

# Exploring incisive decision for performance assessment of materials under utopian environment: A pluri-disciplinary approach

Manik Chandra Das<sup>a\*</sup> & Bijan Sarkar<sup>b</sup>

<sup>a</sup>Department of Industrial Engineering and Management, Maulana Abul Kalam Azad University of Technology, Haringhata, West Bengal, 721 249, India

<sup>b</sup>Production Engineering Department, Jadavpur University, Kolkata 700 032, India

Received: 30 May 2023; Accepted: 7 March 2024

In the era of mass customization material selection for biomedical and other engineering applications has become extremely sensitive under requirement perspective. With the advent of new technologies, exotic materials with diverse features are coming up for various applications. It becomes a concern for biomedical and other professionals to select the best material for the purpose. This paper proposes a new model combining AHP and MABAC method under the environment of rough set. Rough numbers have been used to capture and aggregate the perception of decision makers in vague and imprecise environment. To establish the usefulness of the proposed method, four material selection problems have been illustrated. Comparative analysis and validation of results with published literatures prove the efficacy of the proposed method.

**Keywords:** Rough-AHP, Rough-MABAC, Material selection, Ranking

## 1 Introduction

In the era of mass customization, many new materials are coming up and used in modern manufacturing industry to suit the requirements of customers. Customers of all engineering sectors including biomedical are getting many alternative materials with diverse features including cost for specific applications. Therefore, it has become a research issue to identify and select the best material with respect to selection criteria which may be conflicting in nature. Many multiple criteria decision making (MCDM) methods namely, AHP, ANP, TOPSIS, VIKOR, PROMETHEE, ELECTRE<sup>1-6</sup> and many more have been emerged and used for material selection in the last five decades. These models are further modified by the researchers<sup>7-9</sup> for applying these in fuzzy environment. Wide applications of the models have been found in the area of material selection. Samant *et al.*<sup>10</sup> used preference selection index methodology for selection of suspension coil spring materials. In the field of construction, material selection case studies had been presented by Shoji *et al.*<sup>11</sup>. Soni *et al.*<sup>12</sup> used weighted aggregate sum product assessment (WASPAS) method to rank polymeric composite materials for making floor tiles

and pavements. Tong *et al.*<sup>13</sup> presented a review on envelope material selection for Chinese solar greenhouses. Malaga *et al.*<sup>14</sup> utilized IEM and CODAS for material selection to facilitate metal additive manufacturing processes. In automotive sector, Nicolalde *et al.*<sup>15</sup> used MEREC method for phase change material selection to improve energy storage of heat for energetic efficiency on transportation vehicle. Guo *et al.*<sup>16</sup> presented a review on railway ballast material selection and evaluation.

Many applications of MCDM models for material selection in biomedical field are also found in literatures. Biocompatibility and biostability are the major concern while developing biomaterials for specific applications. For selection of materials to make hip joint prosthesis and other engineering products, Jahan *et al.*<sup>17</sup> used comprehensive VIKOR method. Later Jahan and Edwards<sup>18</sup>, Hafezalkotob and Hafezalkotob<sup>19</sup> and Das and Sarkar<sup>20</sup> proposed alternative methods for the same purpose. Khalid *et al.*<sup>21</sup> used AHP and finite element analysis (FEA) to select green composite materials for orthopedic prosthesis. Jha *et al.*<sup>22</sup> employed TOPSIS method to do ranking the suitable materials for making biomedical products or devices using additive manufacturing techniques. Many applications of various alloy of titanium are found in biomedical field. Pesode *et al.*<sup>23</sup>

\*Corresponding author (E-mail: cd\_manik@rediffmail.com)

used Weighted Sum Model for selection of such alloy materials. Systematic reviews on material selection in biomedical filed had been presented by Hashmi *et al.* and Chandra and Pandey<sup>24-25</sup>.

To facilitate material selection with complex situation, many hybrid models such as BWM-CoCo MULTIMOORA, QFD-ELECTRE III, SWARA-CODAS<sup>26-28</sup> have been introduced. Haq *et al.*<sup>29</sup> proposed single valued neutrosophic-MEREC-MARCOS framework. A novel fermatean fuzzy ELECTRE multi-criteria group decision-making method had been proposed by Kirişci *et al.*<sup>30</sup> for biomedical material selection. To deal with complex decision making process with vagueness and without any prior information, this paper proposes a hybrid decision making model comprising of AHP and multi-attributive border approximation area comparison (MABAC) method in rough environment. Four material selection problems, originally addressed by Jahan *et al.*<sup>17</sup>, such as, material selection for (a) hip joint prosthesis, (b) fuel cell, (c) product operating at high temperature and (d) a sailing boat mast, are chosen for illustration with proposed model. It has been found that, the proposed method is very much useful with high degree of robustness and accuracy in vague and imprecise environment.

## 2 Materials and Methods

Decision making is a pluri-disciplinary project because the opinions of specialists from various domains are being considered for performance assessment and selection of any kind of alternatives in general and biomedical and engineering materials in particular. Figure 1 shows the basic components of a decision making process.

To facilitate decision making in imprecise and inconsistent environment, classical rough set theory was introduced by Pawlak<sup>31</sup> and further extended by Zhai *et al.*<sup>32-33</sup>. For processing inconsistent and imprecise information, the method of using of classical rough set approximation theory can be described as mentioned below.

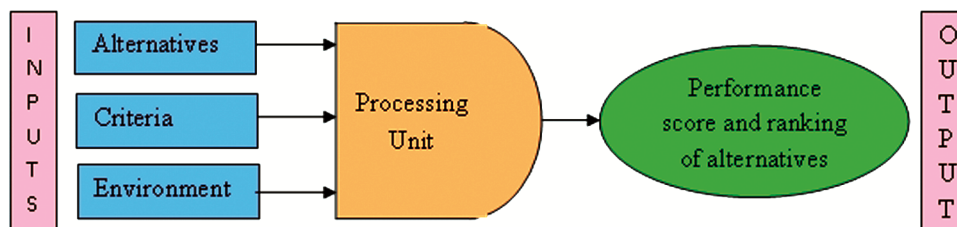


Fig. 1 — Decision making process.

Let X be arbitrary object of universe of discourse U, there exists et of n classes,  $R = \{C_1, C_2, \dots, C_n\}$ , in U. If these classes are ordered, then for anyclass,  $C_i \in R, 1 \leq i \leq n$ , lower approximation of  $C_i$  can be defined as

$$\underline{Apr}(C_i) = U\{X \in U/R(X) \leq C_i\}; \quad \dots (1)$$

upper approximation of  $C_i$  can be expressed as

$$\overline{Apr}(C_i) = U\{X \in U/R(X) \geq C_i\}; \quad \dots (2)$$

and boundary region of  $C_i$  is given by

$$\begin{aligned} Bnd(C_i) &= U\{X \in U/R(X) \neq C_i\}; \\ &= \{X \in U/R(X) > C_i\} \cup \{X \in U/R(X) < C_i\}; \quad \dots (3) \end{aligned}$$

Thus the class,  $C_i$ , can be represented by a rough number (RN) which is defined by its lower limit ( $\underline{Lim}(C_i)$ ) and upper limit ( $\overline{Lim}(C_i)$ ), where

$$\underline{Lim}(C_i) = \frac{1}{M_L} \sum R(X) | X \in \underline{Apr}(C_i) \quad \dots (4)$$

where  $M_L$  is the number of objects contained in the lower approximation of  $C_i$ ; and

$$\overline{Lim}(C_i) = \frac{1}{M_U} \sum R(X) | X \in \overline{Apr}(C_i) \quad \dots (5)$$

where  $M_U$  is the number of objects contained in the upper approximation of  $C_i$ . The interval between the lower limit  $\underline{Lim}(C_i)$  and the upper limit  $\overline{Lim}(C_i)$  becomes the rough boundary interval of  $C_i$ , which is denoted as  $RBnd(C_i)$  as follows.

$$RBnd(C_i) = \overline{Lim}(C_i) - \underline{Lim}(C_i); \quad \dots (6)$$

Accordingly, the vague class  $C_i$  can be expressed by the aforementioned rough number comprising its lower limit and upper limit as follows. Figure 2 shows the basic terminologies of rough set theories.

$$RN(C_i) = [\underline{Lim}(C_i), \overline{Lim}(C_i)] = [x_{ij}^L, x_{ij}^U] \quad \dots (7)$$

In this paper a proposed model combining AHP and MABAC in rough environment (RAHP-RMABAC) has been proposed. RAHP has been chosen to prioritize

the performance evaluation criteria while RMABAC has been used to determine the performance score of alternatives based on the aggregation of approximate and imprecise judgments rendered by the decision makers. Figure 3 shows the flowchart which indicates the phase wise development of the proposed method for materials selection. In the first phase, criteria weights have been determined by taking the opinion of experts in a brainstorming session followed by aggregation of the same using rough AHP. The performance score of alternative materials has been determined in the second phase using rough MABAC method.

As understood in Fig. 3, proposed model has been developed with due consideration to the effects of political, economic, environmental, social and technological (PEEST) aspects on achieving the objective of the materials selection problem. The solution to the problem should be economically viable and eco friendly. Appropriate government policy should ensure the application of advanced technology such as 3D printing, artificial intelligence, internet of things in the background of industry 4.0 should be there to facilitate the development of exotic material in a customized manner.

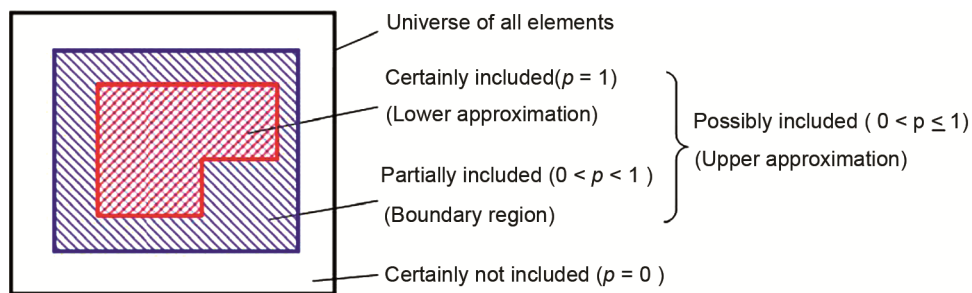


Fig. 2 — Rough set terminologies (Source: Zhai et al., 2009).

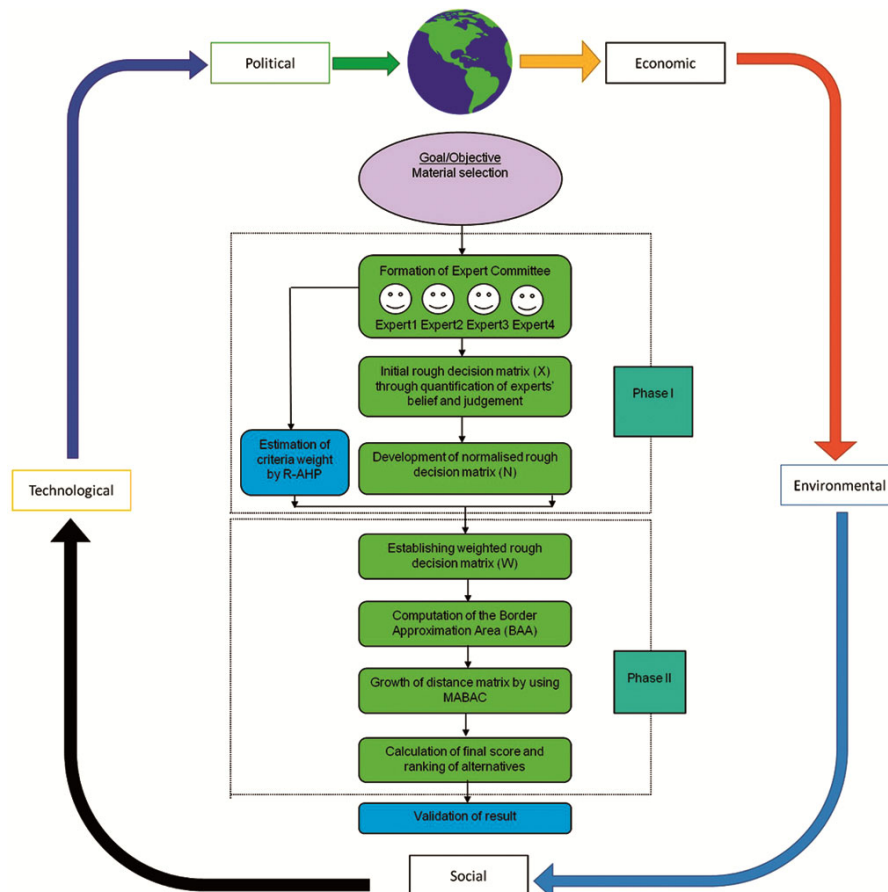


Fig. 3 — Flowchart of the proposed method.

**2.1 Rough analytic hierarchy process (RAHP)**

Though AHP<sup>1</sup> had been extensively used as MCDM method, in this paper AHP in rough environment is used to determine criteria weights for its ability to deal with approximate and imprecise information. Following steps have been followed for the purpose.

Step 1: Taking the opinion of k number of experts, form pairwise comparison matrix (PWCM) for evaluation criteria, corresponding to individual experts (1 ≤ e ≤ k) using Saaty’s 9-point scale. Thus the PWCM for e<sup>th</sup> expert can be expressed as

$$C_e = [c_{ij}^e]_{n \times n} = \begin{bmatrix} 1 & c_{12}^e & \dots & c_{1n}^e \\ c_{21}^e & 1 & \dots & c_{2n}^e \\ \dots & \dots & \dots & \dots \\ c_{n1}^e & c_{n2}^e & \dots & 1 \end{bmatrix} \dots (8)$$

Step 2: Develop k number of PWCM. Check consistency ratio (CR) for each PWCM. If CR < 0.10, accept the PWCM.

Step 3: Form integrated PWCM as mentioned below by aggregating the experts’ opinion.

The integrated PWCM can be expressed as

$$C = [c_{ij}]_{n \times n} = \begin{bmatrix} 1 & c_{12} & \dots & c_{1n} \\ c_{21} & 1 & \dots & c_{2n} \\ \dots & \dots & \dots & \dots \\ c_{n1} & c_{n2} & \dots & 1 \end{bmatrix}$$

Where  $c_{ij} = \{c_{ij}^1, c_{ij}^2, \dots, c_{ij}^k\}$  ... (9)

Step 4: Using eq.(1–7), transform the element  $c_{ij}$  into Rough Number, RN( $c_{ij}^e$ ) of  $c_{ij}$  as follows

$$RN(c_{ij}^e) = [c_{ij}^{eL}, c_{ij}^{eU}], (1 \leq e \leq k) \dots (10)$$

Step 5: Determine average rough interval RN( $c_{ij}$ ) as,

$$\overline{RN(c_{ij})} = [c_{ij}^L, c_{ij}^U] \dots (11)$$

Where,  $c_{ij}^L = \frac{\sum_{e=1}^k c_{ij}^{eL}}{k}$ ,  $c_{ij}^U = \frac{\sum_{e=1}^k c_{ij}^{eU}}{k}$  ... (12)

Thus, the aggregated rough PWCM becomes-

$$M = [m_{ij}]_{n \times n} = \begin{pmatrix} [1,1] & [c_{12}^L, c_{12}^U] & \dots & [c_{1n}^L, c_{1n}^U] \\ [c_{21}^L, c_{21}^U] & [1,1] & \dots & [c_{2n}^L, c_{2n}^U] \\ \dots & \dots & \dots & \dots \\ [c_{n1}^L, c_{n1}^U] & [c_{n2}^L, c_{n2}^U] & \dots & [1,1] \end{pmatrix} \dots (13)$$

Step 6: Compute rough criteria weight  $W_i$  as geometric mean of aggregated rough PWCM.

$$w_i = [w_i^L, w_i^U] = [(\prod_{j=1}^n c_{ij}^L)^{1/n}, (\prod_{j=1}^n c_{ij}^U)^{1/n}] \dots (14)$$

Step 7: Normalize eq. (14) to get relative criteria weights which are expressed as

$$w_i = [w_i^L, w_i^U] = \left[ \frac{w_i^L}{\max(w_i^U)}, \frac{w_i^U}{\max(w_i^U)} \right], \text{ for all } i \dots (15)$$

**2.2 Rough MABAC**

In the present work, for the purpose of performance evaluation of alternatives MABAC method which is an extension of TOPSIS method has been used in rough environment. This method works on Euclidean distance based measure from border approximation area (BAA). The general steps of this method are outlined as follows.

Step 1: Develop a group decision matrix with the opinion of k number of experts using Saaty’s 9-point scale and then convert it into aggregated rough decision matrix (D) using eq. (1-7).

$$D = [x_{ij}^L, x_{ij}^U]_{m \times n} \dots (16)$$

where  $[x_{ij}^L, x_{ij}^U]$  indicates performance of i<sup>th</sup> alternative against j<sup>th</sup> criterion in rough number.

Step 2: Compute normalized rough decision matrix  $D' = [n_{ij}^L, n_{ij}^U]$  using following formula.

(a) For higher-the-better type criteria,  $n_{ij}^L = \frac{x_{ij}^L - x_j^-}{x_j^+ - x_j^-}$ ,  $n_{ij}^U = \frac{x_{ij}^U - x_j^-}{x_j^+ - x_j^-}$  ... (17)

(b) For lower-the-better type criteria,  $n_{ij}^L = \frac{x_{ij}^L - x_j^+}{x_j^- - x_j^+}$ ,  $n_{ij}^U = \frac{x_{ij}^U - x_j^+}{x_j^- - x_j^+}$  ... (18)

Where,  $x_j^+ =$

$$\begin{cases} \max_{1 \leq i \leq m} (x_{ij}^U), & \text{for higher – the – better type criteria} \\ \min_{1 \leq i \leq m} (x_{ij}^L), & \text{for lower – the – better type criteria,} \end{cases} \text{ for all } j \dots (19)$$

and  $x_j^- =$

$$\begin{cases} \min_{1 \leq i \leq m} (x_{ij}^L), & \text{for higher – the – better type criteria} \\ \max_{1 \leq i \leq m} (x_{ij}^U), & \text{for lower – the – better type criteria,} \end{cases} \text{ for all } j \dots (20)$$

Step 3: Calculate weighted normalized matrix ( $D''$ ) using following equation.

$$\begin{cases} D'' = [v_{ij}^L, v_{ij}^U]_{m \times n} \\ v_{ij}^L = w_i^L (n_{ij}^L + 1) \\ v_{ij}^U = w_i^U (n_{ij}^U + 1) \end{cases} \dots (21)$$

Step 4: Taking the geometric mean, compute border approximation area (BAA) for each criterion as mentioned below.

$$\begin{cases} G = [g_j^L, g_j^U], \text{ for all } j \\ g_j^L = (\prod_{i=1}^m v_{ij}^L)^{1/m} \\ g_j^U = (\prod_{i=1}^m v_{ij}^U)^{1/m} \end{cases} \dots (22)$$

Step 5: Using the following formula, determine Euclidean distance of the alternatives from BAA.

$$s_E(v_{ij}, g_j) = \begin{cases} \sqrt{(v_{ij}^L - g_j^U)^2 + (v_{ij}^U - g_j^L)^2}, & \text{for higher – the – better type criteria} \\ \sqrt{(v_{ij}^L - g_j^L)^2 + (v_{ij}^U - g_j^U)^2}, & \text{or lower – the – better type criteria} \end{cases} \dots (23)$$

Step 6: Considering the following condition, form the distance matrix U as follows:

$$U = (u_{ij})_{m \times n} \dots (24)$$

Where

$$u_{ij} = \begin{cases} s_E(v_{ij}, g_j), \text{ if } RN(v_{ij}) > RN(g_j) \\ -s_E(v_{ij}, g_j), \text{ if } RN(v_{ij}) < RN(g_j) \end{cases} \text{ , for higher – the – better type criteria}$$

$$u_{ij} = \begin{cases} -s_E(v_{ij}, g_j), \text{ if } RN(v_{ij}) > RN(g_j) \\ s_E(v_{ij}, g_j), \text{ if } RN(v_{ij}) < RN(g_j) \end{cases} \text{ , for lower – the – better type criteria}$$

Step 7: Determine the performance score of alternatives by adding the row elements of distance matrix U. Thus, the score becomes-

$$S(A_i) = \sum_{j=1}^n u_{ij} \text{ , for all } i. \dots (25)$$

**2.3 Illustrative examples**

To show the efficacy and usefulness of the proposed RAHP-RMABAC method, four material selection problems which were already addressed by earlier researcher<sup>17</sup> have been taken for study. Those problems were solved using comprehensive VIKOR method. Later Jahan & Edwards<sup>18</sup> proposed an alternative method of calculating criteria weights and solved the hip joint prosthesis material selection problem again. Hafezalkotob and Hafezalkotob<sup>19</sup> applied comprehensive multimoora method for hip joint and knee joint material selection. Das & Sarkar<sup>20</sup> used a combination of full consistency method and ideal solution with constraint of values to solve the all four material selection problems addressed by Jahan *et al.*<sup>17</sup>. The proposed method works in two phases. In first phase, relative weights of evaluation criteria are

determined using RAHP and in second phase alternatives are ranked according to the algorithm of RMABAC.

**2.4 Selection of hip joint prosthesis**

Additive and smart manufacturing methods enable materials scientist to design and develop new biomaterials with diverse features for customized applications. This problem deals with 11 alternative materials and 9 evaluation criteria for selection and ranking of materials to make hip joint prosthesis<sup>17</sup>. Table 1 shows the list of criteria.

For the purpose of determining criteria weights, an expert committee (Table 2) comprising of four experts (E<sub>k</sub>, k=1 to 4) has been constituted. Corresponding to each expert, PWCM has been formed using Saaty’s 9-point scale. The same is shown in Table 3.

Now, vague and subjective linguistic judgments of individual experts corresponding to each criterion are aggregated in terms of rough numbers using eq. (1-7). The aggregated rough PWCM is shown in Table 4.

From aggregated rough PWCM, rough weight of each criteria has been determined using eq. (14) followed by normalization of the same using eq. (15). These normalized weights become the final rough weights of each criterion. These are shown in Table 5.

Jahan *et al.*<sup>17</sup> considered 11 alternative materials for making hip joint prosthesis. Following table (Table 6) shows the list of those alternative materials along with the ratings of 4 expert committee members with respect to 9 criteria mentioned earlier. The

Table 1 — List of criteria.

Code	Name of criterion	Type
C1	Tissue tolerance	Higher-the-better
C2	Corrosion resistance	Higher-the-better
C3	Tensile strength	Higher-the-better
C4	Fatigue strength	Higher-the-better
C5	Relative toughness	Higher-the-better
C6	Relative wear resistance	Higher-the-better
C7	Elastic modulus	Nominal-the-better
C8	Specific gravity	Nominal-the-better
C9	Cost	Lower-the-better

Table 2 — Expert committee.

Expert’s profile	Age	Education level	Experience	Working domain
Ex 1	54yrs	PhD	25yrs	Additive and smart manufacturing
Ex 2	37yrs	PhD	10yrs	Material scientist
Ex 3	52yrs	MBBS, MS	20yrs	Orthopedic surgeon
Ex 4	34yrs	M Tech	7yrs	Applied and biomechanics

Table 3 — Initial PWCM.

$E_1 =$	1	1	5	3	5	5	5	5	7	$E_2 =$	1	2	3	3	5	7	5	7	9
	1	1	7	5	5	7	7	7	9		1/2	1	5	5	5	7	5	7	9
	1/5	1/7	1	3	1	1	1	3	1		1/3	1/5	1	3	1	1	1	3	1
	1/3	1/5	1/3	1	1/3	1/3	1/3	1/3	1/5		1/3	1/5	1/3	1	1/3	1/3	1/3	1/3	1/5
	1/5	1/5	1	3	1	1	1	1	2		1/5	1/5	1/3	3	1	3	2	1	2
	1/5	1/7	1	3	1	1	1	1	2		1/7	1/7	1	3	1/3	1	1	1	3
	1/5	1/7	1	3	1	1	1	1	3		1/5	1/5	1	3	1/2	1	1	1	5
	1/5	1/7	1/3	3	1	1	1	1	3		1/7	1/7	1/3	3	1	1	1	1	5
	1/7	1/9	1	5	1/2	1/2	1/3	1/3	1		1/9	1/9	1	5	1/2	1/3	1/5	1/5	1
	$E_3 =$	1	2	4	3	6	6	6	8		9	$E_4 =$	1	1	5	4	6	6	6
1/2		1	4	5	5	7	5	7	8	1	1		4	5	5	6	5	7	8
1/4		1/4	1	3	1	1	1	2	1	1/5	1/4		1	3	1	1	1	2	1
1/3		1/5	1/3	1	1/4	1/4	1/4	1/4	1/5	1/4	1/5		1/3	1	1/4	1/4	1/4	1/4	1/5
1/6		1/5	1	4	1	4	1	1	2	1/6	1/5		1	4	1	3	1	1	2
1/6		1/7	1	4	1/4	1	1	1	3	1/6	1/6		1	4	1/3	1	1	1	3
1/6		1/5	1	4	1	1	1	1	6	1/6	1/5		1	4	1	1	1	1	5
1/8		1/7	1/2	4	1	1	1	1	6	1/8	1/7		1/2	4	1	1	1	1	5
1/9		1/8	1	5	1/2	1/3	1/6	1/6	1	1/7	1/8		1	5	1/2	1/3	1/5	1/5	1

Note: Saaty’s 9-point scale: 1 = very low; 3 = low; 5 = moderate; 7 = high; 9 = very high.

Table 4 — Aggregated rough PWCM.

	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	[1.00,1.00]	[1.25,1.75]	[3.75,4.73]	[3.06,3.44]	[5.25,5.75]	[5.583,6.417]	[5.250,5.750]	[6.250,7.447]	[7.500,8.500]
C2	[0.22,0.29]	[1.00,1.00]	[4.33,5.75]	[5.00,5.00]	[5.00,5.00]	[6.563,6.938]	[5.125,5.875]	[7000,7.000]	[8.250,8.750]
C3	[0.22,0.28]	[0.18,0.24]	[1.00,1.00]	[3.00,3.00]	[1.00,1.00]	[1.000,1.000]	[1.000,1.000]	[2.250,2.750]	[1.000,1.000]
C4	[0.30,0.33]	[0.20,0.20]	[0.33,0.33]	[1.00,1.00]	[0.27,0.31]	[0.271,0.312]	[0.271,0.312]	[0.271,0.312]	[0.200,0.200]
C5	[0.18,0.19]	[0.20,0.20]	[1.00,1.00]	[3.25,3.75]	[1.00,1.00]	[2.104,3.354]	[1.063,1.438]	[1.000,1.000]	[0.200,0.200]
C6	[0.16,0.18]	[0.14,0.15]	[1.00,1.00]	[3.25,3.75]	[0.34,0.65]	[1.000,1.000]	[1.000,1.000]	[1.000,1.000]	[2.563,2.938]
C7	[0.18,0.19]	[0.17,0.20]	[1.00,1.00]	[3.25,3.75]	[0.78,0.97]	[1.000,1.000]	[1.000,1.000]	[1.000,1.000]	[4.104,5.354]
C8	[0.13,0.17]	[0.14,0.14]	[0.38,0.46]	[3.25,3.75]	[1.00,1.00]	[1.000,1.000]	[1.000,1.000]	[1.000,1.000]	[4.104,5.354]
C9	[0.12,0.13]	[0.11,0.12]	[1.00,1.00]	[5.00,5.00]	[0.50,0.50]	[0.344,0.406]	[0.192,0.262]	[0.192,0.262]	[1.000,1.000]

judgments of experts in linguistic form is expressed in numbers using Saaty’s 9-point scale.

In similar manner, using eq. (1-7) aggregated initial rough decision matrix is constituted from these ratings of the experts. The same is presented in Table 7. The ideal solutions  $(x_j^+, x_j^-)$  as identified using formula (19-20) are also shown in Table 7.

Following table (Table 8) shows the normalized rough decision matrix derived from Table 6 using formula (17-18). The last row of the table indicates criteria weights which have been determined earlier using RAHP. Subsequently, weighted normalized rough decision matrix has been developed using formula (21) and shown in Table 9. The last row of Table 9 indicates border approximation area which has been computed using formula (22).

Euclidean distance of all alternatives from border approximation area (BAA) has been determined using formula (23). Thus distance matrix and final performance score computed for all alternative

Table 5 — Final rough weights of criteria.

Criteria	Rough weights	Final rough weights (Normalized)	Ranking of criteria
C1	[3.61,4.18]	[0.86,1.00]	1
C2	[3.29,3.61]	[0.79,0.86]	2
C3	[0.86,0.93]	[0.21,0.22]	3
C4	[0.30,0.33]	[0.07,0.08]	9
C5	[0.72,0.80]	[0.17,0.19]	7
C6	[0.74,0.84]	[0.18,0.20]	6
C7	[0.88,0.97]	[0.21,0.23]	4
C8	[0.77,0.84]	[0.18,0.20]	5
C9	[0.42,0.47]	[0.10,0.11]	8

materials using formula (24-25) has been presented in Table 10. The relative ranking of alternatives are also shown in the same table.

A comparison of ranking order of alternative materials for hip joint prosthesis determined by proposed RAHP-RMABAC with the ranking orders as obtained by earlier researchers has been presented in Table 11. Table 11 indicates that there exists strong statistical significance between various sets of

Table 6 — Expert opinion based decision matrix.

Alternative materials	Experts	C1	C2	C3	C4	C5	C6	C7	C8	C9
A1: Stainless steels 316	1	8	7	7	6	7	7	6	6	6
	2	7	7	7	7	7	7	6	6	6
	3	7	7	6	7	7	8	6	7	7
	4	7	7	6	7	8	7	6	7	5
A2: Stainless steels 317	1	6	7	7	6	7	7	5	5	6
	2	6	6	6	7	7	7	5	5	5
	3	7	5	6	6	7	7	5	7	5
	4	6	5	6	7	7	7	5	7	5
A3: Stainless steels 321	1	5	7	7	6	7	7	5	5	5
	2	6	6	6	7	6	7	5	5	5
	3	6	5	6	6	7	6	5	6	5
	4	6	5	6	7	6	6	5	7	5
A4: Stainless steels 347	1	7	7	7	6	7	7	6	5	6
	2	6	7	7	7	7	7	6	5	6
	3	7	5	6	7	7	7	5	7	5
	4	6	5	6	7	8	7	5	7	5
A5: Co–Cr alloys – Cast alloy (1)	1	8	9	9	8	7	7	6	7	8
	2	8	9	7	7	7	7	6	7	8
	3	8	8	7	7	7	6	7	7	7
	4	9	8	7	7	7	6	7	8	7
A6: Co–Cr alloys – Wrought alloy (2)	1	9	9	8	9	7	8	8	7	9
	2	9	9	8	9	7	8	8	7	9
	3	9	7	9	7	7	8	7	7	9
	4	9	7	9	9	9	9	7	9	7
A7: Unalloyed titanium	1	8	8	7	7	7	8	7	7	6
	2	8	7	7	7	7	8	7	7	6
	3	7	7	7	8	8	7	6	7	6
	4	7	7	7	8	7	7	6	5	7
A8: Ti–6Al–4V	1	8	8	7	7	7	7	7	7	8
	2	8	8	7	7	7	7	7	7	7
	3	8	7	7	7	7	6	7	7	7
	4	8	7	8	6	5	6	6	5	7
A9: Composites (fabric reinforced)-Epoxy-70% glass	1	4	6	6	6	7	7	5	5	5
	2	5	6	5	7	6	6	4	4	4
	3	6	4	5	5	6	6	4	6	4
	4	6	5	5	6	5	6	4	7	4
A10: Composites (fabric reinforced)-Epoxy-63% carbon	1	4	5	5	5	6	5	4	5	5
	2	5	4	4	5	5	3	4	4	4
	3	3	3	4	5	5	3	3	6	4
	4	3	5	4	6	5	3	3	5	4
A11: Composites (fabric reinforced)-Epoxy-62% aramid	1	4	6	5	6	6	6	5	5	5
	2	5	5	5	6	6	6	4	4	4
	3	5	3	5	5	6	6	3	6	4
	4	5	5	5	6	5	6	3	7	4

Note: Saaty's 9-point scale: 1 = very low; 3 = low; 5 = moderate; 7 = high; 9 = very high.

rankings obtained by various MCDM models. At the bottom of Table 11, the result of Spearman's rank correlation coefficient test has been given and the same shows that on an average there exists 91% agreement in ranking between the proposed RAHP-RMABAC method and other MCDM methods

### 2.5 Fuel cell material selection

The proposed RAHP-RMABAC model has been used for selection bipolar plate material to make fuel

cell for electric vehicles. In fuel cell, the chemical energy of fuel is converted into electrical energy by which motor of the vehicle runs. As the fuel cells are eco-friendly and sustainable, people use these in spite of comparatively high price. The selection criteria for fuel cell materials have been taken from the work of Jahan *et al.*<sup>17</sup> and presented in Table 12. The criteria have been formed with various combinations of elastic modulus (E), density ( $\rho$ ), tensile strength ( $\sigma_f$ ),

Table 7 — Initial rough decision matrix.

ALT	C1 Max	C2 Max	C3 Max	C4 Max	C5 Max	C6 Max	C7 Target value	C8 Target value	C9 Min
A1	[7.06,7.44]	[7.00,7.00]	[6.25,6.75]	[6.56,6.94]	[7.06,7.44]	[7.06,7.44]	[6.00,6.00]	[6.25,6.75]	[5.58,6.42]
A2	[6.06,6.44]	[5.27,6.25]	[6.06,6.44]	[6.25,6.75]	[7.00,7.00]	[7.00,7.00]	[5.00,5.00]	[5.50,6.50]	[5.06,5.44]
A3	[5.56,5.94]	[5.27,6.25]	[6.06,6.44]	[6.25,6.75]	[6.25,6.75]	[6.25,6.75]	[5.00,5.00]	[5.27,6.25]	[5.00,5.00]
A4	[6.25,6.75]	[5.50,6.50]	[6.25,6.75]	[6.56,6.94]	[7.06,7.44]	[7.00,7.00]	[5.25,5.75]	[5.50,6.50]	[5.25,5.75]
A5	[8.06,8.44]	[8.25,8.75]	[7.13,7.88]	[7.06,7.44]	[7.00,7.00]	[6.25,6.75]	[6.25,6.75]	[7.06,7.44]	[7.25,7.75]
A6	[9.00,9.00]	[7.50,8.50]	[8.25,8.75]	[8.13,8.88]	[7.38,8.63]	[8.06,8.44]	[7.25,7.75]	[7.38,8.63]	[8.13,8.88]
A7	[7.25,7.75]	[7.06,7.44]	[7.00,7.00]	[7.25,7.75]	[7.06,7.44]	[7.25,7.75]	[6.25,6.75]	[6.13,6.88]	[6.06,6.44]
A8	[8.00,8.00]	[7.25,7.75]	[7.06,7.44]	[6.56,6.94]	[6.13,6.88]	[6.25,6.75]	[6.56,6.94]	[6.13,6.88]	[7.25,7.75]
A9	[4.75,5.73]	[4.75,5.73]	[5.06,5.44]	[5.58,6.50]	[5.58,6.50]	[6.06,6.44]	[4.06,4.44]	[4.75,6.25]	[4.25,4.75]
A10	[3.27,4.25]	[3.75,4.73]	[4.06,4.44]	[5.06,5.44]	[5.06,5.44]	[3.13,3.88]	[3.25,3.75]	[4.58,5.42]	[4.25,4.75]
A11	[4.19,4.81]	[4.10,5.35]	[5.00,5.00]	[5.19,5.81]	[5.19,5.81]	[6.00,6.00]	[3.27,4.25]	[4.75,6.25]	[4.25,4.75]
x+	9.00	8.75	8.75	8.88	8.63	8.44	7.75	8.63	4.25
x-	3.27	3.75	4.06	5.06	5.06	3.13	3.25	4.58	8.88

Table 8 — Normalised rough decision matrix.

ALT	C1	C2	C3	C4	C5	C6	C7	C8	C9
A1	[0.66,0.73]	[0.65,0.65]	[0.47,0.57]	[0.39,0.49]	[0.56,0.67]	[0.74,0.81]	[0.61,0.61]	[0.41,0.54]	[0.71,0.53]
A2	[0.49,0.55]	[0.30,0.50]	[0.43,0.50]	[0.31,0.44]	[0.54,0.54]	[0.73,0.73]	[0.39,0.39]	[0.23,0.47]	[0.82,0.74]
A3	[0.40,0.47]	[0.30,0.50]	[0.43,0.50]	[0.31,0.44]	[0.33,0.47]	[0.59,0.68]	[0.39,0.39]	[0.17,0.41]	[0.84,0.84]
A4	[0.52,0.61]	[0.35,0.55]	[0.47,0.57]	[0.39,0.49]	[0.56,0.67]	[0.73,0.73]	[0.44,0.56]	[0.23,0.47]	[0.78,0.68]
A5	[0.84,0.90]	[0.90,1.00]	[0.65,0.81]	[0.53,0.62]	[0.54,0.54]	[0.59,0.68]	[0.67,0.78]	[0.61,0.71]	[0.35,0.24]
A6	[1.00,1.00]	[0.75,0.95]	[0.89,1.00]	[0.80,1.00]	[0.65,1.00]	[0.93,1.00]	[0.89,1.00]	[0.69,1.00]	[0.16,0.00]
A7	[0.70,0.78]	[0.66,0.74]	[0.63,0.63]	[0.57,0.70]	[0.56,0.67]	[0.78,0.87]	[0.67,0.78]	[0.38,0.57]	[0.61,0.53]
A8	[0.83,0.83]	[0.70,0.80]	[0.64,0.72]	[0.39,0.49]	[0.30,0.51]	[0.59,0.68]	[0.74,0.82]	[0.38,0.57]	[0.35,0.24]
A9	[0.26,0.43]	[0.20,0.40]	[0.21,0.29]	[0.14,0.38]	[0.15,0.40]	[0.55,0.62]	[0.18,0.26]	[0.04,0.41]	[1.00,0.89]
A10	[0.00,0.17]	[0.00,0.20]	[0.00,0.08]	[0.00,0.10]	[0.00,0.11]	[0.00,0.14]	[0.00,0.11]	[0.00,0.21]	[1.00,0.89]
A11	[0.16,0.27]	[0.07,0.32]	[0.20,0.20]	[0.03,0.20]	[0.04,0.21]	[0.54,0.54]	[0.00,0.22]	[0.04,0.41]	[1.00,0.89]
Weights	[0.86,1.00]	[0.79,0.86]	[0.21,0.22]	[0.07,0.08]	[0.17,0.19]	[0.18,0.20]	[0.21,0.23]	[0.18,0.20]	[0.10,0.11]

Table 9 — Weighted normalised rough decision matrix.

ALT	C1	C2	C3	C4	C5	C6	C7	C8	C9
A1	[1.43,1.73]	[1.30,1.42]	[0.30,0.35]	[0.10,0.12]	[0.27,0.32]	[0.31,0.36]	[0.34,0.37]	[0.26,0.31]	[0.17,0.17]
A2	[1.28,1.55]	[1.03,1.29]	[0.30,0.34]	[0.10,0.11]	[0.27,0.30]	[0.30,0.35]	[0.29,0.32]	[0.23,0.30]	[0.18,0.20]
A3	[1.21,1.47]	[1.03,1.29]	[0.30,0.34]	[0.10,0.11]	[0.23,0.28]	[0.28,0.34]	[0.29,0.32]	[0.21,0.28]	[0.19,0.21]
A4	[1.31,1.61]	[1.06,1.34]	[0.30,0.35]	[0.10,0.12]	[0.27,0.32]	[0.3,0.35]	[0.30,0.36]	[0.23,0.30]	[0.18,0.19]
A5	[1.58,1.90]	[1.50,1.73]	[0.34,0.41]	[0.11,0.13]	[0.27,0.30]	[0.28,0.34]	[0.35,0.41]	[0.30,0.34]	[0.14,0.14]
A6	[1.72,2.00]	[1.38,1.68]	[0.39,0.45]	[0.13,0.16]	[0.28,0.38]	[0.34,0.40]	[0.40,0.46]	[0.31,0.40]	[0.12,0.11]
A7	[1.46,1.78]	[1.31,1.50]	[0.34,0.36]	[0.11,0.13]	[0.27,0.32]	[0.31,0.37]	[0.35,0.41]	[0.25,0.32]	[0.16,0.17]
A8	[1.57,1.83]	[1.34,1.55]	[0.34,0.38]	[0.10,0.12]	[0.22,0.29]	[0.28,0.34]	[0.37,0.42]	[0.25,0.32]	[0.14,0.14]
A9	[1.09,1.43]	[0.94,1.20]	[0.25,0.29]	[0.08,0.10]	[0.20,0.27]	[0.27,0.32]	[0.25,0.29]	[0.19,0.28]	[0.20,0.21]
A10	[0.86,1.17]	[0.79,1.03]	[0.21,0.24]	[0.07,0.09]	[0.17,0.21]	[0.18,0.23]	[0.21,0.26]	[0.18,0.24]	[0.20,0.21]
A11	[1.00,1.27]	[0.84,1.14]	[0.25,0.27]	[0.08,0.09]	[0.18,0.23]	[0.27,0.31]	[0.21,0.28]	[0.19,0.28]	[0.20,0.21]
BAA (g)	[1.29,1.59]	[1.11,1.37]	[0.30,0.39]	[0.10,0.12]	[0.23,0.29]	[0.28,0.33]	[0.30,0.35]	[0.23,0.30]	[0.17,0.18]

Table 10 — Distances from BAA, final score and ranking of alternatives.

ALT	C1	C2	C3	C4	C5	C6	C7	C8	C9	Final score S(A <sub>i</sub> )	Rank
A1	0.194	0.194	0.015	0.005	0.045	0.039	0.046	0.026	0.005	0.57	5
A2	-0.041	-0.112	-0.002	-0.003	0.031	0.027	-0.030	0.011	-0.026	-0.14	7
A3	-0.153	-0.112	-0.002	-0.003	-0.009	0.003	-0.030	-0.028	-0.036	-0.37	8
A4	0.023	-0.058	0.015	0.005	0.045	0.027	0.011	0.011	-0.018	0.06	6
A5	0.424	0.525	0.081	0.018	0.031	0.003	0.080	0.074	0.048	1.28	2
A6	0.593	0.413	0.144	0.053	0.106	0.089	0.150	0.125	0.081	1.75	1
A7	0.253	0.236	0.047	0.025	0.045	0.052	0.080	0.023	0.007	0.77	4
A8	0.365	0.293	0.063	0.005	-0.012	0.003	0.100	0.023	0.04	0.88	3
A9	-0.265	-0.233	-0.067	-0.016	-0.043	-0.012	-0.077	-0.047	-0.050	-0.81	9
A10	-0.603	-0.467	-0.132	-0.038	-0.100	-0.148	-0.129	-0.079	-0.050	-1.75	11
A11	-0.436	-0.352	-0.085	-0.030	-0.081	-0.027	-0.111	-0.047	-0.050	-1.22	10

expansion coefficient ( $\alpha$ ), thermal conductivity ( $k$ ), thermal diffusivity ( $\mu$ ), fracture toughness ( $K_{Ic}$ ) and other criteria which are mentioned in Table 12.

For the purpose of determining criteria weights, in the similar manner an expert committee was constituted

inviting four experts ( $E_k$ ,  $k=1$  to 4) from relevant domain. Corresponding PWCM has been formed using Saaty's 9-point scale and shown in Table 13.

This initial PWCM has been converted into aggregated rough PWCM using eq. (1-7), subsequently

Table 11 — Comparison of ranking order obtained by various models.

Material code	Name of material	Ranking order				
		Proposed RAHP-RMABAC model	Ranking by Jahan <i>et al.</i> <sup>17</sup>	Ranking by Jahan and Edwards <sup>18</sup>	Ranking by Hafezalkotob and Hafezalkotob <sup>19</sup>	Ranking by Das <i>et al.</i> <sup>20</sup>
A1	Stainless steels 316	5	5	5	5	7
A2	Stainless steels 317	7	7	7	7	4
A3	Stainless steels 321	8	8	8	8	5
A4	Stainless steels 347	6	6	6	6	3
A5	Co-Cr alloys – Cast alloy (1)	2	2	4	4	6
A6	Co-Cr alloys – Wrought alloy (2)	1	1	1	1	1
A7	Unalloyed titanium	4	4	3	3	8
A8	Ti-6Al-4V	3	3	2	2	2
A9	Composites (fabric reinforced)-Epoxy-70% glass	9	9	9	9	9
A10	Composites (fabric reinforced)-Epoxy-63%carbon	11	11	11	11	11
A11	Composites (fabric reinforced)-Epoxy-62%aramid	10	10	10	10	10
Spearman rank correlation coefficient			1.00	0.97273	0.97273	0.70909
Average Spearman rank correlation coefficient			0.9136375			

Table 12 — List of criteria for fuel cell material selection.

Code	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
Expression of criteria	$\frac{E^{1/3}}{\rho}$	$\frac{\sigma_F^{1/3}}{\rho}$	$\frac{\sigma_f}{E\alpha}$	$\frac{\alpha}{k}$	$\frac{k}{\mu^{1/2}}$	$\frac{K_{Ic}^2}{E}$	Resistivity ( $\mu\Omega cm$ )	Cost (CAN\$/ kg)	Corrosion rate (in/year)	Recycle fraction	Hydrogen permeability
Type	Higher-the-better	Higher-the-better	Higher-the-better	Higher-the-better	Higher-the-better	Higher-the-better	Lower-the-better	Lower-the-better	Lower-the-better	Higher-the-better	Lower-the-better

Table 13 — Initial PWCM.

$E_1 =$	1	3	2	1/5	4	1/3	1	1/7	1/7	3	1/5	$E_2 =$	1	3	4	1/3	4	1/4	1	1/6	1/6	3	1/5
	1/3	1	1/4	1/3	1	1/4	1/3	1/7	1/7	2	1/9		1/3	1	1/4	1/3	1	1/4	1/3	1/7	1/9	2	1/7
	1/2	4	1	1/5	2	1/7	1/3	1/7	1/9	3	1/9		1/4	4	1	1/5	2	1/7	1/3	1/7	1/7	3	1/8
	5	3	5	1	3	1	3	1/7	1/7	4	1/5		3	3	5	1	3	1	3	1/7	1/7	4	1/7
	1/4	1	1/2	1/3	1	1/5	1/3	1/5	1/7	2	1/7		1/4	1	1/2	1/3	1	1/5	1/3	1/5	1/7	2	1/7
	3	4	7	1	5	1	3	2	4	1/5	1/3		4	4	7	1	5	1	3	2	4	1/5	1/5
	1	3	3	1/3	3	1/3	1	1/4	4	1/5	1/9		1	3	3	1/3	3	1/3	1	1/4	4	1/5	1/7
	7	7	7	7	5	1/2	4	1	3	1/3	1/7		6	7	7	7	5	1/2	4	1	3	1/3	1/7
	7	7	9	7	7	1/4	1/4	1/3	1	1/3	1/5		6	7	7	7	7	1/4	1/4	1/3	1	1/3	1/7
	1/3	1/2	1/3	1/4	1/2	5	5	3	3	1	1/7		6	9	7	7	7	1/4	1/4	1/3	1	1/3	1/7
	5	9	9	5	7	3	9	7	5	7	1		1/3	1/2	1/3	1/4	1/2	5	5	3	3	1	1/7
											5	7	8	7	7	5	7	7	3	7	1		
$E_3 =$	1	4	2	1/3	3	1	1	1/5	1/5	2	1/7	$E_4 =$	1	2	3	2	4	1/5	1	1/7	1/9	3	1/9
	1/4	1	1/3	1/4	1	1/5	1/3	1/5	1/7	2	1/9		1/2	1	1/5	1/3	1	1/4	1/3	1/8	1/6	2	1/8
	1/2	3	1	1/3	2	1/7	1/5	1/7	1/9	3	1/7		1/3	5	1	1/5	2	1/6	1/3	1/7	1/9	3	1/7
	3	4	3	1	3	1/3	3	1/5	1/5	4	1/3		1/2	3	5	1	3	1	3	1/7	1/7	4	1/7
	1/3	1	1/2	1/3	1	1/7	1/3	1/5	1/7	2	1/5		1/4	1	1/2	1/3	1	1/3	1/3	1/7	1/7	2	1/7
	1	5	7	3	7	1	2	2	4	1/3	1/3		5	4	6	1	3	1	3	2	4	1/5	1/3
	1	3	5	1/3	3	1/2	1	1/3	4	1/5	1/7		1	3	3	1/3	3	1/3	1	1/4	4	1/3	1/7
	5	5	7	5	5	1/2	3	1	3	1/5	1/5		7	8	7	7	7	1/2	4	1	3	1/3	1/9
	5	7	9	5	7	1/4	1/4	1/3	1	1	1/3		9	6	9	7	7	1/4	1/4	1/3	1	1/5	1/7
	1/2	1/2	1/3	1/4	1/2	3	5	5	1	1	1/9		1/3	1/2	1/3	1/4	1/3	5	3	3	5	1	1/5
	7	9	7	3	5	3	7	5	3	9	1		9	8	7	7	7	3	7	9	7	5	1

Note: Saaty's 9-point scale: 1 = very low; 3 = low; 5 = moderate; 7 = high; 9 = very high.

Table 14 — Final rough weights of criteria.

Criteria	Rough weights	Final rough weights (Normalized)	Ranking of criteria
C1	[0.662,0.862]	[0.115,0.150]	8
C2	[0.337,0.375]	[0.059,0.065]	11
C3	[0.438,0.488]	[0.076,0.085]	9
C4	[1.129,1.305]	[0.196,0.227]	5
C5	[0.370,0.393]	[0.064,0.068]	10
C6	[1.692,2.821]	[0.295,0.491]	2
C7	[0.798,0.859]	[0.139,0.150]	7
C8	[1.941,2.147]	[0.338,0.374]	3
C9	[1.297,1.513]	[0.226,0.263]	4
C10	[0.820,0.937]	[0.143,0.163]	6
C11	[4.718,5.744]	[0.821,1.000]	1

rough weight and normalized rough weight have been computed using eq. (14-15). These weights of eleven performance evaluation criteria have been presented in Table 14.

Jahan *et al.*<sup>17</sup> considered 12 alternative materials for making fuel cell. These materials along with the ratings of experts with respect to 11 criteria have been presented in Table 15.

In similar manner, using eq. (1-7) aggregated initial rough decision matrix is constituted from these ratings of the experts. The same is presented in Table 16. Table 16 contains ideal solutions ( $x_j^+$ ,  $x_j^-$ ) as identified using formula (19-20).

Table 15 — Expert opinion based decision matrix.

Alternative materials	Experts	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
A1: 316 austenitic stainless steel	1	8	9	9	8	7	7	6	7	8	9	7
	2	8	9	7	7	7	7	6	7	8	7	7
	3	8	8	7	7	7	6	7	7	7	7	6
	4	9	8	7	7	7	6	7	8	7	7	6
A2: 310 austenitic stainless steel	1	4	6	6	6	7	7	5	5	5	6	7
	2	5	6	5	7	6	6	4	4	5	5	6
	3	6	4	5	5	6	6	4	6	4	5	6
	4	6	5	5	6	5	6	4	7	4	5	6
A3: 317 austenitic stainless steel	1	8	8	7	7	7	7	7	7	8	7	7
	2	8	8	7	7	7	7	7	7	8	7	7
	3	8	7	7	7	7	6	7	7	7	7	6
	4	8	7	8	6	5	6	6	5	7	8	6
A4: 316L austenitic stainless steel	1	9	9	8	9	7	8	8	7	9	8	8
	2	9	9	8	9	7	8	8	7	9	8	8
	3	9	7	9	7	7	8	7	7	9	9	8
	4	9	7	9	9	9	9	7	9	7	9	9
A5: Aluminium (gold plated)	1	3	4	5	4	5	5	4	5	5	5	5
	2	4	4	3	3	5	2	2	4	5	3	2
	3	2	3	3	4	5	3	2	5	3	3	3
	4	2	4	4	5	5	3	3	3	3	4	3
A6: AISI 446 ferritic stainless steel	1	8	8	7	7	7	8	7	7	6	7	8
	2	8	7	7	7	7	8	7	7	6	7	8
	3	7	7	7	8	8	7	6	7	6	7	7
	4	7	7	7	8	7	7	6	5	7	7	7
A7: AISI 436 ferritic stainless steel	1	5	7	7	6	7	7	5	5	5	7	7
	2	6	6	6	7	6	7	5	5	5	6	7
	3	6	5	6	6	7	6	5	6	5	6	6
	4	6	5	6	7	6	6	5	7	5	6	6
A8: AISI 444 ferritic stainless steel	1	8	7	7	6	7	7	6	6	6	7	7
	2	7	7	7	7	7	7	6	6	6	7	7
	3	7	7	6	7	7	8	6	7	7	6	8
	4	7	7	6	7	8	7	6	7	5	6	7
A9: AISI 434 ferritic stainless steel	1	6	7	7	6	7	7	5	5	6	7	7
	2	6	6	6	7	7	7	5	5	5	6	7
	3	7	5	6	6	7	7	5	7	5	6	7
	4	6	5	6	7	7	7	5	7	5	6	7
A10: 304 austenitic stainless steel	1	4	6	5	6	6	6	5	5	5	5	6
	2	5	5	5	6	6	6	4	4	5	5	6
	3	5	3	5	5	6	6	3	6	4	5	6
	4	5	5	5	6	5	6	3	7	4	5	6

(Contd.)

Table 15 — Expert opinion based decision matrix — (Contd.).

Alternative materials	Experts	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
A11: Titanium (coated with nitride)	1	4	5	5	5	6	5	4	5	5	5	5
	2	5	4	4	5	5	3	4	4	5	4	3
	3	3	3	4	5	5	3	3	6	4	4	3
	4	3	5	4	6	5	3	3	5	4	4	3
A12: A560 (50Cr-Ni)	1	7	7	7	6	7	7	6	5	6	7	7
	2	6	7	7	7	7	7	6	5	6	7	7
	3	7	5	6	7	7	7	5	7	5	6	7
	4	6	5	6	7	8	7	5	7	5	6	7

Note: Saaty’s 9-point scale: 1 = very low; 3 = low; 5 = moderate; 7 = high; 9 = very high.

Table 16 — Initial rough decision matrix.

ALT	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
	Max	Max	Max	Max	Max	Max	Min	Min	Min	Max	Min
A1	[8.06,8.44]	[8.25,8.75]	[7.13,7.88]	[7.06,7.44]	[7.00,7.00]	[6.25,6.75]	[6.25,6.75]	[7.06,7.44]	[7.25,7.75]	[7.13,7.88]	[6.25,6.75]
A2	[4.75,5.73]	[4.75,5.73]	[5.06,5.44]	[5.58,6.50]	[5.58,6.50]	[6.06,6.44]	[4.06,4.44]	[4.75,6.25]	[4.25,4.75]	[5.06,5.44]	[6.06,6.44]
A3	[8.00,8.00]	[7.25,7.75]	[7.06,7.44]	[6.56,6.94]	[6.13,6.88]	[6.25,6.75]	[6.56,6.94]	[6.13,6.88]	[7.25,7.75]	[7.06,7.44]	[6.25,6.75]
A4	[9.00,9.00]	[7.50,8.50]	[8.25,8.75]	[8.13,8.88]	[7.38,8.63]	[8.06,8.44]	[7.25,7.75]	[7.38,8.63]	[8.13,8.88]	[8.25,8.75]	[8.06,8.44]
A5	[2.27,3.25]	[3.56,3.94]	[3.27,4.25]	[3.58,4.50]	[5.00,5.00]	[2.65,3.90]	[2.50,3.71]	[3.75,4.73]	[3.50,4.50]	[3.27,4.25]	[2.65,3.90]
A6	[7.25,7.75]	[7.06,7.44]	[7.00,7.00]	[7.25,7.75]	[7.06,7.44]	[7.25,7.75]	[6.25,6.75]	[6.38,6.88]	[6.06,6.44]	[7.00,7.00]	[7.25,7.75]
A7	[5.56,5.94]	[5.27,6.25]	[6.06,6.44]	[6.25,6.75]	[6.25,6.75]	[6.25,6.75]	[5.00,5.00]	[5.27,6.25]	[5.00,5.00]	[6.06,6.44]	[6.25,6.75]
A8	[7.06,7.44]	[7.00,7.00]	[6.25,6.75]	[6.56,6.94]	[7.06,7.44]	[7.06,7.44]	[6.00,6.00]	[6.25,6.75]	[5.58,6.42]	[6.25,6.75]	[7.06,7.44]
A9	[6.06,6.44]	[5.27,6.25]	[6.06,6.44]	[6.25,6.75]	[7.00,7.00]	[7.00,7.00]	[5.00,5.00]	[5.50,6.50]	[5.06,5.44]	[6.06,6.44]	[7.00,7.00]
A10	[4.19,4.81]	[4.10,5.35]	[5.00,5.00]	[5.19,5.81]	[5.19,5.81]	[6.00,6.00]	[3.27,4.25]	[4.75,6.25]	[4.25,4.75]	[5.00,5.00]	[6.00,6.00]
A11	[3.27,4.25]	[3.75,4.73]	[4.06,4.44]	[5.06,5.44]	[5.06,5.44]	[3.13,3.88]	[3.25,3.75]	[4.58,5.42]	[4.25,4.75]	[4.06,4.44]	[3.13,3.88]
A12	[6.25,6.75]	[5.50,6.50]	[6.25,6.75]	[6.56,6.63]	[7.06,7.13]	[7.00,7.00]	[5.25,5.75]	[5.50,6.50]	[5.25,5.75]	[6.25,6.75]	[7.00,7.00]
x+	9	8.75	8.75	8.88	8.63	8.44	2.5	3.75	3.5	8.75	2.65
x-	2.27	3.56	3.27	3.58	5	2.65	7.75	8.63	8.88	3.27	8.44

Table 17 — Distances from BAA, final score and ranking of alternatives.

ALT	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	Final score S(A <sub>i</sub> )	Ranking using proposed method	Ranking by Jahan <i>et al.</i> <sup>17</sup>
A1	0.36	0.17	0.2	0.51	0.15	0.97	0.25	0.64	0.43	0.39	1.72	5.79	3	2
A2	-0.3	-0.1	-0.2	-0.4	-0.1	0.94	-0.3	-0.8	-0.6	-0.3	-1.8	-4	9	9
A3	0.35	0.15	0.2	0.48	-0.1	0.97	0.24	0.72	0.43	0.38	1.72	5.51	5	3
A4	0.38	0.16	0.22	0.58	0.17	1.14	0.21	0.57	0.37	0.43	1.33	5.56	1	1
A5	-0.2	-0.1	-0.1	-0.3	-0.1	-0.7	-0.4	-1	-0.7	-0.2	-2.4	-6.2	12	12
A6	0.34	0.15	0.19	0.52	0.15	1.06	0.25	0.71	0.51	0.36	1.49	5.76	2	4
A7	-0.3	0.13	0.18	0.47	0.13	0.97	0.31	-0.8	-0.6	0.34	1.72	2.55	8	8
A8	0.33	0.15	0.18	0.48	0.15	1.04	0.27	0.72	0.53	0.35	1.55	5.75	4	5
A9	0.3	0.13	0.18	0.47	0.15	1	0.31	-0.8	-0.6	0.34	1.62	3.13	7	7
A10	-0.3	-0.1	-0.2	-0.4	-0.1	0.9	-0.4	-0.8	-0.6	-0.3	-1.8	-4.1	10	10
A11	-0.2	-0.1	-0.1	-0.4	-0.1	-0.7	-0.4	-0.9	-0.6	-0.3	-2.4	-6.2	11	11
A12	0.31	0.13	0.18	0.47	0.15	1	0.29	-0.8	-0.6	0.35	1.62	3.16	6	6

Data presented in Table 16 are normalized using formula (17-18) and weighted normalized rough decision matrix along with BAA is determined using formula (21-22). Euclidean distance of all alternatives from border approximation area (BAA) has been determined using formula (23). Thus distance matrix and final performance score of all alternative including comparative ranking of materials have been determined using formula (24-25). Table 17 shows the same.

**2.6 Material selection for product operating in high temperature environment**

Table 18 shows the list of criteria chosen for selection of material working at high temperature such as cutting tool materials (adopted from the work of Jahan *et al.*<sup>21</sup>) using proposed RAHP-RMABAC.

For the purpose of determining criteria weights, corresponding PWCM has been formed with the help of experts using Saaty’s 9-point scale and shown in Table 19.

Corresponding aggregated rough PWCM, rough weights and final rough weights of four performance evaluation criteria have been presented in Table 20.

As reported by Jahan *et al.*<sup>17</sup> there are 5 alternative materials for making the product operating at high temperature. These materials along with the ratings of

Table 18 — List of criteria for selecting material working at high temperature.

Code	Name of criterion	Type
C1	Tensile strength (MPa)	Higher-the-better
C2	Young's modulus (GPa)	Higher-the-better
C3	Density (gm/cm <sup>3</sup> )	Lower-the-better
C4	Corrosion resistance	Higher-the-better

Table 19 — Initial PWCM

$$E_1 = \begin{bmatrix} 1 & 2/3 & 1/3 & 5 \\ 3/2 & 1 & 2/3 & 3 \\ 3 & 3/2 & 1 & 7 \\ 1/5 & 1/3 & 1/7 & 1 \end{bmatrix}$$

$$E_2 = \begin{bmatrix} 1 & 1/3 & 2/3 & 7 \\ 3 & 1 & 2/3 & 5 \\ 3/2 & 3/2 & 1 & 9 \\ 1/7 & 1/5 & 1/9 & 1 \end{bmatrix}$$

$$E_3 = \begin{bmatrix} 1 & 1/3 & 2/3 & 7 \\ 3 & 1 & 2/3 & 5 \\ 3/2 & 3/2 & 1 & 9 \\ 1/7 & 1/5 & 1/9 & 1 \end{bmatrix}$$

$$E_4 = \begin{bmatrix} 1 & 1/3 & 1/3 & 7 \\ 3 & 1 & 1/3 & 5 \\ 3 & 3 & 1 & 7 \\ 1/7 & 1/5 & 1/7 & 1 \end{bmatrix}$$

Note: Saaty's 9-point scale: 1 = very low; 3 = low; 5 = moderate; 7 = high; 9 = very high.

experts with respect to 4 criteria have been presented in Table 21.

Data presented in Table 21 are normalized using formula (17-18) and weighted normalized rough decision matrix along with BAA is determined using formula (21-22). Euclidean distance of all alternatives from border approximation area (BAA) has been determined using formula (23). Thus distance matrix and final performance score of all alternative including comparative ranking of materials have been determined using formula (24-25) and shown in Table 22.

**2.7 Material selection for sailing boat mast**

There are 15 alternative materials (A1-A15) and four performance evaluation criteria which were addressed earlier by Jahan *et al.*<sup>17</sup>. The list of criteria and the ratings given by experts have been shown in Table 23 and 24 respectively.

Corresponding aggregated rough PWCM, rough weights and final rough weights of four performance evaluation criteria have been presented in Table 25.

These materials along with the ratings of experts with respect to 4 criteria have been presented in Table 26 & 27.

Table 20 — Aggregated PWCM and RAHP weights of criteria.

Criteria	C1	C2	C3	C4	Rough weights	Final rough weights (Normalized)	Ranking of criteria
C1	[1.00,1.00]	[0.35,0.48]	[0.42,0.63]	[6.13,6.88]	[0.97,1.20]	[0.37,0.46]	3
C2	[2.35,2.91]	[1.00,1.00]	[0.52,0.67]	[4.13,4.88]	[1.50,1.76]	[0.57,0.67]	2
C3	[1.88,2.63]	[1.59,2.16]	[1.00,1.00]	[7.50,8.50]	[2.18,2.63]	[0.83,1.00]	1
C4	[0.14,0.17]	[0.21,0.26]	[0.12,0.14]	[1.00,1.00]	[0.24,0.28]	[0.09,0.11]	4

Table 21 — Expert opinion based decision matrix.

Alternative materials	Experts	C1	C2	C3	C4
A1	1	8	8	7	7
	2	8	8	7	7
	3	8	7	7	7
	4	8	7	8	6
A2	1	8	9	9	8
	2	8	9	7	7
	3	8	8	7	7
	4	9	8	7	7
A3	1	8	7	7	6
	2	7	7	7	7
	3	7	7	6	7
	4	7	7	6	7
A4	1	8	8	7	7
	2	8	7	7	7
	3	7	7	7	8
	4	7	7	7	8
A5	1	9	9	8	9
	2	9	9	8	9
	3	9	7	9	7
	4	9	7	9	9

Note: Saaty's 9-point scale: 1 = very low; 3 = low; 5 = moderate; 7 = high; 9 = very high.

Table 22 — Distances from BAA, final score and ranking of alternatives.

Alternatives	C1	C2	C3	C4	Final score $S(A_i)$	Ranking using proposed method	Ranking by Jahan <i>et al.</i> <sup>17</sup>
A1	0.044	-0.044	-0.091	-0.03	-0.12424	3	3
A2	0.099	0.46	0.097	-0	0.652882	2	2
A3	-0.205	-0.329	-0.472	-0.03	-1.03907	5	5
A4	-0.129	-0.172	-0.263	0.013	-0.55023	4	4
A5	0.317	0.268	0.566	0.075	1.22585	1	1

Table 23 — List of criteria for selecting material of sailing boat mast.

Code	Name of criterion	Type
C1	Specific strength (MPa)	Higher-the-better
C2	Specific modulus (GPa)	Higher-the-better
C3	Corrosion resistance	Higher-the-better
C4	Cost category	Lower-the-better

Table 24 — Initial PWCM.

$$E_1 = \begin{bmatrix} 1 & 2/3 & 7 & 5 \\ 3/2 & 1 & 7 & 7 \\ 1/7 & 1/7 & 1 & 3 \\ 1/5 & 1/7 & 1/3 & 1 \end{bmatrix}$$

$$E_2 = \begin{bmatrix} 1 & 1 & 5 & 7 \\ 1 & 1 & 5 & 5 \\ 1/5 & 1/5 & 1 & 3 \\ 1/7 & 1/5 & 1/3 & 1 \end{bmatrix}$$

$$E_3 = \begin{bmatrix} 1 & 1/3 & 7 & 7 \\ 3 & 1 & 9 & 7 \\ 1/7 & 1/9 & 1 & 9 \\ 1/7 & 1/7 & 1/9 & 1 \end{bmatrix}$$

$$E_4 = \begin{bmatrix} 1 & 2/3 & 5 & 5 \\ 3/2 & 1 & 7 & 3 \\ 1/5 & 1/7 & 1 & 3 \\ 1/5 & 1/3 & 1/3 & 1 \end{bmatrix}$$

Note: Saaty's 9-point scale: 1 = very low; 3 = low; 5 = moderate; 7 = high; 9 = very high.

Table 25 — Aggregated PWCM and RAHP weights of criteria.

Criteria	C1	C2	C3	C4	Rough weights	Final rough weights (Normalized)	Ranking of criteria
C1	[1.00,1.00]	[0.53,0.81]	[5.50,6.50]	[5.50,6.50]	[1.20,2.42]	[0.47,0.57]	2
C2	[1.35,2.19]	[1.00,1.00]	[6.17,7.83]	[4.50,18.83]	[2.48,4.24]	[0.58,1.00]	1
C3	[0.16,1.09]	[0.13,0.17]	[1.00,1.00]	[3.38,5.63]	[0.51,1.01]	[0.12,0.24]	3
C4	[3.62,0.19]	[0.17,0.25]	[0.24,0.32]	[1.00,1.00]	[0.62,0.35]	[0.15,0.08]	4

Table 26 — Expert opinion based decision matrix

Alternative materials	Experts	C1	C2	C3	C4
A1: AISI 1020	1	3	4	5	4
	2	4	4	3	3
	3	2	3	3	4
	4	2	4	4	5
A2: AISI 1040	1	7	7	7	6
	2	6	7	7	7
	3	7	5	6	7
	4	6	5	6	7
A3: ASTM A242 type 1	1	4	6	6	6
	2	5	6	5	7
	3	6	4	5	5
	4	6	5	5	6
A4: AISI 4130	1	8	7	7	6
	2	7	7	7	7
	3	7	7	6	7
	4	7	7	6	7
A5: AISI 316	1	3	4	3	3
	2	3	3	3	3
	3	2	2	3	4
	4	2	2	3	4
A6: AISI 416 heat treated	1	3	4	4	3
	2	3	3	3	3
	3	2	3	3	4
	4	2	3	4	4

(Contd.)

Table 26 — Expert opinion based decision matrix — (Contd.).

Alternative materials	Experts	C1	C2	C3	C4
A7: AISI 431 heat treated	1	4	5	5	5
	2	5	4	4	5
	3	3	3	4	5
	4	3	5	4	6
A8: AA 6061 T6	1	3	4	4	3
	2	4	4	3	3
	3	2	3	3	4
	4	2	4	4	4
A9: AA 2024 T6	1	5	7	7	6
	2	6	6	6	7
	3	6	5	6	6
	4	6	5	6	7
A10: AA 2014 T6	1	4	6	5	6
	2	5	5	5	6
	3	5	3	5	5
	4	5	5	5	6
A11: AA 7075 T6	1	8	8	7	7
	2	8	8	7	7
	3	8	7	7	7
	4	8	7	8	6
A12: Ti-6Al-4V	1	6	7	7	6
	2	6	6	6	7
	3	7	5	6	6
	4	6	5	6	7
A13: Epoxy-70% glass fabric	1	8	9	9	8
	2	8	9	7	7
	3	8	8	7	7
	4	9	8	7	7
A14: Epoxy-63% carbon fabric	1	9	9	8	9
	2	9	9	8	9
	3	9	7	9	7
	4	9	7	9	9
A15: Epoxy-62% aramid fabric	1	8	8	7	7
	2	8	7	7	7
	3	7	7	7	8
	4	7	7	7	8

Note: Saaty's 9-point scale: 1 = very low; 3 = low; 5 = moderate; 7 = high; 9 = very high.

Table 27 — Distances from BAA, final score and ranking of alternatives.

Alternatives	C1	C2	C3	C4	Final score S(A <sub>i</sub> )	Ranking using proposed method	Ranking by Jahan <i>et al.</i> <sup>17</sup>
A1	-0.27	-0.31265	-0.07043	-0.05244	-0.70548	12	12
A2	0.136	0.120053	0.05062	0.031169	0.337838	6	6
A3	-0.021	-0.02702	-0.00898	0.008897	-0.04774	9	9
A4	0.2172	0.259287	0.05062	0.032877	0.559955	5	4
A5	-0.303	-0.46221	-0.11845	-0.06516	-0.94852	15	15
A6	-0.303	-0.40175	-0.08824	-0.06516	-0.85786	14	14
A7	-0.161	-0.19837	-0.05523	-0.01213	-0.42659	11	11
A8	-0.27	-0.31265	-0.08824	-0.06516	-0.73601	13	13
A9	0.0538	0.076957	0.037325	0.024383	0.192416	8	8
A10	-0.082	-0.1061	-0.02678	-0.00654	-0.22153	10	10
A11	0.297	0.364769	0.083596	0.032877	0.778212	3	5
A12	0.1079	0.076957	0.037325	0.024383	0.246541	7	7
A13	0.3267	0.54337	0.100479	0.047779	1.018325	2	2
A14	0.4061	0.476128	0.143152	0.08217	1.107584	1	1
A15	0.2456	0.315364	0.067347	0.054226	0.682524	4	3

Like earlier examples, the distance matrix and final performance score of all alternative including comparative ranking of materials have been determined.

### 3 Results and Discussion

Comparative ranking obtained using various models for hip joint material selection presented in Table 11 shows that various sets of ranking obtained by using various models are strongly correlated. The Spearman's rank correlation coefficient test indicates that on an average there exists 91% agreement in ranking between the proposed RAHP-RMABAC method and other MCDM methods. The alternative material Co–Cr alloys – Wrought alloy (2), coded as A6 declared as best and Composites (fabric reinforced)-Epoxy-63% carbon (A10) as least performer by all the models. Similarly for remaining three other material selection examples namely for making fuel cell, product operating at high temperature and sailing boat mast, ranking obtained by proposed RAHP-RMABAC model remains almost same with ranking obtained by Jahan *et al.*<sup>17</sup>. The specific advantages of proposed model are (i) it can handle decision making process in vague and imprecise environment, (ii) it is easy and simple to implement, (iii) degree of consistency and robustness are high.

### 4 Conclusion

The paper proposes an integrated model comprising of analytic hierarchy process and multi attribute boarder approximation area comparison method in rough environment (RAHP-RMABAC). The model explore and exploits the wisdom of experts in specific domain to deal with vagueness, imprecision and approximation involved in the decision making process. The efficacy and robustness of the proposed model has been illustrated through four material selection problems already addressed by Jahan *et al.*<sup>17</sup>. With the introduction of Industry 4.0, stakeholders of any process wants customized product with minimum response time, high accuracy and at an economical price. The beauty of the proposed model is that it can help decision making in the background of manufacturing process where vagueness and imprecision exist. The best materials as identified by the proposed model are (i) Co–Cr alloys – Wrought alloy (2) for making hip joint, (ii) 316L austenitic stainless steel for fuel cell, (iii) the fifth alternative for

product operating at high temperature and (iv) Epoxy-63% carbon fabric as the material for sailing boat mast. The agreement of the result with earlier works corroborates and validates the usefulness of the proposed method in vague, imprecise and approximate environment.

### Acknowledgement

Authors express their sincere gratitude to the anonymous reviewers and editor of this journal for their suggestions to improve the overall quality of the paper.

### References

- 1 Saaty T L, *Eur J Oper Res*, 48 (1990) 9.
- 2 Saaty T L, *Decision Making with Dependence and Feedback: The Analytic Network Process*, (RWS Publications, Pittsburgh) ISBN 0962031798, 1996, p.26.
- 3 Hwang C L, Lai Y J & Liu T Y, *Comput Oper Res*, 20 (1993) 889.
- 4 Opricovic S & Tzeng G, *Eur J Oper Res*, 178 (2007) 514.
- 5 Roy B, *Rev Fr Inf Rech Opér*, 8 (1968) 57.
- 6 Salvador G, Moura M, Campos P, Cardoso P, Espadinha-Cruz P & Godina R, *Procedia Comput Sci*, 232 (2024) 1759.
- 7 Nath S & Sarkar B, *J Inst Eng India Ser C*, 101 (2020) 473.
- 8 Nath S & Sarkar B, *J Inst Eng India Ser C*, 101(2020) 25.
- 9 Sasikumar G & Ayyappan S, *J Inst Eng India Ser C*, 100 (2019) 707.
- 10 Samant M R, Krisna S K, Khishorre K R & Sreeharan B N, *Mater Today: Proc*, 68 (2022) 2249.
- 11 Shoji D, Ogwezi B & Li V C, *Construc Build Mater*, 349 (2022) 128710.
- 12 Soni A, Chakraborty S, Das P K & Saha A K, *Construc Build Mater*, 348 (2022) 128608.
- 13 Tong G, Chen Q & Xu H, *Sustain Energy Technol Assess*, 50 (2022) 101833.
- 14 Malaga A K, Agrawal R & Wankhede V A, *Mater Today: Proc*, 66 (2022) 1744.
- 15 Nicolalde J F, Cabrera M, Martínez-Gómez J, Salazar R B & Reyes E, *J Energy Storage*, 51 (2022) 104437.
- 16 Guo Y, Xie J, Fan Z, Markine V, Connolly D P & Jing G, *Const Build Mater*, 344 (2022) 128218.
- 17 Jahan A, Mustapha F, Ismail M Y, Sapuan S M & Bahraminasab M, *Mater Des*, 32 (2011) 1215.
- 18 Jahan A & Edwards K L, *Mater Des*, 49 (2013) 1000.
- 19 Hafezalkotob A & Hafezalkotob A, *Mater Des*, 87 (2015) 949.
- 20 Das M C & Sarkar B, *J Inst Eng (India): Series C*, 102 (2021) 1211.
- 21 Khalid R, Jayamani E, Soon K, PVS H P, Jeyanthi S & Sankar R R, *Mater Today: Proc*, 62 (2022) 6857.
- 22 Jha M K, Gupta S, Chaudhary V & Gupta P, *Mater Today: Proc*, 62 (2022) 1452.
- 23 Pesode P, Barve S, Wankhede S V, Jadhav D R & Pawar S K, *Mater Today: Proc*, 72 (2023) 724.
- 24 Hashmi M P, Koester T M, Droege H R, Best P D & Loughrin M R, *Encyclopedia Smart Mater*, 1 (2018) 176.

- 25 Chandra G & Pandey A, *Irbm*, 43 (2022) 229.
- 26 Maghsoodi A I, Soudian S, Martínez L, Herrera-Viedma E & Zavadskas E K, *Appl Soft Comput*, 95 (2020) 106508.
- 27 Chen Z S, Martinez L, Chang J P, Wang X J, Xionge S H & Chin K S, *Eng Appl Artificial Intel*, 85 (2019) 783.
- 28 Ijadi Maghsoodi A, Ijadi Maghsoodi A, Poursoltan P, Antucheviciene J & Turskis Z, *Arch Civil Mech Eng*, 19 (2019) 1194.
- 29 Haq R S U, Saeed M, Mateen N, Siddiqui F, Naqvi M, Yi J B Ahmed S, *Appl Soft Comput*, 128 (2022) 109546.
- 30 Kirişçi M, Demir I & Şimşek N, *Arti Intel Med*, 127 (2022) 102278.
- 31 Pawlak Z, *Int J comput Info Sci*, 11 (1982) 341.
- 32 Zhai L Y, Khoo L P & Zhong Z W, *Int J Adv Manuf Technol*, 37 (2008) 613.
- 33 Zhai L Y, Khoo L P & Zhong Z W, *Adv Eng*, 23 (2009) 222.