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

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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, applying the MCDM problem to determine the best solution of the machining process is both relevant and important.

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 MERE 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 EAMR were used. Besides, two methods of weighting the criteria, Entropy and MERE, 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:

$$
X = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\
\vdots & \ddots & \vdots \\
x_{m1} & \cdots & x_{mn} \end{bmatrix}.
$$  \hspace{1cm} (1)

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

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

$$
k_{ij} = \frac{x_{ij}}{\sqrt{\sum_{k=1}^{m} x_{kj}^2}}.  \hspace{1cm} (2)
$$

Step 3. Finding the weighted normalized decision matrix by:

$$
I_j = w_j \times k_{ij}.  \hspace{1cm} (3)
$$

Step 4. Determining the best alternative $A^+$ and the worst alternative $A^-$ by the following equations:
\[ A^+ = \{ l_1^+, l_2^+, \ldots, l_n^+ \} \]  
\[ A^- = \{ l_1^-, l_2^-, \ldots, l_n^- \} \]  

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

Step 5. Determining \( D_j^+ \) and \( D_j^- \) by:

\[ D_j^+ = \left( \sum_{i=1}^{m} (l_i^+ - l_j^+) \right)^{\frac{1}{2}}, \quad i = 1, 2, \ldots, m. \]  
\[ D_j^- = \left( \sum_{i=1}^{m} (l_i^- - l_j^-) \right)^{\frac{1}{2}}, \quad i = 1, 2, \ldots, m. \]  

Step 6. Calculating ratios \( R_j \) by:

\[ R_j = \frac{D_j^+ - D_j^-}{D_j^+ + D_j^-}, \quad i = 1, 2, \ldots, m. \]  

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 \( P_{y_k} \).

To do that, it is assumed that the criteria are the same in priority and there will be:

\[ P_y = \frac{1}{m}, \quad j = 1, 2, \ldots, n. \]  

Step 3. Determining \( t_y \) by:

\[ t_y = P_y \cdot w_j \quad i = 1, 2, \ldots, m; j = 1, 2, \ldots. \]  

Wherein \( w_j \) is the weight of criterion \( j \).

Step 4. Calculating \( t_y \) by:

\[ t_y = t_y - t_y \]  

if criterion \( j \) is as bigger as better.

\[ t_y = t_y - t_y \]  

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

Step 5. Determining \( g_y \) by:

\[ g_y = t_y - t_y \]  

Step 6. Calculating criterion function values (\( Q_y \)) by:

\[ Q_y = \sum_{j=1}^{n} g_y \]  

The values of \( Q_y \) 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:

\[ X_d = \begin{bmatrix} x_{d1} & x_{d2} & \cdots & x_{dp} \\ x_{d21} & x_{d22} & \cdots & x_{d2p} \\ \vdots & \vdots & \ddots & \vdots \\ x_{dp1} & x_{dp2} & \cdots & x_{dpn} \end{bmatrix} \]  

Where \( d \) is an indicator of the decision-maker; \( 1 \leq d \leq k \) with \( k \) is the decision-maker number.

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

\[ \bar{x}_j = \frac{1}{k} \left( x_{j1}^1 + x_{j2}^2 + \ldots + x_{jn}^n \right). \]  

Step 3. Finding the criterion weights.

Step 4. Determine the weighted average for each criterion:

\[ \bar{w}_j = \frac{1}{k} \left( w_{j1}^1 + w_{j2}^2 + \ldots + w_{jn}^n \right). \]  

Step 5. Calculating \( n_y \) by:

\[ n_y = \frac{\bar{x}_y}{\bar{w}_j}. \]  

In which \( \bar{x}_y \) is calculated by:

\[ \bar{x}_y = \max_{w_{j1}^1, \ldots, w_{jn}^n} \left( \bar{x}_j \right). \]  

Step 6. Finding the normalized weight by:

\[ v_y = n_y \cdot \bar{w}_j. \]  

Step 7. Determining the normalized score of the criteria:

\[ G_y = v_{y1} + v_{y2} + \ldots + v_{yn}, \]  

if criterion \( j \) is as bigger as better.

\[ G_y^- = v_{y1} + v_{y2} + \ldots + v_{yn}, \]  

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

Step 8. Calculating the values of the ranking (RV) from \( G_y^+ \) and \( G_y^- \).

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

\[ S_i = \frac{RV(G_y^+)}{RV(G_y^-)}. \]  

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 MERC 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:

\[ P_y = \frac{x_{y1}}{m + \sum_{i=1}^{n} x_{yi}}. \]
Step 2. Calculating the Entropy value for each criterion:

\[ me_i = -\sum_{i=1}^{n}\left[p_i \times \ln(p_i)\right] - \left(1 - \sum_{i=1}^{n} p_i\right) \times \ln\left(1 - \sum_{i=1}^{n} p_i\right). \]  

(25)

Step 3. Calculating the weight of each criterion by:

\[ w_j = \frac{1 - me_i}{\sum_{i=1}^{n} (1 - me_i)}. \]  

(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:

\[ h_j = \frac{\min x_j}{x_j}, \text{ if criterion } j \text{ is as bigger as better,} \]  

(27)

\[ h_j = \frac{x_j}{\max x_j}, \text{ if criterion } j \text{ is as smaller as better.} \]  

(28)

Step 3. Finding the alternative performance \( S_i \) by:

\[ S_i = \ln\left[1 + \left(\frac{1}{n} \sum_{j=1}^{n} \ln(h_j)\right)\right]. \]  

(29)

Step 4. Calculating the performance of the \( i \)th alternative \( S'_i \) by the following equation:

\[ S'_i = \ln\left[1 + \left(\frac{1}{n} \sum_{j=1}^{n} \ln(h_j)\right)\right]. \]  

(30)

Step 5. Determining the removal effect of the \( j \)th criterion \( E_j \) by:

\[ E_j = \sum_{i} |S'_i - S_i|. \]  

(31)

Step 6. Calculating the criterion weight by:

\[ w_j = \frac{E_j}{\sum_{j=1}^{n} E_j}. \]  

(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 \((6^1 \times 3^3)\). 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>
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<th>3</th>
<th>4</th>
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<td>0.015</td>
<td>0.02</td>
<td>0.025</td>
<td>0.03</td>
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<td>rpm</td>
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<td>4,500</td>
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<td>–</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Feed rate</td>
<td>( F_e )</td>
<td>mm/min</td>
<td>2,000</td>
<td>2,500</td>
<td>3,000</td>
<td>–</td>
<td>–</td>
<td>–</td>
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</tr>
<tr>
<td>Wheel diameter</td>
<td>( d )</td>
<td>mm</td>
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<td>125</td>
<td>150</td>
<td>–</td>
<td>–</td>
<td>–</td>
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<table>
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<th>Parameters</th>
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<tr>
<td>Dresser equipment</td>
<td>V-TDM-2 Vertex (Taiwan)</td>
</tr>
<tr>
<td>Workpiece material</td>
<td>SKD11 tool steel</td>
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<tr>
<td>CBN grinding wheel</td>
<td>B91 KSSRY A V240 (Norton)</td>
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<tr>
<td>Surface roughness tester</td>
<td>Mitutoyo SURFTEST SV-3100 (Japan)</td>
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<tr>
<td>Coolant material</td>
<td>Caltex Aquatex 3180</td>
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</table>

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

Table 1

Table 2

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Specification</th>
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<tbody>
<tr>
<td>Machine</td>
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<td>Coolant material</td>
<td>Caltex Aquatex 3180</td>
</tr>
</tbody>
</table>
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 $p_j$ by formula (24); Calculate the Entropy value for each indicator $w_j$ using equation (25). Finally, find the weight of the criterion $w_i$ 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 $S'_j$ 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 $k_j$ are calculated according to formula (2). The $l_j$ 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 $\Lambda^+$ and $\Lambda^-$ 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.

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 $p_j$ using (9). Next, calculate the value of parameter $t_{ij}$ using (10), noting that the weight of the criterion is calculated. Then, calculate the values of $t_{ij}$ by (11), (12). Table 6 shows $t_{ij}$ and $t_{ij}$ values in the MAIRCA method using the Entropy and MEREC methods for finding the weights of criteria. After that, determine $g_j$ by (13). The

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.
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>
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<tr>
<th>Trial name</th>
<th>$t_{q0}$</th>
<th>$t_{qj}$</th>
<th>$t_{p0}$</th>
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<td>MRS</td>
<td>MRS</td>
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The values of $g_i$, $Q_i$, and ranking of alternatives by the MAIRCA method are presented in Table 7.

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<td>0.0196</td>
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<td>0.0337</td>
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<tr>
<td>17</td>
<td>0.0224</td>
<td>0.0178</td>
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</table>

According to the results in Table 7, 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 $k=1$, $x_i = x_i$. Next, determine the weights for the criteria. Then calculate the average weighted values using formula (17) with the note that since $k=1$, $\bar{w}_i = w_i$. Calculate $n_{ij}$ according to formula (18) with $v_i$ defined by (19). Then determine $v_j$ according to formula (20). Table 8 displays the $n_{ij}$ and $v_j$ 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 $S$ 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.

$\frac{1}{2}$

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

<table>
<thead>
<tr>
<th>Trial name</th>
<th>TOPSIS Entropy</th>
<th>MEREC</th>
<th>MAIRCA Entropy</th>
<th>MEREC</th>
<th>EAMR Entropy</th>
<th>MEREC</th>
</tr>
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</table>

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: \(\alpha_{cd}=0.02\) (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]:

\[
R = 1 - \frac{6 \sum D^2}{n(n^2 - 1)}
\]
Table 11 displays the Spearman’s rank correlation coefficient for rankings obtained using various methods.

Table 11: Spearman’s rank correlation coefficient

<table>
<thead>
<tr>
<th></th>
<th>TOPSIS and MAIRCA</th>
<th>TOPSIS and EAMR</th>
<th>TOPSIS and MAIRCA</th>
<th>TOPSIS and EAMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOPSIS and MAIRCA</td>
<td>0.9987</td>
<td>0.9786</td>
<td>0.9985</td>
<td>0.9703</td>
</tr>
<tr>
<td>TOPSIS and EAMR</td>
<td>0.9786</td>
<td>0.9703</td>
<td>0.9703</td>
<td>0.9703</td>
</tr>
</tbody>
</table>

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); $F_r=2,500$ (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 $F_r$ 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), $F_r=2,500$ (mm/min.), and $d=100$ (mm).

Acknowledgments

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References


