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APPLYING COCOSO, MABAC, MAIRCA, EAMR, TOPSIS AND WEIGHT DETERMINATION METHODS FOR MULTI-CRITERIA DECISION MAKING IN HOLE TURNING PROCESS

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Abstract: The ranking of solutions to determine the best one among many solutions is always the setting goal for all activities of all fields in general and in the turning process in particular. When a solution is evaluated by multiple criteria, this is known as "Multi-Criteria Decision Making - MCDM". Many MCDM methods were proposed by scientists, however, the ranked results of the solutions are not the same. In addition, the ranked results of the solutions also depend on the weighting methods of the criteria. In this study, the ranking of the solutions in the hole turning process was performed by different MCDM methods and with different weighting methods. Five MCDM methods were mentioned in this study including COCOSO, MABAC, MAIRCA, EAMR, and TOPSIS. In this study, five weighting methods were also used including MEREC weight, EQUAl weight, ROC weight, RS weight, and FUCOM weight. The combination of MCDM and weighting methods creates twenty-five ranking results of the solutions. It is interesting to note that all twenty-five ranking results determine the same best solution. The stability in ranking the solutions by MCDM methods was also discussed in this study. From the obtained results, several recommendations were drawn. Some issues that have not been solved in this study and need to be done in near future are also mentioned in the last section of this study.

Keywords: MCDM, COCOSO, MABAC, MAIRCA, EAMR, TOPSIS, FUCOM, Hole turning

1 INTRODUCTION

Up to now, the number of MCDM methods proposed by scientists is increasing, possibly up to several tens of methods. How to perform the ranking of alternatives in each MCDM method is different [1]. This causes confusion in the choice of MCDM method for decision makers. One method that has performed in several studies to solve this problem is comparing the effectiveness of MCDM methods in specific cases. However, comparing the effectiveness of all MCDM methods in one study seems impossible. Instead, in each study, it is common to only compare the effectiveness of several MCDM methods.

The COCOSO method was found in 2019 [2]. This method has been applied to multi-criteria decision making for many problems such as evaluation of the efficiency of private companies in power production [3], selection of materials for construction activities [4]. The COCOSO method has also applied to determine the best solution as the MARCOS, WSPAS, ARAS, TOPSIS, and EDAS methods in the selecting a medical waste treatment solution [5]. This method also has the same accuracy as COPRAS method when using to select the suppliers for construction Company in Madrid [6]. Three methods including COCOSO, TOPSIS, and CODAS together determine the best solution to minimize the financial risks in enterprises [7]. Five methods including COCOSO, MOORA, ARAS, WASPAS, and COPRAS together determine the best solution in choosing the transport company for the enterprises [8], ect.

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The MABAC method was proposed in 2015 [9] and has been used in many applications such as evaluating the economic efficiency of companies in Serbia [10], selecting the anti-flooding method of the Arilje city in Serbia [11], selecting the medicine suppliers during the Covid 19 epidemic [12], ect. Two methods MABAC and TOPSIS both determine a best solution in a transport operation [13]. When selecting the Mobile Crowd Computing, MABAC shows it to be more efficient than EDAS, ARAS, COPRAS, and MARCOS methods [14]. MABAC also determined the best solution like TOPSIS, COPRAS, and EDAS in choosing a solution to manage the construction projects [15]. When slecting the station of a railway line in a transport operation in Serbia, MABAC method has also accurate as the ELECTER and TOPSIS methods [16], ect.

The MAIRCA method was proposed in 2018 [17]. This method has also been applied to multi-criteria decision making in many different fields. Evaluation of the effectiveness of mergers/acquisitions of companies in Turkey [18]. Evaluation of the sustainable economic development of some countries [19]. This method also determined the best solution like the MABAC, VIKOR, and CODAS methods in selecting the city and the work for immigrants to Chile [20], ect.

The EAMR method was first introduced in 2016 [21]. Several studies apply this method to make multi-criteria decisions such as selecting the units to hire for logistic activities [22]; selecting the contract type of health care services [23]; deciding the order quantity for each supplier to ensure environmental criteria [24], ect.

TOPSIS is considered using as the most commonly method in MCDM methods [25-27]. This method has been applied to rank the solutions in many different fields. Only in the mechanical machining field, it also shows that many studies have applied this method. Many studies have been performed to compare TOPSIS with other methods and confirmed that TOPSIS is equivalent to SAW, WASPAS, VIKOR, MOORA, COPRAS, and PIV methods when making the multi-criteria decision in turning process of 150Cr14 steel [28]; TOPSIS is equivalent to MAIRCA, EAMR, and MARCOS methods when making the multi-criteria decision in turning process of SKS3 steel [29]; TOPSIS is equivalent to the EDAS, MARCOS, MOORA, and PIV methods for multi-criteria decision-making in milling process of SB410 steel [30]; TOPSIS is equivalent to MARCOS, EAMR, and MAIRCA methods when making the multi-criteria decision in hole grinding process of SKD11 steel [31]; TOPSIS is equivalent to MARCOS and MAIRCA for multi-criteria decision-making in electrical impulse process of 90CrSi materials [32]; TOPSIS is equivalent to COPRAS when ranking the solutions in drilling process of AZ91 magnesium [33], ect.

From the analysis of the above relevant references, it shows that:

- COCOSO, MABAC, MAIRCA, EAMR, and TOPSIS methods have been used for multi-criteria decision making in various fields. Comparisons of several of these five methods have been performed in several studies. However, there has been not any study that was conducted to compare all five methods. This gap was the first reason for performing this study.
- COCOSO and MABAC methods have been used for multi-criteria decision making in many different fields, but the application of these two methods in multi-criteria decision-making in general mechanical machining and hole turning process in particular has not been mentioned. This is the second reason for the authors to conduct this study.

In addition to depending on the MCDM methods, the ranking results of the solutions also depend on the determination methods of the weights for the criteria [1, 34, 35]. Along with the appearance of MCDM methods, the weight determination methods for the criteria have also been proposed by many scholars. From the eight commonly methods in determining the weights for the criteria, they can be grouped as shown in Table 1.

Table 1. Characteristics of the weight determination groups

Group	Characteristics	Common method
Group 1	Determine the weights for the criteria based on the values of the criteria in the solutions	MEREC weight and ENTROPY weight
Group 2	The weights of the criteria are selected the same.	EQUAl weight
Group 3	The weight of the criteria depends on the order in arrangement of the criteria.	ROC weight and RS weight;
Group 4	The weight of the criteria depends on the priority of the decision maker for each criterion and satisfy certain conditions.	FUCOM weight, AHP weight, and BWM weight.

So, with the four groups of weighting methods as presented in Table 1, the characteristics of each method group are very different, so the weights of the criteria are also different when determining by different method groups. In order to have the firm confidence in the decision results, it should be choosed more than one method of determining the weights. This is the third reason that motivated the authors to carry out this study. The MEREC weight method (first group) was used in this study. This is a high accurate method and is recommended in using [29, 31, 32]. When applied this method, it also gives the same ranking results as the ENTROPY weight method [29, 31, 32]. In the second group, there was only the EQUAl weight method, so it was also used in this study. In the third group, there are two methods (ROC weight and RS weight). Although belonging to the same group, the weights of the criteria determined by these two methods are very different. In the weight calculation section in the next sections of this paper, it wil be described more clearly about this statement. Therefore, both methods are also used together in this study. The three methods in four group have similar accuracy [36]. However, the number of calculation steps of the FUCOM weight method is much less than that of two methods including AHP weight and BWM weight [36]. Therefore, in this study, only the FUCOM weight method was used.

Turning process is considered the most common method in machining processes. Turning workload is about 40% of total machining workload. In a mechanical processing workshop, the lathe group is about 25 to 35% of the total number of machines [37, 38]. Hole turning process is widely used in both roughing and finishing. This method is especially effective when machining holes with non-standard diameter sizes, when drilling - boring - reaming methods are difficult to perform. Compared with grinding process, hole turning also has outstanding advantages such as high universality, creating compressive residual stress - which has the effect of improving the fatigue strength of the parts. Meanwhile, if the grinding method is used, the residual stress on the surface of the part is usually the tensile residual stress, which is a major limitation of the grinding method [39, 40]. As most other cutting methods, the criteria for evaluating the hole turning process often do not simultaneously achieve the setting goals. For example, if having a small surface roughness, the feed rate needs to be reduced, but when reducing the feed rate, it makes the machining productivity low. Similarly, to reduce surface roughness, it is necessary to process with high cutting velocity, but when the cutting velocity increases, the vibration level of the workpiece will increase, which will increase the roundness deviation of the hole, etc. Therefore, in order to simultaneously ensure the goals for the criteria, the multi-criteria decision making is necessary.

From the above analysis, in this study, five MCDM methods including COCOSO, MABAC, MAIRCA, EAMR, and TOPSIS and five weight determination methods including MEREC weight, EQUAl weight, ROC weight, RS weight, and FUCOM weight were used for multi-criteria decision-making in the hole turning process. The next sections of this paper include the steps to rank the solutions according to MCDM methods; the steps to determine the weights

according to different methods; conducting the experimental process in hole turning process; multi-criteria decision-making process; discuss the achieved results; conclusions, and finally about the future research directions.

2 MULTI-CRITERIA DECISION MAKING METHODS

2.1 COCOSO method

Performing the ranking the solutions according the COCOSO method including following steps [2]:

Step 1. Creating a decision matrix as presented in Table 2.

Table 2. Decision matrix

No.	C_1	C_2	C_j	C_n
A_1	y_{11}	y_{12}	y_{1j}	y_{1n}
A_2	y_{21}	y_{22}	y_{2j}	y_{2n}
A_i	y_{i1}	y_{i2}	y_{ij}	y_{in}
A_m	y_{m1}	y_{m2}	y_{mj}	y_{mn}

where m is the number of solutions, n is number of the criteria. A_i presents the solution i, C_j presents the criterion j. y_{ij} the value of criterion j at the solution i, with $i = 1 \div m, j = 1 \div n$.

The C_j criterion can be of the same type, as large as better, or as small as better, and can also be of both.

Step 2. Normalize the data according to the following two equations.

$$n_{ij} = \frac{y_{ij} - \min y_{ij}}{\max y_{ij} - \min y_{ij}} \quad \text{For criterion as large as better.} \tag{1}$$

$$n_{ij} = \frac{\max y_{ij} - y_{ij}}{\max y_{ij} - \min y_{ij}} \quad \text{For criterion as small as better.} \tag{2}$$

Step 3. Calculating the values of S_i and P_i by Eq. (3), Eq. (4).

$$S_i = \sum_{j=1}^{n} w_j . n_{ij} \tag{3}$$

$$P_i = \sum_{j=1}^{n} (n_{ij})^{w_j} \tag{4}$$

where w_j is weight of criterion j.

Step 4. Calculating the values of k_{ia}, k_{ib}, and k_{ic} by Eq. (5), Eq. (6), and Eq. (7).

$$k_{ia} = \frac{P_i + S_i}{\sum_{i=1}^{m} (P_i + S_i)} \tag{5}$$

$$k_{ib} = \frac{S_i}{\min S_i} + \frac{P_i}{\min P_i} \tag{6}$$

$$k_{ic} = \frac{\lambda . S_i + (1-\lambda) P_i}{\lambda . \max S_i + (1-\lambda) \max P_i}; 0 \le \lambda \le 1 \tag{7}$$

Step 5. Calculating the value of k_i by Eq. (8).

$$k_i = (k_{ia}.k_{ib}.k_{ic})^{1/3} + \frac{1}{3}(k_{iaa} + k_{ib} + k_{ic}) \quad (8)$$

Step 6. Ranking the solutions according to the principle that the one with the largest k_i is the best one.

2.2 MABAC methods

According to the MABAC, the ranking process are performed by following steps [9].

Step 1. The same the step 1 of COCOSO method.

Step 2. The same the step 2 of COCOSO method.

Step 3. Calculating the normalized values with the contributing of the weights by Eq. (9).

$$v_{ij} = w_j(n_{ij} + 1) \quad (9)$$

Step 4. Calculating the value of g_j by Eq. (10).

$$g_j = \left(\prod_{i=1}^{m} v_{ij}\right)^{1/m} \quad (10)$$

Step 5. Calculating the value of q_{ij} by Eq. (11).

$$q_{ij} = v_{ij} - g_j \quad (11)$$

Step 6. Calculating the value of S_i by Eq. (12).

$$S_i = \sum_{j=1}^{n} q_{ij} \quad (12)$$

Step 7. Ranking the solutions according to the principle that the one with the largest S_i is the best one.

2.3 MAIRCA method

According to the MAIRCA, the ranking process are performed by following steps [17].

Step 1. The same the step 1 of COCOSO method.

Step 2. Calculating the value of P_{Aj} by Eq. (13).

$$P_{A_j} = \frac{1}{m}, j = 1, 2, \ldots, n \quad (13)$$

Step 3. Calculating the value of t_{p_j} by Eq. (14).

$$t_{p_j} = P_{A_j} \cdot w_j, j = 1, 2, \ldots, n \quad (14)$$

Step 4. Calculating the value of $t_{r_{ij}}$ by Eq. (15) and Eq. (16).

$$t_{r_{ij}} = t_{p_{ij}} \cdot \left(\frac{y_{ij} - \min y_{ij}}{max y_{ij} - \min y_{ij}}\right) \quad \text{For criterion as large as better.} \quad (15)$$

$$t_{r_{ij}} = t_{p_{ij}} \cdot \left(\frac{y_{ij} - \max y_{ij}}{min y_{ij} - \max y_{ij}}\right) \quad \text{For criterion as small as better.} \quad (16)$$

Step 5. Calculating the value of g_{ij} by Eq. (17).

$$g_{ij} = t_{p_{ij}} - t_{r_{ij}} \tag{17}$$

Step 6. Calculating the value of g_j by Eq. (18).

$$Q_i = \left|\sum_{i=1}^{m} g_{ij}\right| \tag{18}$$

Step 7. Ranking the solutions according to the principle that the one with the largest Q_i is the best one.

2.4 EAMR method

EAMR method are performed to rank the solutions by the following steps [21]:

Step 1. The same the step 1 of COCOSO method.

Step 2. Normalize the data by Eq. (19).

$$n_{ij} = \frac{y_{ij}}{\max y_{ij}} \tag{19}$$

Step 3. Calculating the normalized values with the contributing of the weights by Eq. (20).

$$v_{ij} = n_{ij} \cdot w_j \tag{20}$$

Step 4. Calculating the normalized points for the criteria.

$$G_i^+ = v_{i1}^+ + v_{i2}^+ + \cdots + v_{im}^+ \quad \text{For criterion as large as better.} \tag{21}$$

$$G_i^- = v_{i1}^- + v_{i2}^- + \cdots + v_{im}^- \quad \text{For criterion as small as better.} \tag{22}$$

Step 5. Calculating the value of S_i by Eq. (23):

$$S_i = \frac{G_i^+}{G_i^-} \tag{23}$$

Step 6. Ranking the solutions according to the principle that the one with the largest S_i is the best one.

2.5 TOPSIS method

Ranking the solutions using TOPSIS method includes the following steps [41]:

Step 1. The same the step 1 of COCOSO method.

Step 2. Determine the normalized values by Eq. (24).

$$n_{ij} = \frac{y_{ij}}{\sqrt{\sum_{i=1}^{n} y_{ij}^2}} \tag{24}$$

Step 3. Calculating the normalized values with the contributing of the weights by Eq. (25)

$$Y = w_j . n_{ij} \quad (25)$$

Step 4. Determine the best solution A^+ and the worst solution A^- for the criteria by Eq. (26) and Eq. (27).

$$A^+ = \{y_1^+, y_2^+, \dots, y_j^+, \dots, y_n^+\} \quad (26)$$

$$A^- = \{y_1^-, y_2^-, \dots, y_j^-, \dots, y_n^-\} \quad (27)$$

where y_j^+ and y_j^- are the the best value and the worst value of the normalized values with the contributing of the weights for criteron *j*, respectively.

Step 5. Determine the values of S_i^+ and S_i^- by Eq. (28) and Eq. (29).

$$S_i^+ = \sqrt{\sum_{j=1}^{n} \left(y_{ij} - y_j^+\right)^2} \qquad i = 1, 2, \dots, m \quad (28)$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} \left(y_{ij} - y_j^-\right)^2} \qquad i = 1, 2, \dots, m \quad (29)$$

Step 6. Determine the value C_i^* by Eq. (30).

$$\boldsymbol{C_i^*} = \frac{S_i^-}{S_i^+ + S_i^-} \qquad \text{i = 1, 2, …, m; } 0 \le C_i^* \le 1 \quad (30)$$

Step 7. Ranking the solutions according to the principle that the one with the largest C_i^* is the best one.

3 WEIGHT DETERMINATION METHODS

3.1 MEREC weight

MEREC weight is calculated according to the following steps [42]:

Step 1. The same the step 1 of COCOSO method.

Step 2. Calculating the normalized values by Eq. (31) and Eq. (32).

$$n_{ij} = \frac{min y_{ij}}{y_{ij}} \qquad \text{For criterion as large as better.} \quad (31)$$

$$n_{ij} = \frac{y_{ij}}{max\ y_{ij}} \qquad \text{For criterion as small as better.} \quad (32)$$

Step 3. Calculating the value S_i by Eq. (33).

$$S_i = Ln\left[1 + \left(\frac{1}{n}\sum_{j}^{n} \left|ln\left(n_{ij}\right)\right|\right)\right] \quad (33)$$

Step 4. Calculating the value S'_{ij} by E. (34).

$$S'_{ij} = Ln\left[1 + \left(\frac{1}{n}\sum_{k,k\neq j}^{n} \left|ln\left(n_{ij}\right)\right|\right)\right] \quad (34)$$

Step 5. Calculating the value E_j by Eq. (35).

$$E_j = \sum_{i}^{m} \left| S'_{ij} - S_i \right| \quad (35)$$

Step 6. Calculating the weights for the criteria by Eq. (36).

$$w_j = \frac{E_j}{\sum_k^m E_k} \quad (36)$$

3.2 EQUAL weight

According to the QUAL weight method, the weights are calculated by Eq. (37) [43].

$$w_j = \frac{1}{n}, j = 1, 2, \ldots, n \quad (37)$$

3.3 ROC weight

According to the ROC weight method, the weights are calculated by Eq. (38) [44].

$$w_j = \frac{1}{n}\sum_{k=i}^{n} \frac{1}{k}, j = 1, 2, \ldots, n \quad (38)$$

3.4 RS weight

According to the RS weight method, the weights are calculated by Eq. (39) [44].

$$w_j = \frac{2\,(n+1-i)}{n(n+1)}, j = 1, 2, \ldots, n \quad (39)$$

3.5 FUCOM weight

According to the FUCOM weight method, the weights are calculated by the following steps [36, 45]:

Step 1. From the set of criteria of the solutions $C = \{C_1, C_2, \ldots, C_n\}$, performing the arranging process of the criteria in order of priority. The expected criterion with the largest weight is ranked the first.

$$C_{j(1)} > C_{j(2)} > \cdots > C_{j(k)} \quad (40)$$

where *k* is presented for the evaluated criterion. In Eq. (40), the ">" sign will be replaced by an "=" sign if two or more criteria have the same weights.

Step 2. Comparing the priority of the criteria.

Setting $\varphi_{k/(k+1)}$ be the priority of criterion *k* in comparing with criterion *k*+1, the priority of criterion will be decided. Note that the first ranked criterion is compared with itself, so $\varphi_{1/1} = 1$. With *n* criteria, there are *n-1* values of $\varphi_{k/(k+1)}$. The priority of criterion is often selected from 1 to 9 [36, 45].

Step 3. Calculating the weights of the criteria with ensuring the following conditions:

- Condition 1: The ratio between the weights of the criteria must be equal to the priority between those criteria, that means the following equations including Eq. (41) and Eq. (42) must be satisfied.

$$\frac{w_k}{w_{k+1}} = \varphi_{k/(k+1)} \quad (41)$$

- Condition 2: satisfying the condition as presented by Eq. (42).

$$\frac{w_k}{w_{k+2}} = \varphi_{k/(k+1)} * \varphi_{(k+1)/(k+2)} \quad (42)$$

Two conditions as presented by ((41) and (42)) can only be satisfied if they satisfy the condition as presented by Eq. (43) with the minimum value of X.

$$\begin{cases} \left|\frac{w_k}{w_{k+1}} - \varphi_{k/(k+1)}\right| \leq \mathrm{X} \\ \left|\frac{w_k}{w_{k+2}} - \varphi_{k/(k+1)} * \varphi_{(k+1)/(k+2)}\right| \leq \mathrm{X} \end{cases} \quad (43)$$

From Eq. (41), (42), and (43), the final equation that is applied to calculate the criterion weight is presented by Eq. (44).

$$\begin{cases} \left|\frac{w_k}{w_{k+1}} - \varphi_{k/(k+1)}\right| \leq \mathrm{X}, \forall \mathrm{j} \\ \left|\frac{w_k}{w_{k+2}} - \varphi_{k/(k+1)} * \varphi_{(k+1)/(k+2)}\right| \leq \mathrm{X}, \forall \mathrm{j} \\ X \rightarrow min \\ \sum_{j=1}^{n} w_j = 1, \forall \mathrm{j} \\ w_j > 0, \forall \mathrm{j} \end{cases} \quad (44)$$

4 HOLE TURNING PROCESS OF AISI 1045 STEEL

Because the main objective of this study is comparing the ranking results of solutions when using the combination of different MCDM methods with different weighting methods, the experimental section is summarized as follows: The finishing hole turning proces was performed to machine the hole of AISI 1045 steel workpiece. This is a good machinability steel, so, it is very commonly used in machine manufacturing. A wide variety of products can be manufactured from this steel such as shafts, bearings, gears, etc. The workpiece has an inner diameter, an external diameter, and a length of 32 mm, 50 mm, and 50 mm, respectively. The turning process was performed in DOSAN CNC lathe. The cutter that was used in the experimental process was the TiN coated insert. Four parameters are used to evaluate the turning process including surface roughness (*Ra*), roundness error (*RE*), flank tool wear (*VB*), and material removal rate (*MRR*). In which *Ra*, *RE*, and *VB* are in the criterion type as small as better, and *MRR* is in the criterion type as large as better. Using both of criterion types in this study will make the results of ranking solutions more general (it will be better than that one in the cases that only use only one criterion type as small as better, or as large as better).

The ordering of the criteria in the order *Ra* - *RE* - *VB* - *MRR* is performed according to the opinion of experts, and it was explained as follows. Because this is a finishing turning process, the first of the priority was the product quality evaluation criteria (*Ra* and *RE*). Because *Ra* affects on many factors such as wear resistance, fatigue strength, accuracy of joints, product life [46, 47], *Ra* is prioritized before *RE*. *VB* is ranked at number three because *VB* influences on the tool life, it influens on the cost of the machining process, and *VB* also directly affects on the machining accuracy. *MRR* is ranked at the bottom because in the finishing machining process, the machining productivity is prioritized after product quality. In the experimental process, the values of the input parameters at the levels are shown in Table 3.

The experimental matrix was designed according to the Taguchi method. Many advantages of this method can be found in the references [48, 49]. The experimental matrix and experimental results are presented in Table 4.

Table 3. Input parameters and their levels

Parameter	Symbol	Unit	Value at level			
			1	2	3	4
Cutting velocity	v_c	m/min	80	100	120	140
Feed rate	f_d	mm/rev	0.08	0.1	0.12	0.14
Depth of cut	a_p	mm	0.2	0.4	0.6	0.8

The experimental data in table 4 show that *Ra* is smallest in experiment A_8, *RE* is smallest in experiment A_1, *VB* is smallest in experiment A_2, and *MRR* is largest in experiment A_{13}. Thus, it is obvious that there is no solution that simultaneously ensures the minimum value of *Ra*, minimum value of *RE*, minimum value of *VB*, and maximum value of *MRR*. The concept of "smallest" and "maximum" can only be achieved relatively, that means only one solution can be determined that simultaneously ensures the three criteria *Ra*, *RE*, and *VB* are “smallest” and *MRR* is “maximum”. So, this result can only be achieved when performing the multi-criteria decision making.

Table 4. Orthogonal Taguchi matrix L16 and experimental results

No.	Cutting parameter			Response			
	v_c (m/min)	f_d (mm/rev)	a_p (mm)	*Ra* (μm)	*RE* (μm)	*VB* (μm)	*MRR* (mm^3/min)
A_1	80	0.08	0.2	0.238	1.500	2.898	21.330
A_2	80	0.1	0.4	0.755	3.467	0.663	53.330
A_3	80	0.12	0.6	1.271	6.233	3.941	96.000
A_4	80	0.14	0.8	0.146	2.250	2.358	149.330
A_5	100	0.08	0.4	0.442	5.200	2.874	53.330
A_6	100	0.1	0.2	0.958	7.466	3.393	33.330
A_7	100	0.12	0.8	0.389	3.000	1.812	160.000
A_8	100	0.14	0.6	0.128	6.934	2.328	140.000
A_9	120	0.08	0.6	0.644	8.527	2.848	96.000
A_{10}	120	0.1	0.8	0.322	4.800	2.534	160.000
A_{11}	120	0.12	0.2	0.838	7.654	3.048	48.000
A_{12}	120	0.14	0.4	1.073	5.666	3.244	112.000
A_{13}	140	0.08	0.8	0.224	2.400	0.976	170.670
A_{14}	140	0.1	0.6	0.285	4.766	1.486	160.000
A_{15}	140	0.12	0.4	0.520	2.833	1.678	128.000
A_{16}	140	0.14	0.2	0.308	3.600	2.463	74.670

5 MULTI – CRITERIA DECISION MAKING OF THE HOLE TURNING PROCESS

Firstly, the determination of weights for the criteria is performed.

The decision matrix is created by the last four columns in table 4.

Applying the equations from Eq. (31) to Eq. (36), the weights of *Ra*, *RE*, *VB*, and *MRR* that were calculated according to the MEREC weighting method were 0.2838, 0.1771, 0.1463, and 0.3928, respectively.

The EQUAL weights of the criteria were determined according to Eq. (37). By this method, the weights of all four criteria were 0.25.

Using the Eq. (38), the weights of *Ra*, *RE*, *VB*, and *MRR* that were calculated according to the ROC weighting method were 0.5208, 0.2708, 0.1458, and 0.0625, respectively.

Applying the Eq. (39), the weights of the criteria *Ra*, *RE*, *VB*, and *MRR* that were determined by the RS-weighted method were 0.4000, 0.3000, 0.200, and 0.1000, respectively.

Calculating the weight of the criteria according to the FUCOM weighting method as follows:

- Arranging the criteria in descending order of priority. As above analyis, the criteria were arranged in the order *Ra* > *RE* > *VB* > *MRR*.

- Selecting the order of priority for the criteria. After considering the opinions of three colleagues, they are all experts in the field of machining. They both teach at universities and advise at the mechanical factories. Their opinions on the order of priority for the criteria are quite similar as listed in Table 5. From these analyses, the average value of the the order of priority among the criteria is calculated.

Table 5. Priority values among the criteria

	Criteria			
	Ra	*RE*	*VB*	*MRR*
Expert 1	1.00	1.10	1.22	1.40
Expert 2	1.00	1.09	1.27	1.49
Expert 3	1.00	1.05	1.26	1.46
$\varphi_{k/(k+1)}$	1.00	1.08	1.25	1.45

Applying the Eq. (41):

$$\frac{w_{Ra}}{w_{RE}} = 1.08; \qquad \frac{w_{RE}}{w_{VB}} = 1.25; \qquad \frac{w_{VB}}{w_{MRR}} = 1.45;$$

Applying the Eq. (42):

$$\frac{w_{Ra}}{w_{VB}} = 1.08 * 1.25 = 1.35; \qquad \frac{w_{RE}}{w_{MRR}} = 1.25 * 1.45 = 1.81$$

Applying the Eq. (43) and Eq. (44), the final equation that was used to calculate the weights of the criteria was presented by Eq. (45).

$$\begin{cases} \left|\frac{w_{Ra}}{w_{RE}} - 1.08\right| \le X; \left|\frac{w_{RE}}{w_{VB}} - 1.25\right| \le X; \left|\frac{w_{VB}}{w_{MRR}} - 1.45\right| \le X; \\ \left|\frac{w_{Ra}}{w_{VB}} - 1.35\right| \le X; \left|\frac{w_{RE}}{w_{MRR}} - 1.81\right| \le X \\ X \to min \\ \sum_{j=1}^{4} w_j = 1 \\ w_j > 0, \forall j \end{cases} \tag{45}$$

Solving the Eq. (45) by Lingo 17 software, the weights of *Ra*, *RE*, *VB*, and *MRR* were 0.315, 0.291, 0.233, and 0.161, respectively.

Thus, the determination of the weights of the criteria by five different methods was completed and listed in Table 6.

Table 6. Weights of the criteria

Weight method	Criteria			
	Ra	*RE*	*VB*	*MRR*
MEREC weight	0.284	0.177	0.146	0.393
EQUAL weight	0.25	0.25	0.25	0.25
ROC weight	0.521	0.271	0.146	0.063
RS weight	0.4	0.3	0.2	0.1
FUCOM weight	0.315	0.291	0.233	0.161

From the calculation results in Table 6, it shows that the weight of the criteria depends on the weight determination methods. This is also consistent with the statement in published studies. Even in the case in the same group (table 1), the weights of the criteria that were determined by the ROC weight method and RS weight method were also very different.

The ranking of the solutions when using these five weighting methods creates a more holistic view about the results of the ranking of solutions. The next sections present the application of COCOSO, MABAC, MAIRCA, EAMR, and TOPSIS methods in ranking the solutions of the turning process. The ranking processes are sequentially performed with each set of weights as above calculated. First, the set of weights determined by the MEREC weight method was used.

5.1 Applying COCOSO method

Applying the Eq. (1) and Eq. (2), the normalized values were calculated and listed in Table 7.

The values of S_i were calculated by Eq. (3). The values of P_i were calculated by Eq. (4). Applying Eq. (5), (6), and (7) to calculate the values of k_{ia}, k_{ib} và k_{ic}, respectively. Eq. (8) was used to calculate the values of k_i. All calculated values were listed in Table 8. The ranked results of the solutions according to the values of k_i were also listed in this table.

Table 7. Normalized values according to COCOSO method

No.	*Ra*	*RE*	*VB*	*MRR*
A_1	0.904	1.000	0.318	0.000
A_2	0.451	0.720	1.000	0.231
A_3	0.000	0.326	0.000	0.538
A_4	0.984	0.893	0.483	0.923
A_5	0.725	0.473	0.326	0.231
A_6	0.274	0.151	0.167	0.087
A_7	0.772	0.787	0.649	1.000
A_8	1.000	0.227	0.492	0.856
A_9	0.549	0.000	0.333	0.538
A_{10}	0.830	0.530	0.429	1.000
A_{11}	0.379	0.124	0.272	0.192
A_{12}	0.173	0.407	0.213	0.654
A_{13}	0.916	0.872	0.905	0.923
A_{14}	0.863	0.535	0.749	0.856
A_{15}	0.657	0.810	0.690	0.654
A_{16}	0.843	0.701	0.451	0.317

Table 8. The calculated values and ranked results according to the COCOSO method

No.	S_i	P_i	k_{ia}	k_{ib}	k_{ic}	k_i	*Rank*
A_1	0.480	2.817	0.054	4.703	0.685	2.374	11
A_2	0.493	3.304	0.063	5.083	0.788	2.609	9
A_3	0.269	1.604	0.031	2.653	0.389	1.342	16
A_4	0.871	3.844	0.078	7.741	0.979	3.771	2
A_5	0.428	3.200	0.060	4.621	0.753	2.404	10
A_6	0.163	2.560	0.045	2.596	0.565	1.473	15
A_7	0.846	3.826	0.077	7.579	0.970	3.703	3
A_8	0.732	3.611	0.072	6.745	0.902	3.331	6
A_9	0.416	2.479	0.048	4.099	0.601	2.073	13
A_{10}	0.785	3.726	0.074	7.142	0.937	3.510	5
A_{11}	0.245	2.800	0.050	3.249	0.632	1.780	14
A_{12}	0.409	3.105	0.058	4.447	0.730	2.318	12
A_{13}	0.909	3.906	0.079	8.016	1.000	3.892	1
A_{14}	0.785	3.753	0.075	7.160	0.943	3.522	4
A_{15}	0.688	3.645	0.071	6.494	0.900	3.236	7
A_{16}	0.554	3.419	0.065	5.531	0.825	2.809	8

5.2 Applying MABAC method

The normalized values were also determined as by COCOSO method (Table 7).

The normalized values with the contributing of the weights for criterion were calculated by Eq. (9), the calculated results were listed in Table 9.

Table 9. The normalized values with the contributing of the weights of the criteria according to the MABAC method

No.	*Ra*	*RE*	*VB*	*MRR*
A_1	0.540	0.375	0.193	0.356
A_2	0.412	0.320	0.293	0.455
A_3	0.284	0.242	0.146	0.587
A_4	0.563	0.354	0.217	0.753
A_5	0.490	0.271	0.194	0.455
A_6	0.362	0.207	0.171	0.393
A_7	0.503	0.333	0.241	0.786
A_8	0.568	0.222	0.218	0.724
A_9	0.439	0.177	0.195	0.587
A_{10}	0.519	0.282	0.209	0.786
A_{11}	0.391	0.202	0.186	0.438
A_{12}	0.333	0.258	0.177	0.637
A_{13}	0.544	0.350	0.279	0.753
A_{14}	0.529	0.283	0.256	0.724
A_{15}	0.470	0.338	0.247	0.637
A_{16}	0.523	0.316	0.212	0.492

The values of g_i were calculated by Eq. (10), the calculated results were presented in Table 10.

Table 10. The values of gj according to the MABAC metho

	Ra	*RE*	*VB*	*MRR*
g_j	0.044	0.006	0.002	0.112

The values of q_i were calculated by Eq. (11). Applying Eq. (12) to calculate the values of S_i. These calculated values were presented in Table 11. The ranked results of the solutions according to values of S_i were also presented in this table.

Table 11. The calculated values and ranked results according to the MABAC method

No.	q_i				S_i	Rank
	Ra	*RE*	*VB*	*MRR*		
A_1	0.496	0.369	0.191	0.243	1.300	10
A_2	0.368	0.314	0.291	0.342	1.315	9
A_3	0.240	0.236	0.144	0.475	1.095	14
A_4	0.519	0.348	0.215	0.640	1.722	2
A_5	0.446	0.265	0.192	0.342	1.245	11
A_6	0.317	0.201	0.169	0.280	0.968	16
A_7	0.459	0.327	0.239	0.673	1.698	3
A_8	0.523	0.216	0.216	0.611	1.567	6
A_9	0.395	0.171	0.193	0.475	1.234	13
A_{10}	0.475	0.276	0.207	0.673	1.632	4
A_{11}	0.347	0.196	0.184	0.326	1.053	15
A_{12}	0.289	0.252	0.175	0.524	1.241	12
A_{13}	0.500	0.344	0.277	0.640	1.761	1
A_{14}	0.485	0.277	0.254	0.611	1.627	5
A_{15}	0.426	0.332	0.245	0.524	1.528	7
A_{16}	0.479	0.310	0.210	0.380	1.379	8

5.3 Applying MAIRCA method

The normalized values were also determined as by COCOSO method (Table 7).

Using the Eq. (13), the value of P_{Ai} that was calculated was 0.0625.

The values of $t_{p_{ij}}$ were calculated by Eq. (14), the calculated results were presented in Table 12.

Table 12. The values of t_{p_j} according to the MAIRCA method

	Ra	*RE*	*VB*	*MRR*
t_{p_j}	0.018	0.011	0.009	0.025

The values of $t_{r_{ij}}$ were calculated by Eq. (15) and (16). The Eq. (17) was used to calculate the values of g_{ij}. The Eq. (18) was used to calculate the values of Q_i. The calculated values were presented in Table 13. The ranked results of the solutions according to values of Q_i were also presented in this table.

Table 13. The calculated values and ranked results according to the MAIRCA method

No.	$t_{r_{ij}}$				g_{ij}				Q_i	Rank
	Ra	*RE*	*VB*	*MRR*	*Ra*	*RE*	*VB*	*MRR*		
A_1	0.016	0.011	0.003	0.000	0.002	0.000	0.006	0.025	0.032	10
A_2	0.008	0.008	0.009	0.006	0.010	0.003	0.000	0.019	0.032	9
A_3	0.000	0.004	0.000	0.013	0.018	0.007	0.009	0.011	0.046	14
A_4	0.017	0.010	0.004	0.023	0.000	0.001	0.005	0.002	0.008	2
A_5	0.013	0.005	0.003	0.006	0.005	0.006	0.006	0.019	0.036	11
A_6	0.005	0.002	0.002	0.002	0.013	0.009	0.008	0.022	0.052	16
A_7	0.014	0.009	0.006	0.025	0.004	0.002	0.003	0.000	0.010	3
A_8	0.018	0.003	0.004	0.021	0.000	0.009	0.005	0.004	0.017	6
A_9	0.010	0.000	0.003	0.013	0.008	0.011	0.006	0.011	0.037	12
A_{10}	0.015	0.006	0.004	0.025	0.003	0.005	0.005	0.000	0.013	5
A_{11}	0.007	0.001	0.002	0.005	0.011	0.010	0.007	0.020	0.047	15
A_{12}	0.003	0.005	0.002	0.016	0.015	0.007	0.007	0.008	0.037	13
A_{13}	0.016	0.010	0.008	0.023	0.001	0.001	0.001	0.002	0.006	1
A_{14}	0.015	0.006	0.007	0.021	0.002	0.005	0.002	0.004	0.013	4
A_{15}	0.012	0.009	0.006	0.016	0.006	0.002	0.003	0.008	0.020	7
A_{16}	0.015	0.008	0.004	0.008	0.003	0.003	0.005	0.017	0.028	8

5.4 Applying EARM method

Calculating the normalized values by Eq. (19) and (20). The calculated results were presented in Table 14.

Table 14. Normalized values according to the EAMR method

No.	*Ra*	*RE*	*VB*	*MRR*
A_1	0.187	0.176	0.735	0.133
A_2	0.594	0.407	0.168	0.333
A_3	1.000	0.731	1.000	0.600
A_4	0.115	0.264	0.598	0.933
A_5	0.348	0.610	0.729	0.333
A_6	0.754	0.876	0.861	0.208
A_7	0.306	0.352	0.460	1.000
A_8	0.101	0.813	0.591	0.875
A_9	0.507	1.000	0.723	0.600
A_{10}	0.253	0.563	0.643	1.000
A_{11}	0.659	0.898	0.773	0.300
A_{12}	0.844	0.664	0.823	0.700
A_{13}	0.176	0.281	0.248	0.933
A_{14}	0.224	0.559	0.377	0.875
A_{15}	0.409	0.332	0.426	0.700
A_{16}	0.242	0.422	0.625	0.408

Using the Eq. (21), (22), and (23) to calculate the values of G_i^+, G_i^-, and S_i, respectively. The calculated values were listed in Table 15. The ranked results of the solutions were also presented in this table.

Table 15. The calculated values and ranked results according to the EAMR method

No.	G_i^+	G_i^-	S_i	*Rank*
A_1	0.052	0.192	0.273	14
A_2	0.131	0.265	0.494	11
A_3	0.236	0.560	0.421	12
A_4	0.367	0.167	2.197	2
A_5	0.131	0.313	0.418	13
A_6	0.082	0.495	0.165	16
A_7	0.393	0.216	1.815	3
A_8	0.344	0.259	1.327	6
A_9	0.236	0.427	0.553	10
A_{10}	0.393	0.266	1.479	5
A_{11}	0.118	0.459	0.257	15
A_{12}	0.275	0.478	0.576	9
A_{13}	0.367	0.136	2.694	1
A_{14}	0.344	0.218	1.578	4
A_{15}	0.275	0.237	1.159	7
A_{16}	0.160	0.235	0.683	8

5.5 Applying TOPSIS method

The normalized values were calculated by Eq. (24), the normalized values in consideration of the weights were calculated by Eq. (25) and as presented in Table 16. Applying the Eq. (26) and (27) to determine the best solution (A^+) and the worst solution (A^-) as listed in Table 17. The values of S_i^+ were calculated by Eq. (28). Using the Eq. (29) to calculate the values of S_i^-. The Eq. (30) was used to calculate the values of C_i^*. The calculated values were listed in Table 18. The ranked results of the solutions by using the values C_i^* were also listed in this table. Thus, the ranking of the solutions by the five MCDM methods in the case using the MEREC weight method has been completed. Table 19 presents the ranked results in this case.

Table 16. The normalized values (n_{ij}) and the normalized values in consideration of the weights ($w_j.n_{ij}$) according to the TOPSIS method

No.	n_{ij}				$w_j.n_{ij}$			
	Ra	*RE*	*VB*	*MRR*	*Ra*	*RE*	*VB*	*MRR*
A_1	0.094	0.072	0.283	0.049	0.027	0.013	0.041	0.019
A_2	0.298	0.166	0.065	0.122	0.085	0.029	0.009	0.048
A_3	0.502	0.299	0.385	0.219	0.142	0.053	0.056	0.086
A_4	0.058	0.108	0.230	0.340	0.016	0.019	0.034	0.134
A_5	0.175	0.250	0.281	0.122	0.050	0.044	0.041	0.048
A_6	0.378	0.358	0.331	0.076	0.107	0.063	0.048	0.030
A_7	0.154	0.144	0.177	0.365	0.044	0.025	0.026	0.143

A_8	0.051	0.333	0.227	0.319	0.014	0.059	0.033	0.125
A_9	0.254	0.409	0.278	0.219	0.072	0.072	0.041	0.086
A_{10}	0.127	0.230	0.248	0.365	0.036	0.041	0.036	0.143
A_{11}	0.331	0.367	0.298	0.109	0.094	0.065	0.044	0.043
A_{12}	0.424	0.272	0.317	0.255	0.120	0.048	0.046	0.100
A_{13}	0.088	0.115	0.095	0.340	0.025	0.020	0.014	0.134
A_{14}	0.113	0.229	0.145	0.319	0.032	0.041	0.021	0.125
A_{15}	0.205	0.136	0.164	0.255	0.058	0.024	0.024	0.100
A_{16}	0.122	0.173	0.241	0.149	0.035	0.031	0.035	0.059

Table 17. The values A- and A- according to the TOPSIS method

	Ra	*RE*	*VB*	*MRR*
A^+	0.014	0.013	0.009	0.143
A^-	0.142	0.072	0.056	0.019

Table 18. The calculated values and ranked results according to the TOPSIS method

No.	S_i^+	S_i^-	C_i^*	*Rank*
A_1	0.129	0.131	0.504	9
A_2	0.120	0.091	0.431	12
A_3	0.153	0.070	0.312	14
A_4	0.027	0.180	0.870	2
A_5	0.111	0.102	0.479	11
A_6	0.160	0.039	0.194	16
A_7	0.036	0.168	0.824	3
A_8	0.055	0.169	0.754	6
A_9	0.106	0.098	0.482	10
A_{10}	0.044	0.168	0.791	5
A_{11}	0.142	0.056	0.282	15
A_{12}	0.125	0.088	0.413	13
A_{13}	0.017	0.177	0.913	1
A_{14}	0.039	0.161	0.804	4
A_{15}	0.064	0.131	0.671	7
A_{16}	0.093	0.124	0.573	8

Table 19. Ranked results of the solutions using the MEREC weight method

No.	*COCOSO*	*MABAC*	*MAIRCA*	*EAMR*	*TOPSIS*
A_1	11	10	10	14	9
A_2	9	9	9	11	12
A_3	16	14	14	12	14
A_4	2	2	2	2	2
A_5	10	11	11	13	11
A_6	15	16	16	16	16
A_7	3	3	3	3	3

A_8	6	6	6	6	6
A_9	13	13	12	10	10
A_{10}	5	4	5	5	5
A_{11}	14	15	15	15	15
A_{12}	12	12	13	9	13
A_{13}	1	1	1	1	1
A_{14}	4	5	4	4	4
A_{15}	7	7	7	7	7
A_{16}	8	8	8	8	8

The same performing the ranking of solutions with the weight determination of the criteria according to EQUAL weight, ROC weight, RS weight, and FUCOM weight methods, the ranked results are presented in the tables 20, 21, 22, and 23, respectively.

Table 20. Ranked results of the solutions using the EQUAl weight method

No.	*COCOSO*	*MABAC*	*MAIRCA*	*EAMR*	*TOPSIS*
A_1	10	10	10	15	9
A_2	8	8	8	10	10
A_3	16	15	15	12	15
A_4	2	2	2	2	2
A_5	11	11	11	13	11
A_6	15	16	16	16	16
A_7	3	3	3	3	3
A_8	7	7	7	7	7
A_9	13	13	13	11	12
A_{10}	6	6	6	5	6
A_{11}	14	14	14	14	14
A_{12}	12	12	12	9	13
A_{13}	1	1	1	1	1
A_{14}	4	4	4	4	4
A_{15}	5	5	5	6	5
A_{16}	9	9	9	8	8

Table 21. Ranked results of the solutions using the ROC weight method

No.	*COCOSO*	*MABAC*	*MAIRCA*	*EAMR*	*TOPSIS*
A_1	9	3	3	14	3
A_2	10	10	10	11	11
A_3	16	16	16	13	16
A_4	2	2	2	2	2
A_5	11	11	11	12	10
A_6	15	15	15	16	14
A_7	3	4	4	3	6
A_8	8	9	7	6	7

A_9	12	12	12	10	12
A_{10}	7	8	9	5	8
A_{11}	13	14	13	15	13
A_{12}	14	13	14	9	15
A_{13}	1	1	1	1	1
A_{14}	4	5	5	4	4
A_{15}	6	7	8	7	9
A_{16}	5	6	6	8	5

Table 22. Ranked results of the solutions using the RS weight method

No.	*COCOSO*	*MABAC*	*MAIRCA*	*EAMR*	*TOPSIS*
A_1	10	5	5	14	3
A_2	9	10	10	11	11
A_3	16	16	16	12	16
A_4	2	2	2	2	2
A_5	11	11	11	13	10
A_6	15	15	15	16	15
A_7	3	3	3	3	4
A_8	8	9	9	6	9
A_9	13	12	12	10	12
A_{10}	6	7	7	5	7
A_{11}	14	14	14	15	13
A_{12}	12	13	13	9	14
A_{13}	1	1	1	1	1
A_{14}	4	4	4	4	5
A_{15}	5	6	6	7	8
A_{16}	7	8	8	8	6

Table 23. Ranked results of the solutions using the FUCOM weight method

No.	*COCOSO*	*MABAC*	*MAIRCA*	*EAMR*	*TOPSIS*
A_1	10	7	7	14	6
A_2	9	10	10	11	10
A_3	16	15	16	12	16
A_4	2	2	2	2	2
A_5	11	11	11	13	11
A_6	15	16	15	16	15
A_7	3	3	3	3	3
A_8	7	9	8	7	9
A_9	13	13	12	10	12
A_{10}	6	6	6	5	8
A_{11}	14	14	14	15	13
A_{12}	12	12	13	9	14

A_{13}	1	1	1	1	1
A_{14}	4	4	4	4	4
A_{15}	5	5	5	6	5
A_{16}	8	8	9	8	7

From the data in the tables from Table 19 to 23, it shows:

- The ranking order of solutions depends on the MCDM method and the weight determination methods for the criteria. This statement has also been found in several references [1, 34, 35].

- Solution A_{13} is always determined to be the best one, including with all the MCDM methods as well as the used weighting methods.

- Similarly, solution A_4 is consistently ranked as the second best one for all MCDM methods and for all used weighting methods.

From the data in Table 19 to Table 23, in the comparing process, the ranked results of each MCDM method with other weighting methods were described in Figures 1 to 5.

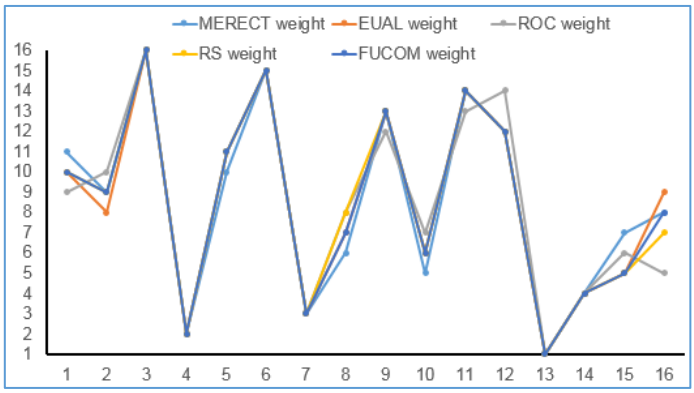


Fig 1. Ranking the solutions according to the COCOSO method

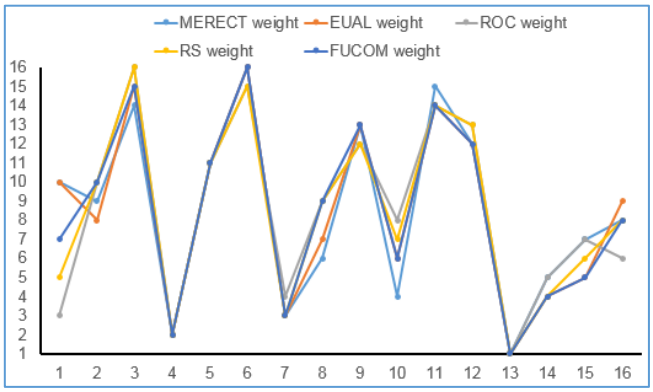


Fig. 2. Ranking the solutions according to the MABAC method

The results from Figures 1 to 5 show that when using different weighting methods, it seems that the EAMR method give the most stable ranking results. This observation is similar to that one in the reference [29]. The authors of this study also showed that when using two different weighting methods (MEREC weight and ENTROPY weight), the EAMR method has a higher stability of the solution ranking than other methods including MAIRCA, MARCOS, and TOPSIS methods. From the results of the ranking according to the EAMR method in tables 19

to 23, it shows that, 10/16 solutions (including: A_3, A_4, A_5, A_6, A_7, A_{10}, A_{12}, A_{13}, A_{14}, and A_{16}) are ranked the same when using different weighting methods.

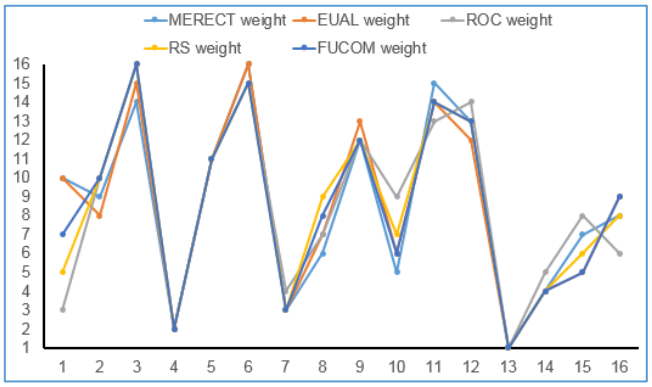


Fig 3. Ranking the solutions according to the MAIRCA method

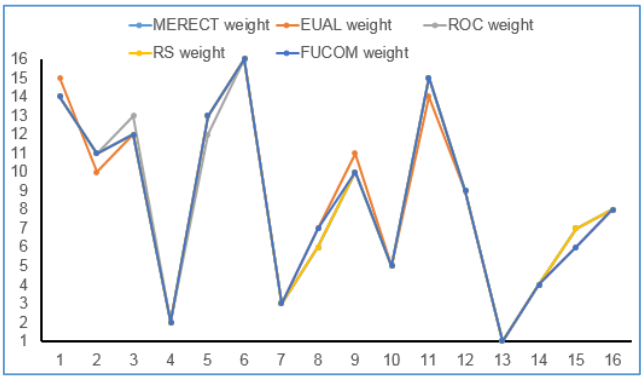


Fig 4. Ranking the solutions according to the EAMR method

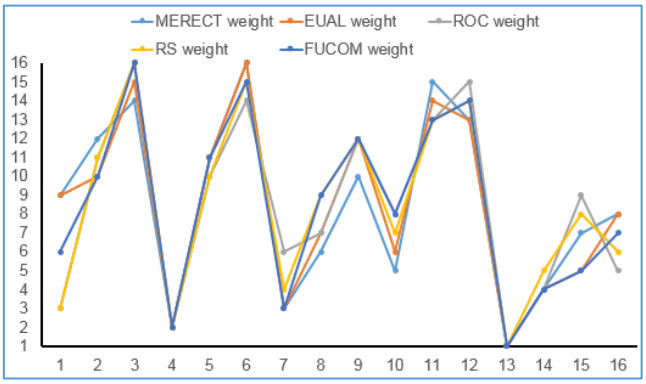


Fig 5. Ranking the solutions according to the TOPSIS method

There are some small differences in the ranking of solutions according to the EAMR method such as:

- For solution A_1, when using EQUAL weighting method, A_1 was ranked 15th and for the remaining four weighting methods, A_1 was ranked 14th.
- For solution A_2, when using EQUAl weighting method, A_2 was ranked 10th and for the remaining four weighting methods, A_2 was ranked 11th.
- For solution A_8, when using MEREC weighting, ROC weighting, and RS weighting methods, A_8 was ranked 6th and when using both EQUAL weighting and FUCOM weighting method, A_8 was ranked 7th.
- For solution A_9, only when using EQUAl weighting method, A_9 was ranked 11th and when using the remaining four weighting methods, A_9 was ranked 10th.

- Similar to solution A_{11}, only when using EQUAl weighting method, A_{11} was ranked 14th and when using the remaining four weighting methods, A_{11} was ranked 15th.
- Solution A_{15} was ranked 7th when using MEREC weighting, ROC weighting, and RS weighting methods and when using the EQUAl weighting and FUCOM weighting methods, A_{15} was ranked 6th.

Although there is still a difference in the ranked results of the solutions with different weighting methods, the difference is very small when using the EAMR method. For example, A_1 was ranked 15th or 14th, A_2 was ranked 10th or 11th, etc. as above analyses. Because the ranked results including 1st, 2nd, 3rd, 4th, and 5th corresponding to the solutions A_{13}, A_4, A_7, A_{14}, and A_{10} are the same. Therefore, it can be proposed a recommendation that the EAMR method should be used in ranking the solutions. The COCOSO method that has the second stability in the ranking process of solutions. It seems that two methods including MABAC and MAIRCA have the same stability in ranking process of the solutions. It seems that the TOPSIS method has the smallest stability in the ranking process of the solutions. From the ranked results by TOPSIS method in Tables 19 to 23, it is shown that there were only two solutions including A_4 and A_{13} that were ranked with the same results when using different weighting methods. For the remaining solutions, the stability when ranking the solutions by TOPSIS method was quite poor. For example, for solution A_1, when using MEREC weighting and EQUAL weighting methods, A_1 was ranked 9th, when using ROC weighting and RS weighting methods, A_1 was ranked 3rd, and when using FUCOM weighting method, A_1 was ranked 6th. Another example is the case for solution A_{16}, when using MEREC weighting and EQUAL weighting methods, A_{16} was ranked 8th, when using ROC weighting method, A_{16} was ranked 5th, when using RS weighting method, A_{16} was ranked 6th, and when using FUCOM weighting method, A_{16} was ranked 7th.

CONCLUSIONS

The ranked results of the solutions depend on the MCDM method as well as the used weighting method. In this study, five MCDM methods including COCOSO, MABAC, MAIRCA, EAMR, and TOPSIS were used to rank the solution in hole turning process of AISI 1045 steel, in which COCOSO and MABAC were the first time applied for the machining processes. In addition, also in this study, five weighting methods including MEREC weight, EQUAL weight, ROC weight, RS weight, and FUCOM weight were also simultaneously used to determine the weights of the criteria. The MEREC weight was used to calculate the weights of the criteria based on the values of the criteria. The EQUAL weight always gives the same weights for the criteria. The ROC weight and RS weight were used to determine the weights of the criteria based only on the ranking of the criteria. The FUCOM weight was used to determine the weights of the criteria from the opinion about the priority among the criteria of the decision maker. The combination of MCDM and weighting methods was created twenty-five ranked results. From the evaluated results of this study, the conclusions are drawn as follows:

- The best ranked solution and the second ranked solution were determined not depending on the MCDM methods and weighting methods.
- When using all five weighting methods, the method that had the highest stability in ranking the solutions was the EAMR method. Meanwhile, if the TOPSIS method is used, the stability is the lowest in comparing to other four MCDM methods.
- When decision makers have difficulty in choosing a weighting method for criteria, the EAMR method should be used to rank the solutions.
- Although TOPSIS is a well-known method, and it has been used a lot to rank the solutions. However, so far, many new MCDM methods have been proposed by scholars. Therefore,

the TOPSIS method could be replaced by another method such as EAMR in ranking processes of the solutions.

- In this study, the FUCOM weighting method was first time used to determine the weight of the criteria in turning process. The obtained results showed that the combination of FUCOM weight with MCDM methods determined the best ranked solution and the second-best ranked solution as other weighting methods. However, the priority among the criteria that were selected in this study may not be the same the opinion of other decision makers. For different decision-makers, when the priority of the criteria is determined with the different opinions, is the ranked results of solutions still the same as that obtained in this study? It is necessary to perform more studies to evaluate these issues.

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