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Multi-criteria decision making under the MARCOS method and the weighting methods: applied to milling, grinding and turning processes

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Abstract. The efficiency of cutting machining methods is generally evaluated through many parameters such as surface roughness, material removal rate, cutting force, etc. A machining process is considered highly efficient when it meets the requirements for these parameters, such as ensuring small surface roughness, high material removal rate, or small cutting force, etc. However, for each specific machining condition, sometimes the objective functions give contradictory requirements. In this case, it is necessary to implement multi-criteria decision making, i.e., make a decision to ensure harmonization of all required objectives. In this paper, a multi-criteria decision-making study is presented for three common machining methods: milling, grinding, and turning. In each machining method, the weights of the criteria were determined by four different methods, including Equal weight, *ROC* weight, *RS* weight and Entropy weight. The *MARCOS* method was applied for multi-criteria decision making. The best alternative was found to be the same as the weights were determined using the Equal weight and Entropy weight methods. In the remaining two weighting methods, the best alternative found depends on the order where the criteria were arranged, not these methods themselves. Direction for further research has been suggested in this study as well.

Keywords: Multi-criteria decision making / MARCOS method / multi-criteria / weight

1 Introduction

In practice, the need to ensure multiple criteria simultaneously is always a requirement for machining processes. For example, when processing by cutting methods, it often requires small surface roughness, significant *MRR*, long tool life, small cutting force, etc. However, the above requirements are not always achieved at the same time, but sometimes they contradict each other. For example, the high-speed turning process to increase productivity often reduces tool life [1], or when grinding, the increase of the cutting depth to increase cutting productivity leads to the rise of the cutting force, the wheel wear rate as well as the spindle vibration [2]. In this case, it is necessary to carry out decision-making to ensure the harmonization of the set goals.

In practice, milling, turning, and grinding are three common machining methods. These methods account for a large volume in manufacturing mechanical products. Also, machines for the mentioned machining types are available [3]. As a result, there have been many studies with the use of different mathematical tools on multi-criteria decision making when implementing these machining methods.

There have been a number of multi-criteria decision-making methods that have been used to make multi-criteria decisions for milling processes such as: using the *RIM* method to solve the multi-objective optimization problem of steel milling SKD11 to ensure simultaneously minimum surface roughness and cutting force, and maximum *MRR* [4]; the *TOPSIS* method is used when milling Ti-6Al-4V alloy to ensure the minimum surface roughness and maximum *MRR* [5]; using the *PIV* method to ensure the minimum surface roughness and the maximum *MRR* simultaneously when milling SCM440 steel [6]; the *MOORA* method was used to provide simultaneous surface roughness and three components of cutting force, and maximum *MRR* when milling Ti-6Al-4V alloy [7]; the *TOPSIS* method and the *WASPAS* method were applied for getting simultaneously the minimum surface roughness and dimensional deviation, and the maximum *MRR* when milling steel EN-31 [8]; the *VIKOR* method has been applied to simultaneously optimize the minimum surface texture and three cutting force components, and the maximum *MRR* when milling aluminum alloy AA3105 [9], etc.

With the grinding method, several studies have been done in multi-criteria decision making. The works include using *TOPSIS* method to ensure simultaneously the

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minimum surface roughness, the minimum wheel shaft vibration, and the maximum *MRR* when grinding DIN 1.2379 steel [2]; applying the *MOORA* method and *COPRAS* method to get both the minimum surface roughness, and the maximum *MRR* when grinding SKD11 steel [10]; using the *PSI* method to ensure the minimum values of two surface texture parameters (*Ra*, *Rz*), and the maximum *MRR* when grinding SCM400 steel [11], etc.

Multi-criteria decision making methods have also been applied for optimization of the turning process. Some results can be listed as follows: the *TOPSIS* method was used to ensure the minimum surface roughness and the maximum *MRR* simultaneously when turning EN8 steel [12]; the *VIKOR* method was used to ensure simultaneously the minimum surface roughness, the minimum workpiece vibration and cutting force, and the maximum *MRR* when turning EN 10503 [13]; the *VIKOR* method was applied to ensure simultaneous the minimum surface roughness, the minimum cutting power, and the maximum *MRR* when turning AISI 1040 steel [14]; the *MOORA* method was used to ensure the minimum cutting force, and the minimum dimensional deviation when turning Al6026-T9 aluminum alloy [15]; The *COPRAS* method was used to ensure that the cutting power, the workpiece vibration, and the surface roughness were minimum when turning ASTM A36 steel [16]. Moreover, the *PSI* method was applied to simultaneously ensure the minimum surface roughness and the maximum *MRR* when turning EN24 [17]; the *WASPAS* method was used to ensure simultaneously the minimum surface roughness, the minimum cutting heat, the minimum cutting energy, and the tool wear, and the maximum *MRR* when turning AISI D3 [18] steels, etc.

From the above analysis, it can be seen that multi-criteria decision making methods (*TOPSIS*, *VIKOR*, *MOORA*, etc.) have been exploited a lot in multi-criteria decision making for milling, turning, grinding processes. This proves the great role of these methods in multi-criteria decision making of machining processes. Therefore, it is very necessary and useful to apply a certain new method to make multi-criteria decisions for mechanical processing processes.

MARCOS is a multi-criteria decision-making method first proposed in 2020 [19]. Although it has only been published for a short time, this method has been applied in a number of studies such as: selection of intermediate models of transport between countries in the Danube region [20]; solving multi-objective problems to reduce risks in road traffic [21]; selection of loading/unloading machines in small warehouses [22]; selection of employees for a shipping company [23]; cost calculation in construction [24]. However, up to now, there have been no studies applying the *MARCOS* method to multi-criteria decision making for cutting methods. This is the first reason why this study was chosen.

Most multi-criteria decision-making methods require weighting of criteria (except for a few methods such as *PSI* [25], *CURLI* [26]). However, for each different weighting method, the criteria also have different weights. In addition, the weight of the criteria greatly affects the ranking of alternatives [27]. Therefore, if only one weighting method is used to implement multi-criteria decision making, the best solution may not be the best. Therefore, to ensure that an alternative is the best, multi-criteria decision making is required when the weights of the criteria are determined by several different methods. Besides, determining the weight according to the Entropy weight method has been used in many studies, and is considered a method with high accuracy [28,29]. Therefore, this method along with three weight determination methods including Equal weight, *ROC* weight, and *RS* weight are selected to solve the multi-objective optimization problem. The application of all four methods of determining weights will increase the reliability of multi-criteria decision making. This is the second reason for conducting this study.

In fact, there is a method to determine the weight where the weight of the criteria does not depend on the ordering of the criteria. In addition, there are methods where the weight of the indicators depends heavily on the ordering of the indicators (this issue will also be clarified in the next section). This is the third reason for doing this study.

From the above analysis, in this study, the *MARCOS* method will be applied for multi-criteria decision making for a milling process, a grinding process, and a turning process. In each case, the weight of the criteria is also determined by four different methods. In which, the data of the milling process is carried out by the experimental process of the author of this study, while the data of the grinding process and the turning process are obtained from published studies. The main objective of this study is to determine the stability of finding the best solution using the *MARCOS* method for different weighting methods as well as for the order of the criteria. This is also the reason why all three methods of milling, turning and grinding have been mentioned in this study.

2 The MARCOS method

The steps to implement multi-criteria decision making according to the *MARCOS* method are as follows [19]:

Step 1: Building the initial matrix according to the following formula:

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ x_{21} & \cdots & x_{2n} \\ \vdots & \cdots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} \tag{1}$$

where, m is the number of options, n is the number of criteria, x_{mn} is the value of the n criterion in m.

Step 2: Constructing an expanded initial matrix by adding an ideal alternative (AI) and the anti-ideal alternative (AAI).

$$X = \begin{matrix} AAI \\ A_1 \\ A_2 \\ \vdots \\ A_m \\ AI \end{matrix} \begin{bmatrix} x_{aa1} & \cdots & x_{aan} \\ x_{11} & \cdots & x_{1n} \\ x_{21} & \cdots & x_{2n} \\ \vdots & \vdots & \vdots \\ x_{m1} & \cdots & x_{mn} \\ x_{ai1} & \cdots & x_{ain} \end{bmatrix} \tag{2}$$

In which: $AAI = \min(x_{ij})$; $i = 1, 2, ..., m$; $j = 1, 2, ..., n$ if j is the larger the better.

$AAI = \max(x_{ij})$; $i = 1, 2, ..., m$; $j = 1, 2, ..., n$ if j is the smaller the better.

$AI = \max(x_{ij})$; $i = 1, 2, ..., m$; $j = 1, 2, ..., n$ if j is the larger the better.

$AI = \min(x_{ij})$; $i = 1, 2, ..., m$; $j = 1, 2, ..., n$ if j is the smaller the better.

Step 3: Normalizing the expanded initial matrix according to the formula.

$$n_{ij} = \frac{x_{AI}}{x_{ij}} \text{ if } j \text{ is the smaller the better.} \tag{3}$$

$$n_{ij} = \frac{x_{ij}}{x_{AI}} \text{ if } j \text{ is the lager the better.} \tag{4}$$

Step 4: Building a normalized matrix taking into account the weights of the criteria, with the normalized value calculated according to the formula.

$$v_{ij} = n_{ij} \cdot w_j \tag{5}$$

where w_j is the weight of the criterion j.

Step 5: Calculating coefficients K_i^+ and K_i^- according to the formula.

$$K_i^- = \frac{S_i}{S_{AAI}} \tag{6}$$

$$K_i^+ = \frac{S_i}{S_{AI}} \tag{7}$$

In which: S_i, S_{AAI} and S_{AI} are the sum of the values of v_{ij}, x_{aai} and x_{ai}, respectively, where $i = 1, 2, ..., m$.

Step 6: Calculate the functions $f(K_i^+)$ and $f(K_i^-)$ according to the formula.

$$f(K_i^-) = \frac{K_i^+}{K_i^+ + K_i^i} \tag{8}$$

$$f(K_i^+) = \frac{K_i^-}{K_i^+ + K_i^i} \tag{9}$$

Step 7: Calculating the function $f(Ki)$ according to the following formula and rank the alternatives.

$$f(K_i) = \frac{K_i^+ + K_i^-}{1 + \frac{1 - f(K_i^+)}{f(K_i^+)} + \frac{1 - f(K_i^-)}{f(K_i^-)}} \tag{10}$$

Ranking the alternatives according to the larger $f(Ki)$ the better.

3 Method of determining the weight

3.1 Equal weight method

Equal weight method is used to calculate the weight according to the following formula [30].

$$w_j = \frac{1}{n} \tag{11}$$

In which, n is the number of objectives.

3.2 ROC weight method

In the *ROC* weight method, the weights of the objectives are calculated based on the following formula [31].

$$w_j = \frac{1}{n} \sum_{k=1}^{n} \frac{1}{k} \tag{12}$$

3.3 RS weight method

In the *RS* weight method, the weight is determined by the following formula [31].

$$w_j = \frac{2(n + 1 - i)}{n(n + 1)} \tag{13}$$

3.4 Entropy weight method

In the entropy weight method, the weights of the objectives can be found by the following steps [32].

Step 1. Determining the normalized values for objectives:

$$p_{\text{ij}} = \frac{y_{\text{ij}}}{m + \sum_{i=1}^{m} y_{\text{ij}}^2} \tag{14}$$

where y_{ij} is the value of criterion j corresponding to test's run i; m is the number of experiments.

Step 2. Calculating the value of the Entropy measure for each criteria.

$$\begin{aligned} e_j = & -\sum_{i=1}^{m} [p_{\text{ij}} \times \ln(p_{\text{ij}})] \\ & -\left(1 - \sum_{i=1}^{m} p_{\text{ij}}\right) \times \ln\left(1 - \sum_{i=1}^{m} p_{\text{ij}}\right) \end{aligned} \tag{15}$$

Step 3. Calculating the weight for each criteria.

$$w_j = \frac{1 - e_j}{\sum_{j=1}^{m} (1 - e_j)}. \tag{16}$$

From the above formulas, it can be seen that, with the Equal weight method and the Entropy weight method, the weights do not depend on the order of the criteria. However, for the other two methods (*ROC* weight and *RS* weight), the weight depends on the order of the criteria.

The following example will illustrate that: There are two criteria C_1, and C_2. If the criteria are arranged in the order C_1, C_2, then when determining the weight for them by *ROC* weight method, the weight value of C_1 is 0.75, the weight value of C_2 is 0.25. If using the *RS* weight method, the weighted value of C_1 is 0.6667, the weighted value of C_2 is 0.3333. However, if the criteria are ranked in the order C_2, C_1, then according to the *ROC* weight method, the

Table 1. Input parameters.

Cutting parameters	Unit	Symbol	Value at level		
			1	2	3
Cutting speed	m/min	v_c	80	120	200
Feed rate	mm/rev	f	0.05	0.1	0.15
Cutting width	mm	a_r	4	8	12
Depth of cut	mm	a_p	0.1	0.3	0.5

Table 2. Orthogonal matrix L9 and experimental results.

Trial.	Cutting parameter				Response	
	v_c (m/min)	f (mm/rev)	a_r (mm)	a_p (mm)	Ra (µm)	MRR (mm^3/min)
A_1	80	0.05	4	0.1	0.970	25.465
A_2	80	0.10	8	0.3	1.085	305.577
A_3	80	0.15	12	0.5	2.032	1145.916
A_4	100	0.05	8	0.5	0.746	318.310
A_5	100	0.10	12	0.1	0.609	190.986
A_6	100	0.15	4	0.3	1.001	286.479
A_7	120	0.05	12	0.3	0.858	343.775
A_8	120	0.10	4	0.5	0.326	381.972
A_9	120	0.15	8	0.1	1.083	229.183

weighted value of C_2 is 0.75, the weighted value of C_1 is 0.25. If using the RS weight method, the weighted values of C_2 are 0.6667, and of C_1 are 0.3333. Thus, when using the ROC weight method and the RS weight method, the weight of the objectives depends on the ordering of the criteria. Does this issue affect the ranking of alternatives? This content will be clarified in the next part of the article.

4 Multi-criteria decision making for milling

4.1 Milling experiment

It is very important to build the setup and conduct the experiment, as well as analyze its results. These things need to be done carefully because they will affect the accuracy of the experiment. However, the main purpose of this study is to determine the stability of the $MARCOS$ method for different weighting methods. The experimental setup can be described as follows: SKS3 steel was used during the test. This is a widely used steel for making dies, cutters, etc. due to its high hardness, high wear resistance. Steel samples are available in length, width and height of 120 mm, 40 mm and 40 mm respectively. The cutting tool used in this study is a TiN coated cutter. This is a cutting tool with high hardness, wear resistance, high toughness, and low chipping rate during machining [33,34]. The cutter body has a diameter of 20 mm, on which two symmetrical cutting pieces are mounted. The experiment was designed according to the Taguchi method with four input parameters that are variable variables in each experiment. Each input parameter was selected with three levels of values as shown in Table 1 [34,35]. The experiments were performed on a 3-axis CNC milling machine TXC540 (Taiwan).

The experimental matrix is shown in Table 2. The experiments were performed according to the experimental plan in this table. The MRR is calculated according to formula (17), where d is the tool diameter, v_c is the cutting speed, f is the feed rate, a_r is the cutting width, a_p is the depth of cut. The surface roughness was measured with an SJ-201. The response values of the experiments have also been included in Table 2.

$$MRR = \frac{1}{\pi \cdot d} \cdot 1000 \cdot v_c \cdot f \cdot a_r \cdot a_p \tag{17}$$

The purpose of the study is to determine the experiment to ensure the minimum Ra and maximum MRR simultaneously. However, the experimental results (Tab. 2) show that Ra has the smallest value in experimental run #8, but MRR has the largest value in run #3. Therefore, it is necessary to perform multi-criteria decision making to determine the experimental run where Ra is considered to be “smallest” and MRR is considered “maximum”.

4.2 Determining the weights for the criteria

Formula (11) is used to determine the weights for the criteria according to the Equal weight method. The weight of each criterion is determined by 0.5.

Table 3. Expanded initial matrix.

	R_a	MRR
AAI	2.032	25.465
A_1	0.970	25.465
A_2	1.085	305.577
A_3	2.032	1145.916
A_4	0.746	318.310
A_5	0.609	190.986
A_6	1.001	286.479
A_7	0.858	343.775
A_8	0.326	381.972
A_9	1.083	229.183
AI	0.326	1145.916

Table 4. Normalized matrix.

	R_a	MRR
AAI	0.1604	0.0222
A_1	0.3361	0.0222
A_2	0.3005	0.2667
A_3	0.1604	1.0000
A_4	0.4370	0.2778
A_5	0.5353	0.1667
A_6	0.3257	0.2500
A_7	0.3800	0.3000
A_8	1.0000	0.3333
A_9	0.3010	0.2000
AI	1.0000	1.0000

Formula (12) is used to determine the weight of the criteria according to the ROC weight method. The weights of the criteria Ra, MRR were found to be 0.75 and 0.25, respectively.

Formula (13) is used to determine the weight of the criteria according to the RS weight method. The weights of the criteria Ra, MRR were found to be 0.6667 and 0.3333, respectively.

The weights for the criteria Ra and MRR according to the Entropy method are calculated according to the formulas (14) to (17) and the results are 0.6618 and 0.3382, respectively.

4.3 Applying the MARCOS method for multi-criteria decision making

Formula (1) is used to determine the original matrix. This matrix is the last two columns in Table 2.

Formula (2) is used to build the expanded initial matrix. The results are presented in Table 3.

Formulas (3), (4) are used to determine the normalized matrix. The results are presented in Table 4.

Table 5. Normalized matrix with weights.

	R_a	MRR
AAI	0.0802	0.0111
A_1	0.1680	0.0111
A_2	0.1502	0.1333
A_3	0.0802	0.5000
A_4	0.2185	0.1389
A_5	0.2677	0.0833
A_6	0.1628	0.1250
A_7	0.1900	0.1500
A_8	0.5000	0.1667
A_9	0.1505	0.1000
AI	0.5000	0.5000

Formula (5) is used to build a normalized matrix taking into account the weights of the criteria. In which, the weight of the criteria is determined by the equal weight method (i.e. $w_j = 0.5$, with $j = 1 \div 2$). The results are presented in Table 5.

Apply formulas (6), (7), (8), (9) and (10) to calculate the respective values K_i^-, K_i^+, $f(K_i^-)$, $f(K_i^+)$ and $f(K_i)$. The results are presented in Table 6. The results of ranking the alternatives according to the value of $f(K_i)$ have also been included in this table.

Proceeding in the same way, the alternatives corresponding to different weighting methods (ROC weight, RS weight, Entropy weight) are ranked as shown in Table 7.

The results in Table 7 show that, with different weighting methods, the ranking results of the alternatives are also different. This is in complete agreement with the comment in [27]. However, it is surprising to find that with all four different weighting methods, A_8 is still determined to be the best solution, and A_1 is still considered the worst solution. The data in Table 2 demonstrates that the MRR at A_1 is significantly lower than that at other alternatives. Hence, it is appropriate to conclude that A_1 is the worst alternative. In contrast, Ra at A_8 is the lowest among the eight alternatives, while the MRR at A_8 is only lower than the MRR at A_3. For that reason, A_8 is considered as the best. This is explained by the fact that the $MARCOS$ method considers the ideal solution (AI) and the anti-ideal solution (AAI). In addition, when the weight of the criteria is determined by the RS method and the Entropy method, the ranking order of the alternatives is completely identical.

5 Multi-criteria decision making for grinding process

In this section, the results of the steel grinding test SCM400 [11] were used. In this experiment, nine experiments with the Taguchi design were conducted. At each experiment, the part speed, feed rate, and depth of cut were changed. In addition, surface roughness (Ra, Rz) was measured and MRR was calculated with each experiment. The results of this experiment are presented in Table 8. In this study, the

Table 6. Some parameters in MARCOS and ranking of alternatives.

Trial.	K_i^-	K_i^+	$f(K_i^-)$	$f(K_i^+)$	$f(K_i)$	Rank
A_1	0.006515	0.000156	0.023427	0.976573	0.000156	9
A_2	0.010313	0.000247	0.023427	0.976573	0.000247	7
A_3	0.021101	0.000506	0.023427	0.976573	0.000506	2
A_4	0.012997	0.000312	0.023427	0.976573	0.000312	3
A_5	0.012764	0.000306	0.023427	0.976573	0.000306	4
A_6	0.010468	0.000251	0.023427	0.976573	0.000251	6
A_7	0.012364	0.000297	0.023427	0.976573	0.000296	5
A_8	0.024245	0.000582	0.023427	0.976573	0.000581	1
A_9	0.009110	0.000219	0.023427	0.976573	0.000218	8

Table 7. Ranking of alternatives for different weighting methods

Trial.	Criteria		Weighting methods			
	Ra (μm)	*MRR* (mm^3/min)	Equal weight	*ROC* weight	*RS* weight	Entropy weight
A_1	0.970	25.465	9	9	9	9
A_2	1.085	305.577	7	7	7	7
A_3	2.032	1145.916	2	4	2	2
A_4	0.746	318.310	3	3	4	4
A_5	0.609	190.986	4	2	3	3
A_6	1.001	286.479	6	6	6	6
A_7	0.858	343.775	5	5	5	5
A_8	0.326	381.972	1	1	1	1
A_9	1.083	229.183	8	8	8	8

PSI method for multi-criteria decision making was used. The purpose of this study is to identify one experiment out of a total of nine experiments where *Ra* and *Rz* are the smallest and the *MRR* is the largest. However, in this study, the author did not compare the *MARCOS* method and the *PSI* method, but determined the stability of the multi-criteria decision making by the *MARCOS* method when using the identification methods assign different weights.

The weights of the criterias have been determined according to four methods including the Equal weight, the *ROC* weight, the *RS* weight, and the Entropy weight and the results are presented in Table 9.

With four sets of weights of the criteria as shown in Table 9, the *MARCOS* method is applied to rank the alternatives. The results obtained are presented in Table 10.

The ranking results of the alternatives in Table 10 show that, with different weighting methods, the ranking results of the options are also different [27]. However, with all four different weighting methods, A_4 was determined to be the best solution. In addition, when using the Equal weight method, the *ROC* weight method, and *RS* weight method, A_2 is the worst option. According to the data in Table 8, both *Ra* and *Rz* at A_4 are the lowest among nine experiments. As a result, A_4 is found as the best solution. On the contrary, *Rz* is the highest and *Ra* is also great (only lower than *Ra* at A_6) at *A2*. Therefore, it is appropriate to conclude that A_2 is the worst option.

6 Multi-criteria decision making for turning process

In this section, 6063 aluminum turning test results [36] were used. In which, twenty-seven experiments were designed according to the Taguchi method with input parameters as part speed, feed amount, depth of cut, and percentage of TiC additive in lubricant. At each experiment, surface roughness (*Rz*), cutting force (*Fc*), and *MRR* were calculated. The obtained results are shown in Table 11. In this study, the *WASPAS* method and the *MOORA* method were also used for multi-criteria decision making to determine the experiment that simultaneously ensures the largest *MRR*, *Fc* and *Rz* are the smallest. However, the comparison of the *MARCOS* methods, the *WASPAS* method, and the *MOORA* method was not performed, but only the stability assessment of multi-criteria decision-making was carried out by the *MARCOS* method corresponding to the identified methods different weights.

Table 8. Experimental results of SCM400 steel grinding process [11].

Trial.	*Cutting parameter*			*Response*		
	n (rev/min)	f (mm/rev)	a_r (mm)	Ra (µm)	Rz (µm)	MRR (mm^3/min)
A_1	400	0.05	0.01	0.51	2.06	82.439
A_2	400	0.075	0.015	0.73	4.52	105.976
A_3	400	0.09	0.02	0.59	4.24	169.533
A_4	600	0.05	0.015	0.38	1.77	70.650
A_5	600	0.075	0.02	0.42	3.53	141.277
A_6	600	0.09	0.01	0.76	2.12	84.795
A_7	800	0.05	0.02	0.39	2.35	94.185
A_8	800	0.075	0.01	0.59	1.97	70.662
A_9	800	0.09	0.015	0.64	3.18	127.171

Table 9. Weights of objectives corresponding to different weighting methods.

Weighting methods	Criteria		
	Ra	Rz	MRR
Equal weight	1/3	1/3	1/3
ROC weight	0.6111	0.2778	0.1111
RS weight	0.5000	0.3333	0.1667
Entropy weight	0.4138	0.3641	0.2222

Table 10. Ranking of alternatives for different weighting methods.

Trial.	Criterias			Weighting methods			
	Ra (µm)	Rz (µm)	MRR (mm^3/min)	Equal weight	*ROC* weight	*RS* weight	Entropy weight
A_1	0.51	2.06	82.439	4	4	4	5
A_2	0.73	4.52	105.976	9	9	9	3
A_3	0.59	4.24	169.533	5	6	6	7
A_4	0.38	1.77	70.650	1	1	1	1
A_5	0.42	3.53	141.277	3	3	3	4
A_6	0.76	2.12	84.795	8	8	7	8
A_7	0.39	2.35	94.185	2	2	2	2
A_8	0.59	1.97	70.662	6	5	5	6
A_9	0.64	3.18	127.171	7	7	8	9

Four methods Equal weight, *ROC* weight, *RS* weight and Entropy weight were again used to determine the weights for the criteria, and the results are presented in Table 12. The *MARCOS* method was also applied to rank the indicators. The plans and results are presented in Table 13.

The ranking results of the alternatives in Table 13 also show that, with different weighting methods, the ranking results of the alternatives are also different [27]. However, alternative A_{16} was determined to be the best option, and alternative A_{21} was still determined to be the worst option. From the data in Table 11, the MRR is remarkably high (only lower than the MRR at A_{18}) and the Fc and Rz at A_{16} by are fairly low at A_{16}. This contributes to the conclusion that A_{16} is the best alternative.

From the ranking results of the three machining processes (milling, grinding, turning) (Tables 7, 10 and 13), as well as from the content discussed about them, the *MARCOS* method always determines the best test for although the weights of the criteria are determined by different methods. Furthermore, although the number of experiments is different in the milling, grinding and turning cases, the best alternative in each case is defined to be the same using the different weighting methods. This is explained by the fact that the *MARCOS* method refers to the ideal and anti-ideal alternatives [19].

However, if the weights of the indicators are determined by the Equal weight method or the Entropy weight method, their values do not depend on the order of the

Table 11. Experimental results of 6063 aluminum turning process [36].

Trial.	Input parameters				Responses		
	n (rev/min)	f (mm/rev)	a_r (mm)	TiC (%)	MRR (mm^3/min)	F_c (N)	Rz (μm)
A_1	950	0.1	0.3	10	5892	128	4.91
A_2	950	0.13	0.3	5	6128	118	4.11
A_3	700	0.13	0.1	10	6523	120	4.55
A_4	950	0.14	0.2	10	6395	123	4.56
A_5	950	0.13	0.1	15	6129	120	4.4
A_6	950	0.13	0.3	15	5569	123	4.32
A_7	1200	0.16	0.2	10	5235	116	3.88
A_8	1200	0.13	0.1	10	5702	120	4.4
A_9	950	0.16	0.1	10	5269	119	4.46
A_{10}	950	0.1	0.1	10	4892	111	3.98
A_{11}	700	0.1	0.2	10	6524	110	4.01
A_{12}	950	0.16	0.2	15	5689	113	4.26
A_{13}	700	0.13	0.2	15	5512	126	4.74
A_{14}	700	0.16	0.2	10	6582	124	5.13
A_{15}	950	0.13	0.2	10	5834	116	4.28
A_{16}	1200	0.13	0.2	5	6924	118	4.42
A_{17}	950	0.16	0.1	10	6596	115	4.16
A_{18}	950	0.13	0.2	10	6952	121	4.53
A_{19}	1200	0.1	0.2	10	6524	126	4.69
A_{20}	700	0.13	0.3	10	5362	124	4.52
A_{21}	1200	0.13	0.3	10	4206	120	4.12
A_{22}	700	0.13	0.2	5	4857	119	3.73
A_{23}	950	0.13	0.1	5	5695	120	4.4
A_{24}	950	0.16	0.2	5	5425	124	4.54
A_{25}	950	0.1	0.2	10	6325	125	4.71
A_{26}	1200	0.13	0.2	10	6321	116	4.44
A_{27}	950	0.1	0.2	5	5125	117	4.06

Table 12. Weights of criteria corresponding to different weighting methods.

Weight method	Criteria		
	MRR	*Fc*	*Rz*
Equal weight	1/3	1/3	1/3
ROC weight	0.6111	0.2778	0.1111
RS weight	0.5000	0.3333	0.1667
Entropy weight	0.6766	0.0727	0.2508

criteria. However, with two methods *ROC* weight and *RS* weight, the result is different. The question is when the criteria are arranged in different order, will it make the ranking of the different criteria or not. Tables 14–16 present the ranking results of the plans for milling, grinding, and turning when the order of criteria is arranged in different ways.

Table 14 shows:

- When the order of criteria is arranged in the order *Ra* to *MRR*, then A_8 is considered the best option in both cases where the weight is determined by *ROC* weight method and *RS* weight method. According to experimental data in Table 2, A_8 is the solution with the smallest *Ra* ($Ra = 0.326$ μm).

Table 13. Ranking of alternatives for different weighting methods.

Trial.	Criteria			Weighting methods			
	MRR (mm3/min)	*Fc* (N)	*Rz* (μm)	Equal weight	*ROC* weight	*RS* weight	Entropy method
A_1	5892	128	4.91	25	17	20	17
A_2	6128	118	4.11	5	10	7	9
A_3	6523	120	4.55	7	5	5	5
A_4	6395	123	4.56	12	9	8	8
A_5	6129	120	4.4	11	12	11	12
A_6	5569	123	4.32	21	18	18	18
A_7	5235	116	3.88	9	19	17	19
A_8	5702	120	4.4	17	15	15	15
A_9	5269	119	4.46	22	23	22	25
A_{10}	4892	111	3.98	13	24	19	26
A_{11}	6524	110	4.01	3	3	3	3
A_{12}	5689	113	4.26	8	14	14	14
A_{13}	5512	126	4.74	26	21	26	22
A_{14}	6582	124	5.13	20	7	10	10
A_{15}	5834	116	4.28	10	13	12	13
A_{16}	6924	118	4.42	1	1	1	1
A_{17}	6596	115	4.16	2	4	2	4
A_{18}	6952	121	4.53	4	2	4	2
A_{19}	6524	126	4.69	15	8	9	6
A_{20}	5362	124	4.52	24	25	25	23
A_{21}	4206	120	4.12	27	27	27	27
A_{22}	4857	119	3.73	14	26	23	24
A_{23}	5695	120	4.4	18	16	16	16
A_{24}	5425	124	4.54	23	20	24	20
A_{25}	6325	125	4.71	19	11	13	11
A_{26}	6321	116	4.44	6	6	6	7
A_{27}	5125	117	4.06	16	22	21	21

Table 14. Ranking of alternatives of milling according to the arrangement of criteria.

Trial.	*ROC* weight		*RS* weight	
	Ra, MRR (1)	*MRR, Ra* (2)	*Ra, MRR* (3)	*MRR, Ra* (4)
A_1	9	9	9	9
A_2	7	5	7	6
A_3	4	1	2	1
A_4	3	4	4	3
A_5	2	7	3	5
A_6	6	6	6	7
A_7	5	3	5	4
A_8	1	2	1	2
A_9	8	8	8	8

Table 15. Ranking of alternatives of grinding process according to the arrangement of criteria.

Trial.	ROC weight						RS weight					
	Ra, Rz, MRR (1)	*Ra*, *MRR*, *Rz* (2)	*Rz*, *Ra*, *MRR* (3)	*Rz*, *MRR*, *Ra* (4)	*MRR*, *Ra*, Rz (5)	*MRR*, *Rz*, *Ra* (6)	*Ra*, Rz, MRR (7)	*Ra*, *MRR*, Rz (8)	*Rz*, Ra, MRR (9)	*Rz*, MRR, *Ra* (10)	*MRR*, *Ra*, Rz (11)	*MRR*, *Rz*, *Ra* (12)
A_1	4	5	3	2	6	6	4	5	3	3	6	6
A_2	9	9	9	9	7	9	9	9	9	9	9	9
A_3	6	4	8	8	1	1	6	4	8	7	1	1
A_4	1	2	1	1	5	5	1	2	1	1	4	3
A_5	3	1	6	6	2	2	3	1	5	5	2	2
A_6	8	8	5	5	8	7	7	8	6	6	8	8
A_7	2	3	2	4	3	4	2	3	2	2	3	4
A_8	5	7	4	3	9	8	5	7	4	4	7	7
A_9	7	6	7	7	4	3	8	6	7	8	5	5

– When the order of criteria is arranged in the order *MRR* to *Ra*, A_3 is determined to be the best option. At A_3. In Table 2, the *MRR* also has the largest value ($MRR = 1145{,}916$ mm^3/min).

This is considered as the result of ranking the options that have oriented towards the priority for the criterion ranked in the top position. Specifically, when the criteria are arranged in the order *Ra* to *MRR*, the best solution is also the one with the smallest *Ra*. Besides, when the criteria are arranged in order of *MRR* to *Ra*, the best solution is also the one with the largest *MRR*. It is easy to see that the best solution depends on the ordering of the criteria, not on the weighting method.

From the Table 15, it was reported that:

- When the criteria are arranged in the order *Ra*, *Rz* to *MRR* (column (1) and column (7)), then A_4 is determined to be the best option. From Table 8, in run A_4, both *Ra* and *Rz* have the smallest value ($Ra = 0.38$ µm, $Rz = 1.77$ µm).
- When the criteria are arranged in the order *Ra*, *MRR* to *Rz* (column (2) and column (8)), A_5 is determined to be the best solution with which *Ra* is very small ($Ra = 0.42$ µm), and *MRR* is the largest ($MRR = 141.277$ mm^3/min).
- In columns (3), (4), (9) and (10) are the results of ranking methods when *Rz* is selected as the first criterion. In all four cases, A_4 is determined to be the best solution, and in this case, *Rz* also has the smallest value.
- When *MRR* is selected as the first criterion (columns (5), (6), (11), (12)), then A_3 is determined as the best option. At A_3, *MRR* also has the largest value.

Thus, from Table 15, it can be seen that the best solution is towards the one in which the first ranking criterion achieves the best results. Specifically, if *Ra* is sorted as the number one criterion, then the best alternative will have the smallest *Ra*, or if the sorted *MRR* is the number one criterion, the best alternative will have the largest *MRR*. In addition, the best-determined alternative depends on the ordering of the criteria and not on the weighting method.

From Table 16 it can be noted that:

- In columns (1), (2), (7) and (8), when *MRR* is selected as the number one indicator, A_{16} is the best option. From Table 11 it can be seen that in this alternative, the *MRR* also has the largest value ($MRR = 6924$ mm^3/min).
- In columns (3), (4), (9) and (10), when *Rz* is selected as the first indicator, A_{11} is considered the best option. In this option, *Rz* also has the small value among the total of 27 solutions. *Rz* in plan A_{11} is equal to 4.01 µm, only a very small amount greater than *Rz* in plans A_7, A_{10}, A_{22}.
- When *Fc* is ranked as the number one criterion (column (5), (6), (11), (12)), A_{11} is also determined to be the best option. In this alternative, *Fc* also has the smallest value among the total of 27 options, $Fc = 110$ (N).
- The solution is determined to be the best depending only on the ordering of the criteria, not on the weighting method. This can also be due to the issue of mentioning the ideal alternative under the *MARCOS* method.

Table 16. Ranking of alternatives of turning process according to the arrangement of criteria.

Trial.	*ROC* weight						*RS* weight					
	MRR, Fc, Rz (1)	*MRR, Rz,* Fc (2)	*Rz, MRR, Fc* (3)	*Rz, Fc, MRR* (4)	*Fc, MRR, Rz* (5)	*Fc, Rz, MRR* (6)	*MRR, Fc,* Rz (7)	*MRR, Rz,* Fc (8)	*Rz, MRR, Fc* (9)	*Rz,* Fc, MRR (10)	*Fc, MRR, Rz* (11)	*Fc,* Rz, MRR (12)
A_1	17	19	27	26	25	27	20	27	26	27	25	27
A_2	10	6	4	6	7	7	7	6	4	6	6	5
A_3	5	5	14	18	8	14	5	13	9	14	7	13
A_4	9	9	15	20	13	19	8	17	14	18	11	17
A_5	12	11	13	13	11	13	11	14	12	13	10	14
A_6	18	18	16	15	22	20	18	19	19	17	22	18
A_7	19	17	5	3	12	4	17	4	6	4	13	4
A_8	15	15	17	16	16	15	15	15	17	15	18	15
A_9	23	26	21	19	21	17	22	18	22	20	23	19
A_{10}	24	23	8	4	10	2	19	3	13	5	12	3
A_{11}	3	2	1	1	1	1	3	**7**	1	1	1	1
A_{12}	14	14	12	8	6	5	14	5	11	8	8	6
A_{13}	21	24	26	25	26	26	26	26	27	26	26	26
A_{14}	7	10	25	27	14	25	10	25	21	25	15	25
A_{15}	13	13	10	9	9	8	12	10	10	10	9	10
A_{16}	1	1	6	10	3	9	1	**1**	3	7	3	7
A_{17}	4	4	2	5	2	3	2	2	2	2	2	2
A_{18}	2	3	7	14	5	12	4	12	5	12	4	12
A_{19}	8	8	19	23	15	22	9	21	16	21	14	21
A_{20}	25	25	24	21	24	23	25	24	24	23	17	24
A_{21}	27	27	22	12	27	18	27	20	25	19	27	20
A_{22}	26	21	3	2	20	6	23	8	7	3	21	8
A_{23}	16	16	18	17	17	16	16	16	18	16	19	16
A_{24}	20	22	23	22	23	24	24	23	23	24	24	23
A_{25}	11	12	20	24	19	21	13	22	20	22	16	22
A_{26}	6	7	9	11	4	10	6	9	8	11	5	9
A_{27}	22	20	11	7	18	11	21	11	15	9	20	11

7 Conclusions

In this study, multi-criteria decision making for three different machining processes including milling, grinding and turning was performed. In each process, the weights of the indicators were determined according to four methods including the Equal weight method, the *ROC* weight method, the *RS* weight method, and Entropy weight method. The *MARCOS* alternative was first applied to multi-criteria decision making for mechanical processing. The effect of ordering the criteria on decision making to choose the best option has also been carefully considered, and some very interesting issues have been discovered. Some conclusions are drawn after applying all three machining methods as follows:

– When the weights of the criteria are determined by the Equal weight method and the Entropy weight method, the weighted values of the alternative do not depend on the ranking order of the criteria and the best solution is always indicated systematically between the two methods.
– When the weights of the alternatives are determined by methods where the value of the weights depends on the arrangement of the criteria (the *ROC* weight, and the *RS* weight criteria), the best solution is determined depending on the sort order of the criteria. When the same ordering of the criteria, the best solution is determined uniformly for both methods.
– When using two methods including the *ROC* weight method and the *RS* weight method, if the best alternative is to give priority to any criteria, that criteria need to be ranked at the first position in the order of ranking criteria.
– By referring to the ideal alternative, it appears that the *MARCOS* method always determines the best solution when the different weighting methods are used.
– Evaluation of the stability of the alternative rank using the different weighting methods as well as comparison of the *MARCOS* method with other multi-criteria decision making methods, such as *TOPSIS*, *MOORA*, *VIKOR*, etc. are necessary to be carried out in the future.

Abbreviations

MARCOS:	Measurement Alternatives and Ranking according to COmpromise Solution
ROC:	Rank Order Centroind
RS:	Rank Sum
RIM:	Reference Ideal Method
TOPSIS:	Technique for Order of Preference by Similarity to Ideal Solution
PIV:	Proximity Indexed Value
MOORA:	Multi Objective Optimization on the basis of Ratio Analysis.
WASPAS:	Weighted Aggregated Sum Product ASsessment
VIKOR:	VIsekriterijumska optimizacija I KOmpromisno Resenje
COPRAS:	COmplex Proportional ASsessment.
PSI:	Preference Selection Index
CURLI:	Collaborative Unbiased Rank List integration
MRR:	Material Removal Rate
Ra:	The arithmetical mean deviation of the assessed profile
Rz:	The minimum value of the profile maximum height
Fc:	Cutting force

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