PA6/1 wt% MWCNT (Nanocomposite Foam)
M-3	PA6/1.5 wt% MWCNT (Nanocomposite Foam)
M-4	PC/0.5 wt% Nano Alumina (Nanocomposite)
M-5	PC/1 wt% Nano Alumina (Nanocomposite)
M-6	PC/1.5 wt% Nano Alumina (Nanocomposite)

matrix of order n by Eq.1:

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

3. Consistency ratio (CR) is then calculated using Eq.2:

$$CR = CI/RI \quad (2)$$

where RI denotes average random index, and its value is 0.9 for n=4. For consistency, CR value should be less than 0.1.

3. 1. 2. Entropy

Entropy can be calculated based on the variation of index value. The performing of the entropy method is as followings [8]:

The decision matrix of a multi-criteria problem with m alternatives and n criteria is as following matrix:

$$A=\begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix}$$

where x_{ij} (i= 1, 2, ..., m; j= 1, 2, …, n) is the performance value of the ith alternative to the jth factor.

In calculating weights by entropy method the normalized matrix element for benefits indicators and cost indicators calculated as Eq. 3 and Eq. 4, respectively.

$$y_{ij} = \frac{x_{ij} - min_j\{x_{ij}\}}{max_j\{x_{ij}\} - min_j\{x_{ij}\}} \quad (3)$$

$$y_{ij} = \frac{max_j\{x_{ij}\} - x_{ij}}{max_j\{x_{ij}\} - min_j\{x_{ij}\}} \quad (4)$$

And:

$$P_{ij} = \frac{y_{ij}}{\sum_{j=1}^{m} y_{ij}}$$

The entropy of the *j*th criteria calculated as Eq. 5:

$$P_{ij} = \frac{y_{ij}}{\sum_{j=1}^{m} y_{ij}} \quad (5)$$

where k represents a constant : $k = \frac{1}{\ln m}$; which guarantees that $0 \leq E_j \leq 1$.

The degree of diversification of the information provided by the *j*th criteria calculated as Eq. 6:

$$d_j = |1 - E_j| \quad (6)$$

Then the weight of entropy of *j*th factor could be defined as Eq. 7:

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j} \quad (7)$$

3. 2. Alternative Ranking

3. 2. 1. TOPSIS Method

TOPSIS method is a typical MCDM tool that consists of the following steps [22]:

Step 1. Calculate the normalized decision matrix as Eq. 8:

$$y_{ij} = \frac{x_{ij}}{\sqrt{\sum_{k=1}^{m} x_{kj}^2}} \quad (8)$$

where y_{ij} is the normalized value, m is the number of criteria, x_{ij} is the value of the observed data, and x_{kj} is that of the observed data in the same row as x_{ij}.

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Step 2.Normalization of weights using Eq. 9:

$$v_{ij} = y_{ij} * w_{ij} \tag{9}$$

where v_{ij} is the weighted normalized value, y_{ij} is the normalized value, and w_{ij} is the weight of the each criterion.

Step 3. Determine the ideal and negative-ideal solutions using Eq. 10 and Eq. 11, respectively:

$$A^* = \{v_1^*, \dots, v_n^*\} = \{(\max_j v_{ij} | i \in I'), (\min_j v_{ij} | i \in I'')\} \tag{10}$$

$$A^- = \{v_1^-, \dots, v_n^-\} = \{(\min_j v_{ij} | i \in I'), (\max_j v_{ij} | i \in I'')\} \tag{11}$$

where I' is associated with benefit criteria and I'' is associated with cost criteria.

Step 4. The distance (D) of each alternative from positive and negative ideal solution was calculated as Eq. 12 and Eq. 13, respectively:

$$D_j^* = \sqrt{\sum_{i=1}^{n} (v_{ij} - v_i^*)^2} \tag{12}$$

$$D_j^- = \sqrt{\sum_{i=1}^{n} (v_{ij} - v_i^-)^2} \tag{13}$$

Step 5. The closeness coefficient (C) of each alternative was calculated via Eq. 14:

$$C = \frac{D_i^-}{D_i^* + D_j^-} \tag{14}$$

Step 6. The ranking of the alternatives was determined based on the highest C values.

3. 2. 2. MOORA Method

MOORA method is started with a decision matrix showing the performance of different alternatives with respect to various attributes (objectives) [23].The normalization of the decision matrix is performed using Eq. 15:

$$x_{ij}^* = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \qquad j= 1, 2, \dots, n \tag{15}$$

The normalized assessment value calculated as Eq. 16:

$$y_i = \sum_{j=1}^{g} x_{ij}^* - \sum_{j=g+1}^{n} x_{ij}^* \tag{16}$$

where g is the number of attributes to be maximized, (n-g) is the number of attributes to be minimized, and y_i is the normalized assessment value of ith alternative with respect to all the attributes. The ranking of the alternatives was determined based on the highest y_i values.

4. RESULTS AND DISCUSSION

The purpose of the present study is selecting the proper polymeric nanocomposite material for bumper beam. In this regard, six nanocomposite materials were produced (see Table 1). The tensile test with 10 mm/min speed of test and impact test with the samples that are notched with 2 mm of depth, 45° of notch angle and 11.5*3.2 mm^2 of cross-section area were performed according to ASTM-D638 and ASTM-D6110 standard, respectively. Results of the tensile and impact tests and required data to determine the most appropriate polymer nanocomposite for bumper beam are presented in Table 3. It should be noted that the cost of raw materials is estimated in range between high cost (i.e. 6) and low cost (i.e. 1). Also according to the experience of authors during production of the nanocomposite samples, the difficulty of manufacturing process is estimated in range between the most difficult (i.e. 6) and the easiest (i.e. 1).

According to the best knowledge and experience of the authors, the pairwise comparison of criteria with respect to purpose of

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the research is shown in Table 4. For example the intensity of importance of 5 for impact strength in comparison with the manufacturing process shows that for our purpose, the impact strength is much more significant than manufacturing process. As it is mentioned previously, for automotive bumper beam, impact strength is the most important criteria due to purpose of accident energy absorbing. Going in details regarding the pairwise comparison matrix it is concluded that the data of Table 4 clearly shows that impact strength is considered as the most important criteria in our experimentations.

4. 1. Criteria Weighting

In this research work, the weights of criteria were determined using AHP and Entropy methods. Results of criteria weighting by AHP is depicted in Fig. 4-a. Criteria weighting by AHP indicated that the impact strength with the weight of 0.579 is the most important criteria for selecting the best nanocomposite material for automotive bumper beam. Fig. 4-a also shows that the cost and manufacturing process with the weight of 0.109 are the less important criteria. Another important result that could be obtained from the AHP criteria weighting of this study is that the value of C.R. is 0.001 which means obtained results are so reliable. Results of criteria weighting via Entropy is also reveals in Fig. 4-b. As the results illustrated, the tensile strength with the weight of 0.405 is the most important criteria for determining the appropriate nanocomposite material. Similar to the results of AHP criteria weighting, Fig. 4-b indicated that the cost and manufacturing process with the weight of 0.195 are the less important criteria.

4. 2. Alternatives Ranking

As mentioned previously, to determine the most proper polymeric nanocomposite material for bumper beam, two methods are implemented i.e. TOPSIS and MOORA methods. Both of these two methods were performed using two criteria weighting methods (AHP and Entropy). The ranking of most appropriate polymeric nanocomposite material for automotive bumper beam is shown in Table 5 for four approaches (i.e. AHP-TOPSIS, AHP-MOORA, Entropy-TOPSIS and Entropy-MOORA). Table 5 indicates that for four different procedures, fourth alternative (i.e. polycarbonate containing 0.5 wt% nano alumina) is the best selection for automotive bumper beam. The reason of this result is the high impact and tensile strengths in addition to the lowest cost of raw materials of the M-4. Also, Table 5 illustrates that third alternative (i.e. polyamide 6/ 1.5 wt% MWCNT nanocomposite foam) is the worst material for bumper beam. M-3 has lowest impact strength and highest cost among alternatives.

4. 3. Sensitivity Analysis

In the following, the sensitivity analysis is performed. The purpose of performing the sensitivity analysis is to study the effect of different factors on deciding the best decision option. This analysis is shown in Fig. 5. The sensitivity analysis shows that the M4 (i.e. the best alternative) is the best choice from impact strength and cost point of view. Whiles M6 and M1 are the best alternatives from tensile strength and manufacturing process points of view, respectively. Also, the results indicate that M3 is the worst alternative in respect to all criteria except manufacturing process. Furthermore M6 has the lowest weight with regard to manufacturing process and M5 is the second alternative in respect to all criteria except manufacturing process.

5. CONCLUSIONS

In this research, six polymeric nanocomposite materials were produced and considered as alternatives to solve material selection problem of automotive bumper beam. Tensile strength (TS), impact strength (IS), cost (Co) and manufacturing process (MP) are considered as criteria for selection most proper polymeric nanocomposite material for bumper beam. Results showed that the impact and tensile strengths are the most important criteria for material selection according to criteria weighting using AHP and Entropy methods, respectively.

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Ranking of alternatives implemented using TOPSIS and MOORA methods respect to two different criteria weighting. All the four different procedure indicated that material alternative

Table 3. The decision matrix

Alternative	Criteria			
	Tensile Strength (MPa)	Impact Strength (MPa)	Cost	Manufacturing Process
M-1	25.00	113.07	4	1
M-2	37.55	103.54	5	2
M-3	34.79	96.51	6	3
M-4	135.38	224.58	1	4
M-5	141.71	154.06	2	5
M-6	141.92	133.53	3	6

Table 4. The pairwise comparison matrix with goal of selecting the best polymeric nanocomposite material

	Tensile Strength	Impact Strength	Cost	Manufacturing Process
Tensile Strength	1	1/3	2	2
Impact Strength	3	1	5	5
Cost	1/2	1/5	1	1
Manufacturing Process	1/2	1/5	1	1

Table 5. The ranking of alternatives based on four different procedures

Procedure / Alternative	AHP-TOPSIS	AHP-MOORA	Entropy-TOPSIS	Entropy-MOORA
M-1	4	4	4	4
M-2	5	5	5	5
M-3	6	6	6	6
M-4	1	1	1	1
M-5	2	2	2	2
M-6	3	3	3	3

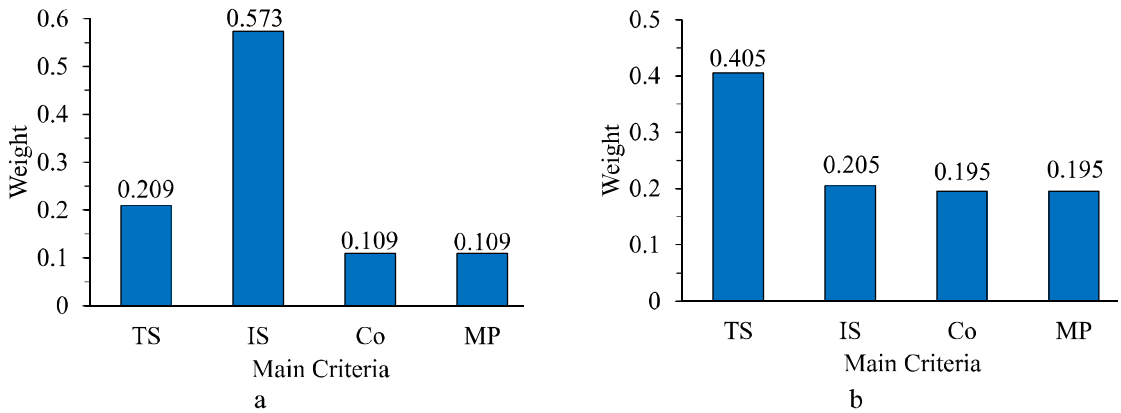

Fig. 4. Criteria weighting using a) AHP and b) Entropy methods

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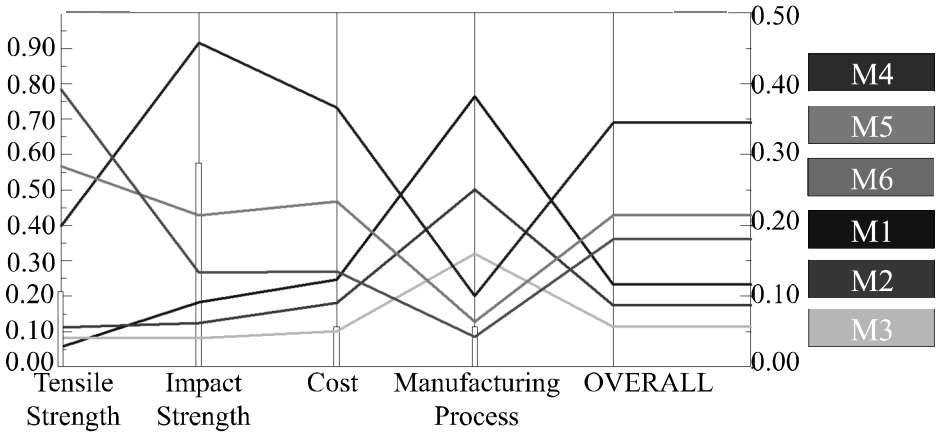

Fig. 5. The sensitivity analysis

number 4 (M-4, i.e. polycarbonate containing 0.5 wt% of nano alumina) is the most appropriate polymeric nanocomposite material due to its high impact and tensile strengths and its lowest cost. Results also clarified that material alternative number 3 (M-3, i.e. polyamide6 nanocomposite foam containing 1.5 wt% MWCNT) is the worst material based on all four procedure due to its low impact strength and highest cost.

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