UDC 004
DOI: 10.15587/1729-4061.2022.260093

APPLICATION OF TOPSIS, MAIRCA AND EAMR METHODS FOR MULTI-CRITERIA DECISION MAKING IN CUBIC BORON NITRIDE GRINDING

Trieu Quy Huy
PhD
Department of Mechanical Engineering
University of Economics-Technology for Industries
Minh Khai str., 456, Vinh Tuy ward, Hanoi, Vietnam, 11622

Bui Thanh Hien
Master of Science*

Tran Huu Danh
PhD
Department of Mechanical Engineering
Vinh Long University of Technology Education
73 Nguyen Hue str., Ward 2, Vinh Long City, Vietnam, 85110

Pham Duc Lam
Master of Science
Department of Mechanical Engineering
Nguyen Tat Thanh University
Nguyen Tat Thanh str., 300A, Ward 13, Dist. 4,
Ho Chi Minh City, Vietnam, 72820

Nguyen Hong Linh
PhD
Department of Mechanical Engineering
Electric Power University
Hoang Quoc Viet str., 235, Hanoi City, Vietnam, 129823

Vu Van Khoa
PhD, Vice Director
National Research Institute of Mechanical Engineering
Pham Van Dong str., 4, Hanoi City, Vietnam, 511309

Le Xuan Hung
PhD*

Vu Ngoc Pi
Corresponding author
PhD, Associate Professor*
E-mail: vungocpi@tnut.edu.vn
*Department of Mechanical Engineering
Thai Nguyen University of Technology
3/2 str., 666, Thai Nguyen City, Vietnam, 251750

Determining the best cutting mode is a common problem for machining processes as well as for CBN (Cubic Boron Nitride) grinding on Computer Numerical Control (CNC) machines. It is even more important when it is necessary to choose a solution that meets many goals, which are in conflict. This paper presents the results of a multi-criteria decision-making (MCDM) study on CBN grinding of cylindrical-shaped parts on CNC milling machines. Three MCDM methods, including TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution), MAIRCA (Multi-Attributive Ideal-Real Comparative Analysis), and EAMR (Evaluation by an Area-based Method of Ranking) were applied in this work. Besides, MEREC (Method based on the Removal Effects of Criteria) and Entropy methods were used to determine the weights of the criteria. In addition, the Taguchi method with L18 orthogonal array ($6^{\wedge 1}+3^{\wedge 3}$) design was used for the design of an experiment, which has four input factors including the depth of dressing cut, the spindle speed, the feed rate, and the wheel diameter. Two criteria, including the surface roughness (SR) and the material removal speed (MRS) were selected as the response outputs. The reason for choosing these two criteria is because SR and MRS are two very important output factors of a mechanical machining process as well as of the CBN grinding process on a CNC milling machine. In particular, these two criteria are always in conflict with each other. Small SR requirements will require small values of the feed speed and the depth of cut. This will lead to the reduction of MRS. From the results of this study, the use of different methods for MCDM was evaluated. In addition, rankings of alternatives have been given according to MCDM methods. Furthermore, the best alternative to guarantee both the minimum SR and the maximum MRS has been found

Keywords: CBN grinding, multi-criteria decision making, MCDM, TOPSIS, MAIRCA, EARM

Received date 12.04.2022
Accepted date 10.06.2022
Published date 30.06.2022

How to Cite: *Huy, T. Q., Hien, B. T., Danh, T. H., Lam, P. D., Linh, N. H., Khoa, V. V., Hung, L. X., Pi, V. N. (2022). Application of topsis, mairca and EAMR methods for multi-criteria decision making in cubic boron nitride grinding. Eastern-European Journal of Enterprise Technologies, 3 (1 (117)), 58–66. doi: https://doi.org/10.15587/1729-4061.2022.260093*

1. Introduction

Multi-criteria decision making (MCDM) problem is used to find the best alternative among many different alternatives. It is widely applied in medicine [1, 2], business [3, 4], rescue operations [5], weather forecasting [6, 7], etc. Recently, this problem has been used for mechanical machining processes.

Machining processes often require simultaneous fulfillment of several criteria, such as maximum material removal rate (MRR), minimum surface roughness (SR), or maximum tool life. These criteria often conflict with each other as increasing MRR will require increasing the depth of cut and increasing the feed rate and it will increase SR and decrease the tool life. Therefore, applying the MCDM problem to determine the best solution of the machining process is both relevant and important.

2. Literature review and problem statement

The MCDM problem has been applied to mechanical machining processes. The selection of material for the tool holder for the hard milling process has been reported in [8]. The purpose of this research is to ensure high stiffness and to be able to dissipate the energy generated during interrupted cutting. In this work, the EXPROM2, TOPSIS and VIKOR methods were applied to solve the MCDM problems. The results of this study confirmed that MCDM methods can be used for the solution of real-time material selection problems. An advantage of this study is that Spearman's rank correlation coefficient was used to evaluate the similarity between MCDM methods. In addition, this coefficient has been used to compare the results of other studies. For the turning process, the MCDM problem was solved in [9]. Especially, in this study, eight methods including SAW, WASPAS, TOPSIS, VIKOR, MOORA, COPRAS, PIV, and PSI were used. Besides, the TOPSIS and PIV methods have been applied for the selection of the best alternative in the hard turning process [10]. In this study, the SR, the tool wear, and the roundness error were selected for the criteria of the problem. A plus point of this study is that it has solved the MCDM problem using three different weighting methods: Equal, ROC, and Entropy. In [11], the TOPSIS and COPRAS methods have been chosen for the MCDM problem in drilling magnesium AZ91. Also, the burr and the SR have been chosen as the responses of the study. To find the best alternative in the external grinding process of 65G steel, two criteria including SR and MRR have been selected for MCDM [12]. The Principal Component Analysis (PCA) method has been used to solve the MCDM problem for getting the maximum MRR and the minimum electrode wear rate simultaneously in electrical discharge machining (EDM) of A2 tool steel [13]. From the results of the study, optimum input factors of the EDM process were proposed. The studies from [9] to [13] all deal with mechanical machining processes and employ various MCDM methods. However, they have the same limitation of not using scientific tools (e.g. Spearman's rank correlation coefficient) to compare the ratings of different methods other than to determine the best alternative. This is also a general limitation of previous research on MCDM for mechanical machining processes. This research will also deal with the MCDM of a mechanical machining process (CBN grinding), but it will overcome this common disadvantage.

Grinding is an abrasive machining method that uses a grinding wheel as a cutting tool. It is widely used in finishing and semi-finishing grinding as it can produce high precision and small surface roughness. CBN (Cubic Boron Nitride) grinding allows improving material removal rate, grinding quality as well as wheel life. Therefore, it is often used for grinding hard alloy cutting tools, camshafts, etc. because these parts require high precision grinding and long wheel life. Recently, CBN grinding has been applied to process cylindrical-shaped parts on CNC milling machines [14]. As previously stated, many studies on MCDM for machining processes have been conducted to date. However, no research has been conducted on MCDM for the CBN grinding process on CNC milling machines. This research will help to solve this problem.

3. The aim and objectives of the study

The aim of this study is to use different MCDM and weight calculation methods to find the best cutting regime when CBN grinding of cylindrical-shaped parts on CNC milling machines to get the minimum surface roughness and maximum material removal rate simultaneously.

To achieve this aim, the following objectives are accomplished:

– to assess and calculate the weight of criteria by using the Entropy and MEREC methods;

– to solve the MCDM problem to find the best alternative in CBN grinding on CNC machines using the TOPSIS, MAIRCA and EAMR methods;

– to find the best experimental setup for CBN grinding on CNC milling machines to get minimum SR and maximum MRS simultaneously.

4. Materials and methods

A key tool used in this study is MCDM methods. As previously stated, they are used to find the best solution among numerous alternatives. In this study, three MCDM methods including TOPSIS, MAIRCA, and ERM were used. Besides, two methods of weighting the criteria, Entropy and MEREC, are also used. In addition, another tool used in this study to design an experiment for CBN grinding on CNC milling machines is the Taguchi method.

4. 1. Methods for multi-criteria decision making

4. 1. 1. Technique for order of preference by similarity to ideal solution method

The sequence of the TOPSIS method is described in [15] and it has also been reported in [16]. Specifically, as follows:

Step 1. Constructing the initial matrix by:

$$X=\begin{bmatrix} x_{11} & \cdots & x_{1n} \\ x_{21} & \cdots & x_{2n} \\ \vdots & \cdots & \vdots \\ x_{mn} & \cdots & x_{mn} \end{bmatrix}. \quad (1)$$

In which n is the criterion number; m is the alternative number.

Step 2. Determining the normalized values k_{ij} by:

$$k_{ij}=\frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}. \quad (2)$$

Step 3. Finding the weighted normalized decision matrix by:

$$l_{ij}=w_j \times k_{ij}. \quad (3)$$

Step 4. Determining the best alternative A^+ and the worst alternative A^- by the following equations:

$$A^{+}=\left\{l_1^{+},l_2^{+},\ldots,l_j^{+},\ldots,l_n^{+}\right\}, \quad (4)$$

$$A^{-}=\left\{l_1^{-},l_2^{-},\ldots,l_j^{-},\ldots,l_n^{-}\right\}. \quad (5)$$

In which, l_j^{+} and l_j^{-} are the best and worst values of the j criterion ($j=1, 2, ..., n$).

Step 5. Determining D_i^{+} and D_i^{-} by:

$$D_i^{+}=\sqrt{\sum_{j=1}^{n}\left(l_{ij}-l_j^{+}\right)^2},\ i=1, 2, ..., m, \quad (6)$$

$$D_i^{-}=\sqrt{\sum_{j=1}^{n}\left(l_{ij}-l_j^{-}\right)^2},\ i=1, 2, ..., m. \quad (7)$$

Step 6. Calculating ratios R_i by:

$$R_i=\frac{D_i^{-}}{D_i^{-}+D_i^{+}},\ i=1, 2, ..., m. \quad (8)$$

Step 7. Maximizing R to rank the order of alternatives.

4. 1. 2. Multi-Attributive Ideal-Real Comparative Analysis method

The steps to do the MAIRCA method have been reported in [17], and it has also been presented in [16]. In particular, as described:

Step 1. Generating the initial matrix as in the TOPSIS method.

Step 2. Calculate the preferences of each alternative P_{A_j}. To do that, it is assumed that the criteria are the same in priority and there will be:

$$P_{A_j}=\frac{1}{m},\ j=1, 2, ..., n, \quad (9)$$

Step 3. Determining t_{pij} by:

$$t_{p_{ij}}=P_{A_j}\cdot w_j,\ i=1, 2, ..., m; j=1, 2,.... \quad (10)$$

Wherein w_j is the weight of criterion j.

Step 4. Calculating t_{rij} by:

$$t_{r_{ij}}=t_{p_{ij}}\cdot\left(\frac{x_{ij}-x_i^{-}}{x_i^{+}-x_i^{-}}\right), \text{if criterion } j \text{ is as bigger as better,} \quad (11)$$

$$t_{r_{ij}}=t_{p_{ij}}\cdot\left(\frac{x_{ij}-x_i^{+}}{x_i^{-}-x_i^{+}}\right), \text{if criterion } j \text{ is as smaller as better.} \quad (12)$$

Step 5. Determining g_{ij} by:

$$g_{ij}=t_{p_{ij}}-t_{r_{ij}}. \quad (13)$$

Step 6. Calculating criterion function values (Q_i) by:

$$Q_i=\sum_{i=1}^{m}g_{ij}. \quad (14)$$

The values of Q_i are used to rank alternatives by their ordering.

4. 1. 3. Evaluation by an Area-based Method of Ranking method

The steps for using the EAMR method are described in [18], and it is also discussed in [16]. In particular, as described:

Step 1. Creating the decision matrix by:

$$X_d=\begin{bmatrix} x_{11}^d & \cdots & x_{1n}^d \\ x_{21}^d & \cdots & x_{21}^d \\ \vdots & \cdots & \vdots \\ x_{m1}^d & \cdots & x_{mn}^d \end{bmatrix}. \quad (15)$$

Where d is an indicator of the decision-maker; $1\le d\le k$ with k is the decision-maker number.

Step 2. Calculating the mean value of each alternative with each criterion by the following equation:

$$\bar{x}_{ij}=\frac{1}{k}\left(x_{ij}^1+x_{ij}^2+\ldots+x_{ij}^k\right). \quad (16)$$

Step 3. Finding the criterion weights.

Step 4. Determine the weighted average for each criterion:

$$\bar{w}_j=\frac{1}{k}\left(w_j^1+w_j^2+\ldots+w_j^k\right). \quad (17)$$

Step 5. Calculating n_{ij} by:

$$n_{ij}=\frac{\bar{x}_{ij}}{e_j}. \quad (18)$$

In which e_j is calculated by:

$$e_j=max_{i\in\{1,\ldots,m\}}\left(\bar{x}_{ij}\right). \quad (19)$$

Step 6. Finding the normalized weight by:

$$v_{ij}=n_{ij}\cdot\bar{w}_j. \quad (20)$$

Step 7. Determining the normalized score of the criteria:

$$G_i^{+}=v_{i1}^{+}+v_{i2}^{+}+\ldots+v_{im}^{+},$$

if criterion j is as bigger as better, (21)

$$G_i^{-}=v_{i1}^{-}+v_{i2}^{-}+\ldots+v_{im}^{-+},$$

if criterion j is as smaller as better. (22)

Step 8. Calculating the values of the ranking (RV) from G_i^{+} and G_i^{-}.

Step 9. Calculating the evaluation score of the alternatives by:

$$S_i=\frac{RV\left(G_i^{+}\right)}{RV\left(G_i^{-}\right)}. \quad (23)$$

Determine the best alternative – the one with the largest S_i.

4. 2. Methods for determination of the weights of criteria

This section describes how to apply the Entropy and MEREC methods to calculate the weights of the criteria.

4. 2. 1. Entropy method

To calculate the weight of the criteria by the Entropy method, follow these steps [19]:

Step 1. Determining the normalized values of indicators by the following equation:

$$p_{ij}=\frac{x_{ij}}{m+\sum_{i=1}^{m}x_{ij}^2}. \quad (24)$$

Step 2. Calculating the Entropy value for each criterion:

$$me_j = -\sum_{i=1}^{m}\left[p_{ij} \times ln\left(p_{ij}\right)\right] - \left(1 - \sum_{i=1}^{m} p_{ij}\right) \times ln\left(1 - \sum_{i=1}^{m} p_{ij}\right). \quad (25)$$

Step 3. Calculating the weight of each criterion by:

$$w_j = \frac{1 - me_j}{\sum_{j=1}^{m}\left(1 - me_j\right)}. \quad (26)$$

(26) is used to determine the criterion weight by the Entropy method when solving the MCDM problem.

4. 2. 2. MEREC method

The determination of the criteria weights by the MEREC method is performed in the following order [20]:

Step 1. Forming the initial matrix as in the TOPSIS method.

Step 2. Calculating the normalized values by:

$$h_{ij} = \frac{minx_{ij}}{x_{ij}}, \text{ if criterion } j \text{ is as bigger as better}, \quad (27)$$

$$h_{ij} = \frac{x_{ij}}{maxx_{ij}}, \text{ if criterion } j \text{ is as smaller as better}. \quad (28)$$

Step 3. Finding the alternative performance S_i by:

$$S_i = ln\left[1 + \left(\frac{1}{n}\sum_j \left|ln\left(h_{ij}\right)\right|\right)\right]. \quad (29)$$

Step 4. Calculating the performance of the i^{th} alternative S'_{ij} by the following equation:

$$S'_{ij} = Ln\left[1 + \left(\frac{1}{n}\sum_{k,k\neq j} \left|ln\left(h_{ij}\right)\right|\right)\right]. \quad (30)$$

Step 5. Determining the removal effect of the j^{th} criterion E_j by:

$$E_j = \sum_i \left|S'_{ij} - S_i\right|. \quad (31)$$

Step 6. Calculating the criterion weight by:

$$w_j = \frac{E_j}{\sum_k E_k}. \quad (32)$$

(32) is used to determine the criterion weight by the MEREC method when solving the MCDM problem.

4. 3. Experimental design and setup

To solve the MCDM problem, an experiment was conducted. The experiment was designed using the Taguchi method with the design L18 (6^1+3^3). The input factors and their levels of the experiment are shown in Table 1. In addition, the setup of the experiment is described in Fig. 1 with the Specification shown in Table 2. After accompanying experiments, the SR (in this case Ra (μm)) was measured and the MRS (g/h) was calculated. Table 3 shows the experimental plan and the responses (Ra and MRS).

The output results (Ra and MRS) of each option (Table 3) will be used to determine the alternative ratings using three different MCDM methods including TOPSIS, MAIRCA, and EAMR with two weighting methods (Entropy and MEREC). These calculation results will be presented.

Table 1

Input factors

Input factors	Code	Unit	Level					
			1	2	3	4	5	6
Depth of cut	a_{ed}	mm	0.005	0.01	0.015	0.02	0.025	0.03
Spindle speed	R_{pm}	rpm	4,000	4,500	5,000	–	–	–
Feed rate	F_e	mm/min	2,000	2,500	3,000	–	–	–
Wheel diameter	d	mm	100	125	150	–	–	–

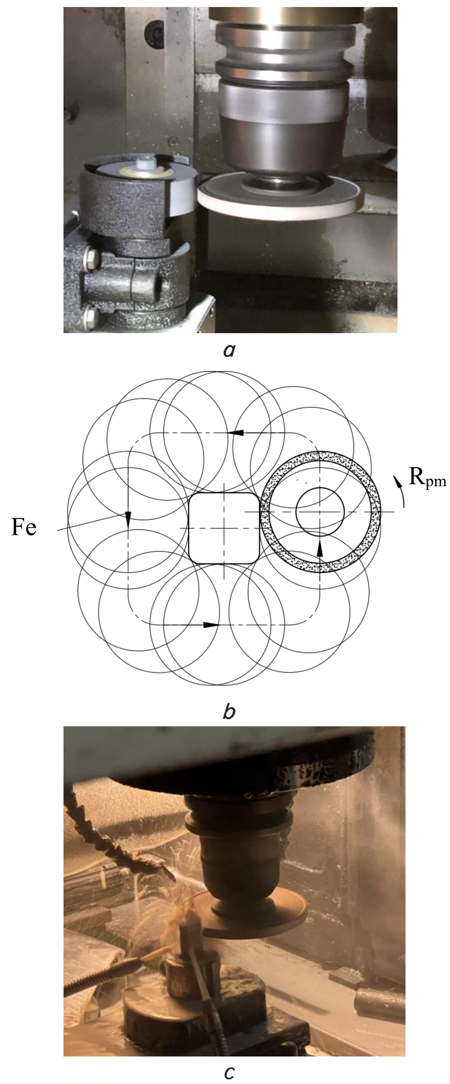

Fig. 1. Experimental setup: *a* — dressing setup; *b* — grinding schema; *c* — grinding setup

Table 2

Specification of the experimental setup

Parameters	Specification
Machine	CNC milling machine M-V50C (Japan)
Dresser equipment	V-TDM-2 Vertex (Taiwan)
Workpiece material	SKD11 tool steel
CBN grinding wheel	B91 KSSRY A V240 (Norton)
Surface roughness tester	Mitutoyo SURFTEST SV-3100 (Japan)
Coolant material	Caltex Aquatex 3180

Table 3

Experimental plan and output results

No.	Input parameters				Output results	
	a_{ed}	R_{pm}	F_e	d	Ra (μm)	MRS (g/h)
1	0.005	4,000	2,000	100	0.5640	2.1933
2	0.005	4,500	2,500	125	0.5140	21.4465
3	0.005	5,000	3,000	150	0.2660	0.9161
4	0.01	4,000	2,000	125	0.3950	3.6771
5	0.01	4,500	2,500	150	0.3613	1.2421
6	0.01	5,000	3,000	100	0.3993	5.7262
7	0.015	4,000	2,500	100	0.3997	5.9976
8	0.015	4,500	3,000	125	0.2820	3.2727
9	0.015	5,000	2,000	150	0.2037	3.3251
10	0.02	4,000	3,000	150	0.7403	3.7553
11	0.02	4,500	2,000	100	0.5997	4.7941
12	0.02	5,000	2,500	125	0.3277	20.9084
13	0.025	4,000	2,500	150	0.6490	3.4458
14	0.025	4,500	3,000	100	0.7457	7.8089
15	0.025	5,000	2,000	125	0.2737	5.0633
16	0.03	4,000	3,000	125	0.8177	4.0054
17	0.03	4,500	2,000	150	0.4487	3.6447
18	0.03	5,000	2,500	100	0.6483	6.5775

Table 4

Converted and normalized matrix values in the TOPSIS method

Trial name	Entropy method				MEREC method			
	k_{ij}		l_{ij}		k_{ij}		l_{ij}	
	Ra	MRS	Ra	MRS	Ra	MRS	Ra	MRS
1	0.2780	0.0644	0.1551	0.0285	0.2780	0.0644	0.2021	0.0176
2	0.2534	0.6297	0.1414	0.2783	0.2534	0.6297	0.1841	0.1720
3	0.1311	0.0269	0.0732	0.0119	0.1311	0.0269	0.0953	0.0073
4	0.1947	0.1080	0.1086	0.0477	0.1947	0.1080	0.1415	0.0295
5	0.1781	0.0365	0.0994	0.0161	0.1781	0.0365	0.1294	0.0100
6	0.1968	0.1681	0.1098	0.0743	0.1968	0.1681	0.1431	0.0459
7	0.1970	0.1761	0.1099	0.0778	0.1970	0.1761	0.1432	0.0481
8	0.1390	0.0961	0.0776	0.0425	0.1390	0.0961	0.1010	0.0263
9	0.1004	0.0976	0.0560	0.0432	0.1004	0.0976	0.0730	0.0267
10	0.3649	0.1103	0.2036	0.0487	0.3649	0.1103	0.2652	0.0301
11	0.2956	0.1408	0.1649	0.0622	0.2956	0.1408	0.2148	0.0385
12	0.1615	0.6139	0.0901	0.2714	0.1615	0.6139	0.1174	0.1677
13	0.3199	0.1012	0.1785	0.0447	0.3199	0.1012	0.2325	0.0276
14	0.3676	0.2293	0.2051	0.1013	0.3676	0.2293	0.2671	0.0626
15	0.1349	0.1487	0.0753	0.0657	0.1349	0.1487	0.0980	0.0406
16	0.4031	0.1176	0.2249	0.0520	0.4031	0.1176	0.2929	0.0321
17	0.2212	0.1070	0.1234	0.0473	0.2212	0.1070	0.1607	0.0292
18	0.3196	0.1931	0.1783	0.0854	0.3196	0.1931	0.2323	0.0528

Table 5

Several parameters and ranking by the TOPSIS method

Trial name	Entropy method				MEREC method			
	D_i^+	D_i^-	R_i	Rank	D_i^+	D_i^-	R_i	Rank
1	0.2688	0.0717	0.2106	15	0.1851	0.1971	0.5157	12
2	0.0854	0.2792	0.7659	2	0.1725	0.1672	0.4922	2
3	0.2670	0.1517	0.3624	8	0.2296	0.0916	0.2851	6
4	0.2365	0.1216	0.3396	9	0.1832	0.1961	0.5171	9
5	0.2658	0.1256	0.3209	10	0.1130	0.2077	0.6477	10
6	0.2110	0.1309	0.3829	7	0.2582	0.0271	0.0948	8
7	0.2076	0.1325	0.3896	5	0.1656	0.2006	0.5478	7
8	0.2368	0.1505	0.3885	6	0.1025	0.1936	0.6540	5
9	0.2352	0.1717	0.4221	4	0.1272	0.1527	0.5456	3
10	0.2730	0.0425	0.1349	17	0.0660	0.2311	0.7779	17
11	0.2420	0.0783	0.2444	14	0.1857	0.1057	0.3626	13
12	0.0348	0.2924	0.8936	1	0.1792	0.1400	0.4386	1
13	0.2638	0.0568	0.1773	16	0.0416	0.2498	0.8573	15
14	0.2314	0.0916	0.2836	12	0.1625	0.1329	0.4498	16
15	0.2135	0.1590	0.4269	3	0.1750	0.1675	0.4891	4
16	0.2824	0.0401	0.1243	18	0.1453	0.2135	0.5951	18
17	0.2407	0.1075	0.3087	11	0.0658	0.2343	0.7807	11
18	0.2285	0.0870	0.2758	13	0.1388	0.1737	0.5559	14

5. Results of the study of multi-criteria decision making in cubic boron nitride grinding

5. 1. Results of the calculation of the weight of criteria using the Entropy and MEREC methods

The determination of the criterion weights using the Entropy method is performed according to the following steps. Determine the normalized values of p_{ij} by formula (24); Calculate the Entropy value for each indicator me_j using equation (25). Finally, find the weight of the criterion w_j according to formula (26). It was reported that the weights of Ra and MRS are 0.558 and 0.442, respectively.

Using the MEREC method to calculate the weights for the criteria is done by the following steps: Calculate the normalized values using (27), (28); Determine S_i and S'_{ij} according to (29), (30). Next, determine the criterion removal efficiency using (31). Finally, calculate the criterion weight w_j according to (32). The results show that the weights of Ra and MRS are 0.7268 and 0.2732, respectively.

5. 2. Results of solving the MCDM problem to find the best alternative in CBN grinding on CNC machines using the TOPSIS, MAIRCA and EAMR methods

5. 2. 1. Results of MCDM when using the TOPSIS method

The MCDM problem is solved by the TOPSIS method in the following order: The normalized values of k_{ij} are calculated according to formula (2). The l_{ij} normalized weighted values are determined using formula (3). Table 4 describes the converted and normalized matrix values in the TOPSIS method using the Entropy and MEREC methods for calculating the weights of criteria. Besides, the A^+ and A^- values of Ra and MRS are found according to formulas (4), (5). Also, the values D_i^+ and D_i^- are found according to (6), (7). Finally, the ratio R_i is calculated by formula (8). Several calculated results and ranking of alternatives when using the TOPSIS method are presented in Table 5 using the Entropy and MEREC methods for calculating the weights of criteria.

From the results in Table 5, with the TOPSIS method, using both the Entropy and MEREC methods for weight calculation gives the best option 12.

5. 2. 2. Results of MCDM when using the MAIRCA method

Using the MAIRCA method for MCDM is done as follows: Create the initial matrix according to (1). Determine the priority of criterion P_{A_j} using (9). Next, calculate the value of parameter $t_{p_{ij}}$ using (10), noting that the weight of the criterion is calculated. Then, calculate the values of $t_{r_{ij}}$ by (11), (12). Table 6 shows $t_{p_{ij}}$ and $t_{r_{ij}}$ values in the MAIRCA method using the Entropy and MEREC methods for finding the weights of criteria. After that, determine g_{ij} by (13). The final Q_i values are then found by (14). Several calculated results and alternative ranking when using the MAIRCA method are presented in Table 7 using the Entropy and MEREC methods for calculating the weights of criteria.

Table 6

Values of t_{pij} and t_{rij} in the MAIRCA method

Trial name	Entropy method				MEREC method			
	t_{pij}		t_{rij}		t_{pij}		t_{rij}	
	Ra	MRS	Ra	MRS	Ra	MRS	Ra	MRS
1	0.0310	0.0246	0.0153	0.0246	0.0404	0.0152	0.0167	0.0009
2	0.0310	0.0246	0.0279	0.0000	0.0404	0.0152	0.0200	0.0152
3	0.0310	0.0246	0.0213	0.0033	0.0404	0.0152	0.0363	0.0000
4	0.0310	0.0246	0.0230	0.0004	0.0404	0.0152	0.0278	0.0020
5	0.0310	0.0246	0.0211	0.0058	0.0404	0.0152	0.0300	0.0002
6	0.0310	0.0246	0.0211	0.0061	0.0404	0.0152	0.0275	0.0036
7	0.0310	0.0246	0.0270	0.0028	0.0404	0.0152	0.0275	0.0038
8	0.0310	0.0246	0.0310	0.0029	0.0404	0.0152	0.0352	0.0017
9	0.0310	0.0246	0.0039	0.0034	0.0404	0.0152	0.0404	0.0018
10	0.0310	0.0246	0.0110	0.0046	0.0404	0.0152	0.0051	0.0021
11	0.0310	0.0246	0.0247	0.0239	0.0404	0.0152	0.0143	0.0029
12	0.0310	0.0246	0.0085	0.0030	0.0404	0.0152	0.0322	0.0148
13	0.0310	0.0246	0.0036	0.0082	0.0404	0.0152	0.0111	0.0019
14	0.0310	0.0246	0.0275	0.0050	0.0404	0.0152	0.0047	0.0051
15	0.0310	0.0246	0.0000	0.0037	0.0404	0.0152	0.0358	0.0031
16	0.0310	0.0246	0.0186	0.0033	0.0404	0.0152	0.0000	0.0023
17	0.0310	0.0246	0.0085	0.0068	0.0404	0.0152	0.0243	0.0020
18	0.0310	0.0246	0.0224	0.0178	0.0404	0.0152	0.0111	0.0042

Table 7

Values of g_i, Q_i and ranking of alternatives by the MAIRCA method

Trial name	Entropy method				MEREC method			
	g_i		Q_i	Rank	g_i		Q_i	Rank
	Ra	MRS			Ra	MRS		
1	0.0182	0.0230	0.0412	14	0.0237	0.0142	0.0379	12
2	0.0157	0.0000	0.0157	2	0.0204	0.0000	0.0204	6
3	0.0031	0.0246	0.0277	6	0.0041	0.0152	0.0193	5
4	0.0097	0.0213	0.0309	9	0.0126	0.0131	0.0257	10
5	0.0080	0.0242	0.0321	10	0.0104	0.0149	0.0253	9
6	0.0099	0.0188	0.0287	8	0.0129	0.0116	0.0245	8
7	0.0099	0.0185	0.0284	7	0.0129	0.0114	0.0243	7
8	0.0040	0.0217	0.0257	5	0.0052	0.0134	0.0186	4
9	0.0000	0.0217	0.0217	3	0.0000	0.0134	0.0134	2
10	0.0271	0.0212	0.0483	17	0.0353	0.0131	0.0484	17
11	0.0200	0.0199	0.0399	12	0.0260	0.0123	0.0384	13
12	0.0063	0.0006	0.0069	1	0.0082	0.0004	0.0086	1
13	0.0225	0.0215	0.0440	16	0.0293	0.0133	0.0426	15
14	0.0274	0.0163	0.0437	15	0.0356	0.0101	0.0457	16
15	0.0035	0.0196	0.0231	4	0.0046	0.0121	0.0167	3
16	0.0310	0.0209	0.0519	18	0.0404	0.0129	0.0533	18
17	0.0124	0.0213	0.0337	11	0.0161	0.0132	0.0293	11
18	0.0224	0.0178	0.0402	13	0.0292	0.0110	0.0402	14

According to the results in Table 7, with the MAIRCA method, using both the Entropy and MEREC methods for weight calculation yields the best option 12.

5. 2. 3. Results of MCDM when using the EAMR method

The application of the EAMR method for MCDM is carried out according to the following steps: Set up the decision matrix according to formula (15) with the note that $k=1$ because there is only one result set. Determine the mean of the alternatives for each criterion according to (16) with the note that since $k=1$, $\bar{x}_{ij}=x_{ij}$. Next, determine the weights for the criteria. Then calculate the average weighted values using formula (17) with the note that since $k=1$, $\bar{w}_j=w_j$. Calculate n_{ij} according to formula (18) with e_j defined by (19). Then determine v_{ij} according to formula (20). Table 8 displays the n_{ij} and v_{ij} values in the EAMR method when using the Entropy and MEREC methods to determine the weights of criteria. Formulas (21), (22) are used to calculate the respective values of G_i. Finally, calculate the S_i value according to (23). Several calculated results and alternative rankings when using the EAMR method are presented in Table 9 when using the Entropy and MEREC methods to calculate criteria weights.

Table 8

Values of n_{ij} and v_{ij} in the EAMR method

Trial name	Entropy method				MEREC method			
	n_{ij}		v_{ij}		n_{ij}		v_{ij}	
	Ra	MRS	Ra	MRS	Ra	MRS	Ra	MRS
1	0.6898	0.1023	0.3849	0.0452	0.6898	0.1023	0.5013	0.0279
2	0.6286	1.0000	0.3508	0.4420	0.6286	1.0000	0.4569	0.2732
3	0.3253	0.0438	0.1815	0.0194	0.3253	0.0438	0.2364	0.0120
4	0.4831	0.1759	0.2696	0.0777	0.4831	0.1759	0.3511	0.0481
5	0.4419	0.0594	0.2466	0.0263	0.4419	0.0594	0.3212	0.0162
6	0.4884	0.2739	0.2725	0.1211	0.4884	0.2739	0.3549	0.0748
7	0.4888	0.2869	0.2727	0.1268	0.4888	0.2869	0.3552	0.0784
8	0.3449	0.1565	0.1924	0.0692	0.3449	0.1565	0.2507	0.0428
9	0.2491	0.1590	0.1390	0.0703	0.2491	0.1590	0.1810	0.0434
10	0.9054	0.1796	0.5052	0.0794	0.9054	0.1796	0.6580	0.0491
11	0.7334	0.2293	0.4092	0.1013	0.7334	0.2293	0.5330	0.0626
12	0.4007	1.0000	0.2236	0.4420	0.4007	1.0000	0.2912	0.2732
13	0.7937	0.4413	0.4429	0.1950	0.7937	0.4413	0.5769	0.1206
14	0.9119	1.0000	0.5088	0.4420	0.9119	1.0000	0.6628	0.2732
15	0.3347	0.7698	0.1868	0.3403	0.3347	0.7698	0.2432	0.2103
16	1.0000	0.6090	0.5580	0.2692	1.0000	0.6090	0.7268	0.1664
17	0.5487	0.5541	0.3062	0.2449	0.5487	0.5541	0.3988	0.1514
18	0.7929	1.0000	0.4424	0.4420	0.7929	1.0000	0.5763	0.2732

Table 9

Values of G_i, S_i and ranking of alternatives by the EAMR method

Trial name	Entropy method				MEREC method			
	G_i		S_i	Rank	G_i		S_i	Rank
	Ra	MRS			Ra	MRS		
1	0.385	0.045	0.117	16	0.5013	0.0279	0.0557	16
2	0.351	0.442	1.260	3	0.4569	0.2732	0.5980	2
3	0.182	0.019	0.107	17	0.2364	0.0120	0.0506	17
4	0.270	0.078	0.288	13	0.3511	0.0481	0.1369	11
5	0.247	0.026	0.106	18	0.3212	0.0162	0.0505	18
6	0.273	0.121	0.444	10	0.3549	0.0748	0.2108	6
7	0.273	0.127	0.465	9	0.3552	0.0784	0.2206	5
8	0.192	0.069	0.360	12	0.2507	0.0428	0.1706	9
9	0.139	0.070	0.506	7	0.1810	0.0434	0.2400	4
10	0.505	0.079	0.157	15	0.6580	0.0491	0.0746	15
11	0.409	0.101	0.248	14	0.5330	0.0626	0.1175	12
12	0.224	0.442	1.977	1	0.2912	0.2732	0.9381	1
13	0.443	0.195	0.440	11	0.5769	0.1206	0.2090	13
14	0.509	0.442	0.869	5	0.6628	0.2732	0.4122	7
15	0.187	0.340	1.822	2	0.2432	0.2103	0.8646	3
16	0.558	0.269	0.482	8	0.7268	0.1664	0.2289	14
17	0.306	0.245	0.800	6	0.3988	0.1514	0.3796	10
18	0.442	0.442	0.999	4	0.5763	0.2732	0.4741	8

According to the results in Table 9, using both the Entropy and MEREC methods for weight calculation with the EAMR method produced the best option 12.

5. 3. Results of finding the best experimental setup for CBN grinding on CNC milling machines to get minimum SR and maximum MRS simultaneously

The results of ranking of alternatives when applying three MCDM methods including TOPSIS, MAIRCA and EAMR with the weight calculation by the Entropy and MEREC methods are described in Table 10. From the Table 10, it was noted that the best alternative was 12.

Table 10

Ranking or alternatives when using the TOPSIS, MAIRCA, and EAMR methods

Trial name	TOPSIS		MAIRCA		EAMR	
	Entropy	MEREC	Entropy	MEREC	Entropy	MEREC
1	15	12	14	12	16	16
2	2	2	2	6	3	2
3	8	6	6	5	17	17
4	9	9	9	10	13	11
5	10	10	10	9	18	18
6	7	8	8	8	10	6
7	5	7	7	7	9	5
8	6	5	5	4	12	9
9	4	3	3	2	7	4
10	17	17	17	17	15	15
11	14	13	12	13	14	12
12	1	1	1	1	1	1
13	16	15	16	15	11	13
14	12	16	15	16	5	7
15	3	4	4	3	2	3
16	18	18	18	18	8	14
17	11	11	11	11	6	10
18	13	14	13	14	4	8

Fig. 2 shows another way to evaluate the application of the above methods to solve the MCDM problem. From Fig. 2, it is easy to see that the same best solution can be identified (option 12) when using three MCDM methods including TOPSIS (Fig. 2, *a*), MAIRCA (Fig. 2, *b*) and EAMR (Fig. 2, *c*). That result does not depend on the calculation of the weights of criteria by the Entropy or MEREC methods.

From the above results, the best experimental setup for CBN grinding on a CNC milling machine to achieve the minimum SR and maximum MRS simultaneously are: a_{ed}=0.02 (mm); R_{pm}=5,000 (rpm); F_e=2,500 (mm/min.); d=125 (mm).

6. Discussion of multi-criteria decision making results

From these results, the following observations can be given:

– the use of TOPSIS, MAIRCA, and EAMR methods along with the weight calculation by MEREC and Entropy to solve the MCDM problem when CBN grinding on CNC milling machines will give different ranking results;

– all three MCDM methods mentioned above have identified the same best solution, option 12. That result does not depend on the weighting of the indicators according to the Entropy or MEREC method. That allows us to say that determining the best alternative does not depend on the MCDM method and the weighting method used (at least with the methods used in this study);

– to compare the degree of association between ranks obtained using various MCDM methods, the Spearman's rank correlation coefficient (R) was used. This coefficient can be determined as follows [12]:

$$R = 1 - \frac{6\cdot\sum_{i=1}^{n} D_i^2}{n\cdot\left(n^2-1\right)}.$$

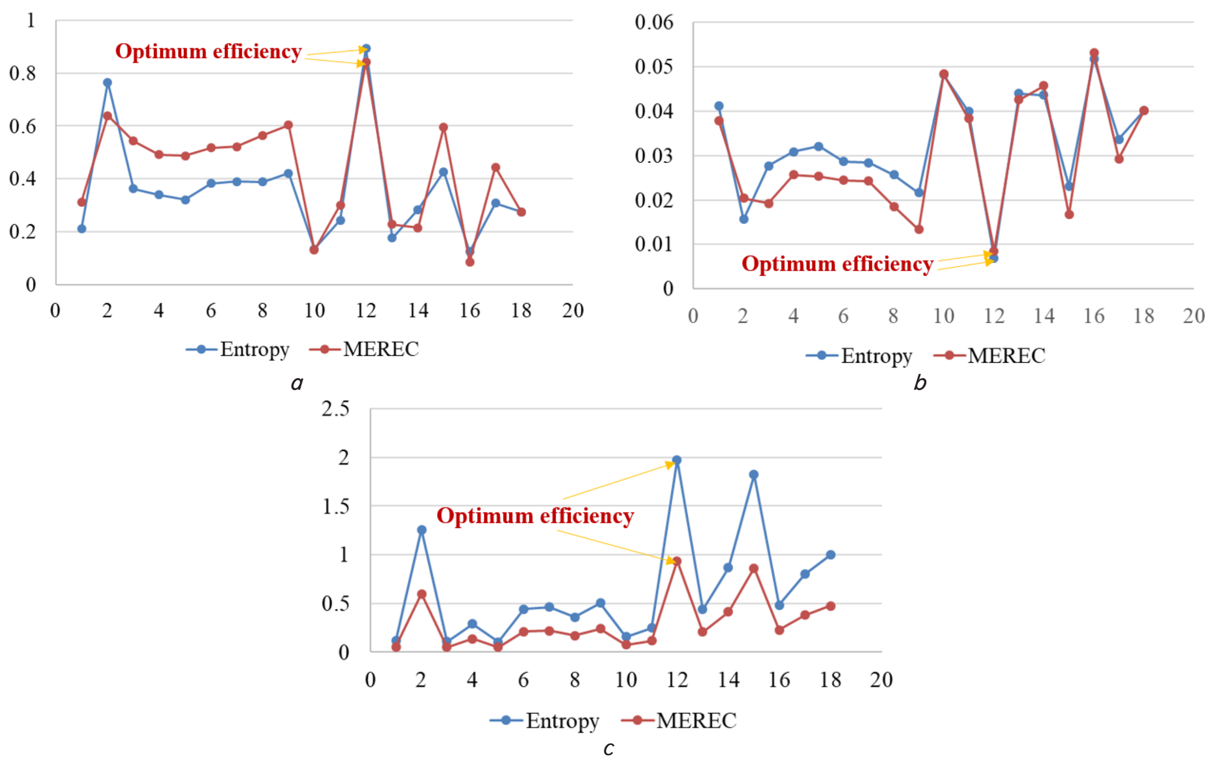

Fig. 2. Comparison graph of three MCDM methods: *a* – TOPSIS; *b* – MAIRCA; *c* – EAMR

Where n is the number of alternatives; D is the difference between ranks.

Table 11 displays the Spearman's rank correlation coefficient for rankings obtained using various methods.

Table 11

Spearman's rank correlation coefficient

Spearman's rank correlation coefficient			
TOPSIS and MAIRCA	TOPSIS and EAMR	TOPSIS and MAIRCA	TOPSIS and EAMR
0.9987	0.9786	0.9985	0.9703

Table 11 shows that the highest correlation coefficient is 0.9987 for TOPSIS and MAIRCA, while the lowest is 0.9703 for TOPSIS and EAMR. The correlations obtained between these methods are generally very good, compared to 0.96 in [8] and 0.83 in [21].

The input process parameters of the best alternative when CBN grinding on a CNC milling machine to achieve the minimum SR and maximum MRS simultaneously are: a_{ed}=0.02 (mm); R_{pm}=5,000 (rpm); F_e=2,500 (mm/min.); d=125 (mm). The depth of cut and feed rate take the average value in their range of input parameters, while R_{pm} is the maximum value in the input parameter (Table 1). This is due to the fact that for getting small roughness, a_{ed} and F_e must be small, while R_{pm} must be large. Besides, for maximum MRS, R_{pm} must be the largest.

The TOPSIS, MAIRCA and EAMR methods are applicable to MCDM when CBN grinding on CNC milling machines. In addition, the calculation of the weights of the criteria can be performed using either the Entropy method or the MEREC method.

The limitation of this study is that the results of the problem have not been compared with other types of grinding or with CBN grinding on other machines such as external cylindrical grinding machines, surface grinding machines, etc. That is also a recommendation for further research to be carried out.

7. Conclusions

1. The weights of Ra and MRS are 0.558 and 0.442, respectively when using the Entropy method and 0.7268 and 0.2732 using the MEREC method.

2. The results of using three MCDM methods including TOPSIS, MAIRCA, and EAMR in CBN grinding on CNC milling machines are presented. The ranking results of the three methods have been shown in tables and figures for evaluation. TOPSIS and MAIRCA methods have been reported to be quite suitable for MCDM problems when CBN grinding on CNC machines. Specifically, these two methods have 11/18 options ranked the same (options 1, 6, 7, 10, 11, 12, 13, 14, 16, 17, and 18) when the weight calculation using the MEREC method and 8/18 options rank the same (Options 4, 5, 10, 11, 12, 13, 16, 17, and 18) when using the Entropy method. Meanwhile, the EAMR method has only the best solution (option 12) similar to other methods. In addition, the selection of the best alternative does not depend on the MCDM method as well as the criterion weight calculation method (at least for the methods used in this study). The best alternative, option 12, has been identified by all three MCDM methods mentioned above.

3. The best experimental setup for CBN grinding on CNC milling machines to get minimum SR and maximum MRS simultaneously is: a_{ed}=0.02 (mm), R_{pm}=5,000 (rpm), F_e=2,500 (mm/min.), and d=100 (mm).

Acknowledgments

This work was supported by the Thai Nguyen University of Technology (Vietnam).

References

1. Mühlbacher, A. C., Kaczynski, A. (2015). Making Good Decisions in Healthcare with Multi-Criteria Decision Analysis: The Use, Current Research and Future Development of MCDA. Applied Health Economics and Health Policy, 14 (1), 29–40. doi: http://doi.org/10.1007/s40258-015-0203-4
2. Wu, H., Xu, Z., Ren, P., Liao, H. (2018). Hesitant fuzzy linguistic projection model to multi-criteria decision making for hospital decision support systems. Computers & Industrial Engineering, 115, 449–458. doi: http://doi.org/10.1016/j.cie.2017.11.023
3. Shaikh, S. A., Memon, M., Kim, K.-S. (2021). A Multi-Criteria Decision-Making Approach for Ideal Business Location Identification. Applied Sciences, 11 (11), 4983. doi: http://doi.org/10.3390/app11114983
4. Rostamzadeh, R., Ismail, K., Zavadskas, E. K. (2014). Multi criteria decision making for assisting business angels in investments. Technological and Economic Development of Economy, 20 (4), 696–720. doi: http://doi.org/10.3846/20294913.2014.984364
5. Basilico, N., Amigoni, F. (2011). Exploration strategies based on multi-criteria decision making for searching environments in rescue operations. Autonomous Robots, 31 (4), 401–417. doi: http://doi.org/10.1007/s10514-011-9249-9
6. Caruzzo, A., Belderrain, M. C. N., Fisch, G., Young, G. S., Hanlon, C. J., Verlinde, J. (2018). Modelling weather risk preferences with multi-criteria decision analysis for an aerospace vehicle launch. Meteorological Applications, 25 (3), 456–465. doi: http://doi.org/10.1002/met.1713
7. Yahyai, S. A., Charabi, Y., Badi, A. A., Gastli, A. (2013). Wind resource assessment using numerical weather prediction models and multi-criteria decision making technique: case study (Masirah Island, Oman). International Journal of Renewable Energy Technology, 4 (1), 17–33. doi: http://doi.org/10.1504/ijret.2013.051070
8. Çalışkan, H., Kurşuncu, B., Kurbanoğlu, C., Güven, Ş. Y. (2013). Material selection for the tool holder working under hard milling conditions using different multi criteria decision making methods. Materials & Design, 45, 473–479. doi: http://doi.org/10.1016/j.matdes.2012.09.042

9. Do, D. T. (2021). A combination method for multi-criteria decision making problem in turning process. Manufacturing Review, 8, 26. doi: http://doi.org/10.1051/mfreview/2021024
10. Duc, T. (2021). Application of TOPSIS an PIV methods for Multi-Criteria Decision Making in hard turning process. Journal of Machine Engineering, 21 (4), 57–71. doi: http://doi.org/10.36897/jme/142599
11. Varatharajulu, M., Duraiselvam, M., Kumar, M. B., Jayaprakash, G., Baskar, N. (2021). Multi criteria decision making through TOPSIS and COPRAS on drilling parameters of magnesium AZ91. Journal of Magnesium and Alloys. doi: http://doi.org/10.1016/j.jma.2021.05.006
12. Do, T. (2021). The Combination of Taguchi – Entropy – WASPAS - PIV Methods for Multi-Criteria Decision Making when External Cylindrical Grinding of 65G Steel. Journal of Machine Engineering, 21 (4), 90–105. doi: http://doi.org/10.36897/jme/144260
13. Sahu, S. N., Nayak, N. C. (2018). Multi-criteria decision making with PCA in EDM of A2 tool steel. Materials Today: Proceedings, 5 (9), 18641–18648. doi: http://doi.org/10.1016/j.matpr.2018.06.209
14. Vu, N.-P., Nguyen, Q.-T., Tran, T.-H., Le, H.-K., Nguyen, A.-T., Luu, A.-T., Nguyen, V.-T., Le, X.-H. (2019). Optimization of grinding parameters for minimum grinding time when grinding tablet punches by CBN wheel on CNC milling machine. Applied sciences, 9 (5), 957. doi: http://doi.org/10.3390/app9050957
15. Hwang, C.-L., Lai, Y.-J., Liu, T.-Y. (1993). A new approach for multiple objective decision making. Computers & Operations Research, 20 (8), 889–899. doi: http://doi.org/10.1016/0305-0548(93)90109-v
16. Nguyen, H.-Q., Le, X.-H., Nguyen, T.-T., Tran, Q.-H., Vu, N.-P. (2022). A Comparative Study on Multi-Criteria Decision-Making in Dressing Process for Internal Grinding. Machines, 10 (5), 303. doi: http://doi.org/10.3390/machines10050303
17. Pamučar, D.V. L., Lukovac, V. (2014). Selection of railway level crossings for investing in security equipment using hybrid DEMATEL-MARICA model. Proceedings of the XVI International Scientific-expert Conference on Railways. Niš: Railcon, 89–92.
18. Amiri, M., Antucheviciene, J. (2016). Evaluation by an area-based method of ranking interval type-2 fuzzy sets (EAMRIT-2F) for multi-criteria group decision-making. Transform Bus Econ, 15 (3), 39.
19. Hieu, T. T., Thao, N. X., Thuy, L. (2019). Application of MOORA and COPRAS Models to Select Materials for Mushroom Cultivation. Vietnam Journal of Agricultural Sciences, 17 (4), 322–331.
20. Keshavarz-Ghorabaee, M. (2021). Assessment of distribution center locations using a multi-expert subjective-objective decision-making approach. Scientific Reports, 11 (1). doi: http://doi.org/10.1038/s41598-021-98698-y
21. Athawale, V. M., Chatterjee, P., Chakraborty, S. (2010). Selection of industrial robots using compromise ranking method. Proceedings of the 2010 International Conference on Industrial Engineering and Operations Management.