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CHOOSING THE BEST MACHINE TOOL IN MECHANICAL MANUFACTURING

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Abstract

Machine tools are indispensable components and play an important role in mechanical manufacturing. The equipment of machine tools has a huge effect on the operational efficiency of businesses. Each machine tool type is described by many different criteria, such as cost, technological capabilities, accuracy, energy consumption, convenience in operation, safety for workers, working noise, etc. If the selection of machine is only based on one or several criteria, it will be really easy to make mistakes, which means it is not possible to choose the real best machine. A machine is considered to be the best only when it is chosen based on all of its criteria. This work is called multi-criteria decision-making (MCDM). In this study, the selection of machine tools has been done using two different multi-criteria decision-making methods, including the FUCA method (Faire Un Choix Adéquat) and the CURLI method (Collaborative Unbiased Rank List Intergration). These are two methods with very different characteristics. When using the FUCA method, it is necessary to normalize the data and determine the weights for the criteria. Meanwhile, if using the CURLI method, these two things are not necessary. The selection of these two distinct methods is intended to produce the most generalizable conclusions. Three types of machine tool, which are considered in this study, include grinding machine, drilling machine and milling machine. The number of grinders that were offered for selection was twelve, the number of drills that were surveyed in this study was thirteen, while nine were the number of milling machines that were given for selection. The objective of this study is to determine the best solution in each type of machine. The results of ranking the machines are very similar when using the two mentioned methods. Specially, in all the surveyed cases, the two methods FUCA and CURLI always find the same best alternative. Accordingly, it is possible to firmly come to a conclusion that the FUCA method and the CURLI method are equally effective in machine tool selection. In addition, this study has determined the best three machines corresponding to the three different machine types.

Keywords: Machine tool selection, Machining, MCDM, FUCA method, CURLI method.

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1. Introduction

Labor tools are indispensable components in every production activities. In mechanical manufacturing, machine tools are indispensable components. Choosing a machine tool that is considered the best among the many available machines is very complicated as there are many different criteria that need to be considered. If choosing a machine tool is only based on one or several criteria of the machine, it will be really easy to make wrong decisions [1]. Wrong decisions are understood that the chosen machine tool is not the best one among the available machines. Many criteria are used to describe for each machine such as technological ability, accuracy, safety when using, level of noise when working, price, cost during use, etc. To choose the best machine among available machines according to the information from the suppliers, we have to consider all of these criteria. However, this is not simple because the criteria often have contradictory features, for example, a machine with lower price, also has lower accuracy, technological ability is also lower, and vice versa [2]. Therefore, in order to choose the best machine, multi-criteria decision-making must be performed [3].

Multi-criteria decision-making methods were used widely to choose the best alternatives in many different fields [4–6]. Machine tool selection using multi-criteria decision-making was also performed in some studies. The best lathe was chosen by using some methods such as *TOPSIS* [7], Fuzzy *TOPSIS* [8], *AHP* [9], and *FUCA* [10]. The four methods *TOPSIS*, *MOORA*, *COPRAS*, *ELECTRE I* were used simultaneously to find out the best CNC lathe [11]. The TOPSIS method was also used to choose the best rice milling system [12]. The best CNC machining center was chosen by using the *AHP* method [13]. In [14], the two methods *TOPSIS* and *VIKOR* were used to choose the best flotation machine. The two methods including *AHP* and *PROMETHEE* were used simultaneously to choose the best excavation machine [15], and to choose the best milling machine [16]. The three methods including *CODAS*, *TOPSIS* and *AHP* were used simultaneously to select the best mixer for cake company [17], etc.

Thus, it can be seen that *MCDM* methods were used a lot to select machine tools in mechanical manufacturing. However, the number of studies on milling machine selection is quite small. Specially, up to present, there have been no published studies on grinding machine and drilling machine selections. On the other hand, in published studies, there is only one certain machine type that is chosen in each study. In order to add more useful information to this research direction, in this study, three different types of machine will be selected simultaneously, including grinding machine, drilling machine and milling machine. This is the reason why this study is performed.

FUCA is a new multi-criteria decision-making method that has been found recently (2021). Up to now, only a few studies have applied this method for multi-criteria decision-making [18–23]. This is the reason for this study to use the *FUCA* method in selecting three different machine tools.

CURLI is a special multi-criteria decision-making. The difference of the *CURLI* method compared with the other *MCDM* methods is that it does not need to normalize data or determine the weights for the criteria [24–26]. This difference of the *CURLI* method is the reason it is used in this study.

In the second part of this paper, the steps for implementation of multi-criteria decision-making according to the *FUCA* method and the *CURLI* method will be presented. The content of machine tool selection will be presented in the third part of this paper. The three best machines in each category have been identified in this section. The following two parts of this study is the discussion about the results, and the conclusion discovered in this study.

2. Materials and methods

2. 1. The FUCA method

The *FUCA* method ranks the alternatives according to the followed steps [18, 19]:

Step 1. Ranking the alternatives for each criterion (r_{ij}). Assuming that there are m alternatives, the best value is ranked first, otherwise, the worst value is ranked m. If there are n criteria, perform n ranking times for each criterion.

Step 2. Scoring for each alternative according to the formula (1):

$$v_i = \sum_{j=1}^{n} r_{ij} \cdot w_j. \quad (1)$$

Where w_j is the weight of criterion *j*.

Step 3. Ranking the alternatives according to the values of v_i. The best alternative is the alternative with the smallest v_i, and vice versa.

2. 2. The CURLI method

The steps to rank the alternatives according to the *CURLI* method are as follows [24]:

Step 1. Building *n* square matrices of *m* levels, with *n* and *m* are the number of criteria and the number of alternative, respectively. Each square matrix is the scoring result of each criterion. The rule of scoring for each criterion is as follows. Assuming that with criterion *j* which has its value at A_1 better than its value at A_2, then score 1 in the cell corresponding to row 2 and column 1. Otherwise, let's score –1. Of course, if the value of criterion *j* at A_1 and A_2 are equal, let's score 0 in the cell corresponding to row 2 and column 1. For the cells that lie in the main diagonal of the matrix, let's score 0. This matrix is called the scoring matrix for criterion *j*.

Step 2. The process scoring matrix (call it *Q* matrix) is established by adding all the scoring matrices for each criterion into a single matrix.

Step 3. Rearrange the *Q* matrix by moving the rows and columns. The purpose of this rearrangement is to maximize the number of the cells with non-positive values above the main diagonal of the matrix. The perfect case is that all the cells with non-positive values lie above the main diagonal of the matrix, and all the cells with non-negative values lie below the main diagonal of the matrix. The *Q* matrix after moving the positions of the rows and columns will have the same order of the rows as the order of the columns. Then, the alternative, which is ranked first (also the alternative in column 1), is the best alternative. On the contrary, the alternative which is ranked in the last rows (row *m*) is the worst alternative.

3. Results and discussion

3. 1. Case 1: Selecting grinding machine

There are twelve types of old grinding machine whose names are KURODA 110×315, NAGASE 300×600, NAGASE 300×600-1998, NAGASE 400×600, NICCO 110×315, NICCO 110×315, NICCO 200×500, OKAMOTO 200×500, OKAMOTO 500×1200, OKMAMOTO 500×600, OKAMOTO 700×1500, and KURODA 200×500 have been considered and ranked in this case. They are denoted as *M*1, *M*2, …, *M*12, respectively. In which *M*2, *M*3 and *M*4 were all manufactured by the same company. The *M*5, *M*6 and *M*7 machines are also manufactured by the same company. Another company has also produced four machines from *M*8 to *M*11. The data of these twelve machines has been introduced by the suppliers and presented in **Table 1** [27]:

Table 1

Grinding machine types [27]

M/*C*	*C*1	*C*2	*C*3	*C*4	*C*5	*C*6	*C*7	*C*8
*M*1	315	110	300	205	38.5	2.2	0.005	2016
*M*2	600	300	350	305	28	3.7	0.005	2016
*M*3	600	300	350	305	28	3.7	0.005	1998
*M*4	600	400	380	305	28	3.7	0.005	1992
*M*5	315	110	300	205	38.5	2.2	0.005	2002
*M*6	315	110	300	205	38.5	2.2	0.002	2009
*M*7	500	200	350	205	31.5	3.7	0.005	2009
*M*8	510	205	355	205	31.5	3.7	0.005	2014
*M*9	1280	550	600	510	53.5	3.4	0.002	2017
*M*10	600	500	400	355	37	3.7	0.002	2018
*M*11	1600	720	650	510	53.5	4.2	0.002	2014
*M*12	510	205	355	205	31.5	3.7	0.005	2016
Unit	mm	mm	mm	mm	m/s	kW	mm	Year
Type	max	max	max	max	max	max	min	max

In **Table 1**, the quantities C_i with $i = 1 \div 8$ are the criteria to describe each type of machine. The unit and form of each criterion have also been summarized in the last two rows of this table.

Where:

*C*1: is the maximum stroke of the Table in *X* direction. This is a the-larger-the-better parameter, it decides the maximum length of a product that can be ground on the machine;

*C*2: is the maximum stroke of the Table in *Y* direction. This is also a the-larger-the-better parameter, it decides the maximum width of a product that can be ground on the machine;

*C*3: is the maximum stroke of the Table in *Z* direction. This is also a the-larger-the-better parameter, it is the parameter that decides the maximum height of a product that can be ground on the machine;

*C*4: is the largest diameter of the grinding wheel that can be installed on the machine. With a certain value of the spindle speed, the larger the diameter of the grinding wheel, the higher cutting speed, which means the surface roughness is smaller. Besides, the larger the size of the grinding wheel, the more durable it will be, reducing the cost for repairing and replacing the stone. Which means this is also a the-larger-the-better criterion;

*C*5: is the highest speed of the grinding wheel. The higher the speed of the grinding wheel, the smaller the surface roughness will be, and vice versa;

*C*6: is the capacity of the machine. A machine is better when the capacity is higher;

*C*7: is the accuracy that the machine can achieve. For example, $C7 = 0.005$, that means the accuracy of machining dimensions can reach five over a thousandths. This is a the-smaller-the-better criterion;

*C*8*:* is the year that the machine was manufactured, this is a the-larger-the-better criterion.

The task of selecting the grinder in this example is to choose the one that is considered to be the best of the twelve available machines. The grinder that is considered the best is the one in which the criteria *C*1, *C*2, *C*3, *C*4, *C*5, *C*6, *C*8 are considered «largest» and *C*7 is considered the «smallest».

Apply Step 1 of the *FUCA* method to rank the machine types for each criterion. The results are summarized in **Table 2**.

Step 2 of the *FUCA* method is applied to calculate the score v_i for each machine type. To make it simple, the weights of the criteria have been chosen to be equal, which are 1/8. The score of each machine type was summarized in **Table 3**.

Step 3 of the *FUCA* method has also been applied to rank the machine typed, the results are also summarized in **Table 3**.

So, the work of ranking the grinding machine types using the *FUCA* method has been completed. Accordingly, the priority order of grinding machine types is in the following sequence *M*11–*M*9–*M*10–*M*2–*M*4–*M*12–*M*8–*M*3–*M*6–*M*1–*M*5–*M*7. The content of ranking the machine types using the CURLI method will be presented right now.

Table 2
Ranking the machine types for each criterion

M*/*C	r_{ij}							
	***C*1**	***C*2**	***C*3**	***C*4**	***C*5**	***C*6**	***C*7**	***C*8**
*M*1	11	11	11	9.5	4	11	8.5	4
*M*2	4.5	5.5	8	5	11	5	8.5	4
*M*3	4.5	5.5	8	5	11	5	8.5	11
*M*4	4.5	4	4	5	11	5	8.5	12
*M*5	11	11	11	9.5	4	11	8.5	10
*M*6	11	11	11	9.5	4	11	2.5	8.5
*M*7	9	9	88	9.5	8	5	8.5	8.5
*M*8	7.5	7.5	5.5	9.5	8	5	8.5	6.5
*M*9	2	2	2	1.5	1.5	9	2.5	2
*M*10	4.5	3	3	3	6	5	2.5	1
*M*11	1	1	1	1.5	1.5	1	2.5	6.5
*M*12	7.5	7.5	5.5	9.5	8	5	8.5	4

Table 3
Score of each machine and ranking them

M/*C*	w_j*r_{ij}								v_i	Rank
	*C*1	*C*2	*C*3	*C*4	*C*5	*C*6	*C*7	*C*8		
*M*1	1.375	1.375	1.375	1.188	0.500	1.375	1.063	0.500	8.750	10
*M*2	0.563	0.688	1.000	0.625	1.375	0.625	1.063	0.500	6.438	4
*M*3	0.563	0.688	1.000	0.625	1.375	0.625	1.063	1.375	7.313	8
*M*4	0.563	0.500	0.500	0.625	1.375	0.625	1.063	1.500	6.750	5
*M*5	1.375	1.375	1.375	1.188	0.500	1.375	1.063	1.250	9.500	11
*M*6	1.375	1.375	1.375	1.188	0.500	1.375	0.313	1.063	8.563	9
*M*7	1.125	1.125	11.000	1.188	1.000	0.625	1.063	1.063	18.188	12
*M*8	0.938	0.938	0.688	1.188	1.000	0.625	1.063	0.813	7.250	7
*M*9	0.250	0.250	0.250	0.188	0.188	1.125	0.313	0.250	2.813	2
*M*10	0.563	0.375	0.375	0.375	0.750	0.625	0.313	0.125	3.500	3
*M*11	0.125	0.125	0.125	0.188	0.188	0.125	0.313	0.813	2.000	1
*M*12	0.938	0.938	0.688	1.188	1.000	0.625	1.063	0.500	6.938	6

Apply Step 1 of the *CURLI* method, each machine type has been scored for each criterion, the results are shown in the tables from **Tables 4–11**:

Table 4
Scoring for each machine type for criterion *C*1

M/*P*	*P*1	*P*2	*P*3	*P*4	*P*5	*P*6	*P*7	*P*8	*P*9	*P*10	*P*11	*P*12
*M*1	0	1	1	1	0	0	1	1	1	1	1	1
*M*2	–1	0	0	0	–1	–1	–1	–1	1	0	1	–1
*M*3	–1	0	0	0	–1	–1	–1	–1	1	0	1	–1
*M*4	–1	0	0	0	–1	–1	–1	–1	1	0	1	–1
*M*5	0	1	1	1	0	0	1	1	1	1	1	1
*M*6	0	1	1	1	0	0	1	1	1	1	1	1
*M*7	–1	1	1	1	–1	–1	0	1	1	1	1	1
*M*8	–1	1	1	1	–1	–1	–1	0	1	1	1	0
*M*9	–1	–1	–1	–1	–1	–1	–1	–1	0	–1	1	–1
*M*10	–1	0	0	0	–1	–1	–1	–1	1	0	1	–1
*M*11	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	0	–1
*M*12	–1	1	1	1	–1	–1	–1	0	1	1	1	0

Table 5
Scoring for each machine type for criterion *C*2

M/*P*	*P*1	*P*2	*P*3	*P*4	*P*5	*P*6	*P*7	*P*8	*P*9	*P*10	*P*11	*P*12
*M*1	0	1	1	1	0	0	1	1	1	1	1	1
*M*2	–1	0	0	1	–1	–1	–1	–1	1	1	1	–1
*M*3	–1	0	0	1	–1	–1	–1	–1	1	1	1	–1
*M*4	–1	–1	–1	0	–1	–1	–1	–1	1	1	1	–1
*M*5	0	1	1	1	0	0	1	1	1	1	1	1
*M*6	0	1	1	1	0	0	1	1	1	1	1	1
*M*7	–1	1	1	1	–1	–1	0	1	1	1	1	1
*M*8	–1	1	1	1	–1	–1	–1	0	1	1	1	0
*M*9	–1	–1	–1	–1	–1	–1	–1	–1	0	–1	1	–1
*M*10	–1	–1	–1	–1	–1	–1	–1	–1	1	0	1	–1
*M*11	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	0	–1
*M*12	–1	1	1	1	–1	–1	–1	0	1	1	1	0

Table 6

Scoring for each machine type for criterion *C*3

M*/*P	***P*1**	***P*2**	***P*3**	***P*4**	***P*5**	***P*6**	***P*7**	***P*8**	***P*9**	***P*10**	***P*11**	***P*12**
*M*1	0	1	1	1	0	0	1	1	1	1	1	1
*M*2	–1	0	0	1	–1	–1	0	1	1	1	1	1
*M*3	–1	0	0	1	–1	–1	0	1	1	1	1	1
*M*4	–1	–1	–1	0	–1	–1	–1	–1	1	1	1	–1
*M*5	0	1	1	1	0	0	1	1	1	1	1	1
*M*6	0	1	1	1	0	0	1	1	1	1	1	1
*M*7	–1	0	0	1	–1	–1	0	1	1	1	1	1
*M*8	–1	–1	–1	1	–1	–1	–1	0	1	1	1	0
*M*9	–1	–1	–1	–1	–1	–1	–1	–1	0	–1	1	–1
*M*10	–1	–1	–1	–1	–1	–1	–1	–1	1	0	1	–1
*M*11	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	0	–1
*M*12	–1	–1	–1	1	–1	–1	–1	0	1	1	1	0

Table 7

Scoring for each machine type for criterion *C*4

M*/*P	***P*1**	***P*2**	***P*3**	***P*4**	***P*5**	***P*6**	***P*7**	***P*8**	***P*9**	***P*10**	***P*11**	***P*12**
*M*1	0	1	1	1	0	0	0	0	1	1	1	0
*M*2	–1	0	0	0	–1	–1	–1	–1	1	1	1	–1
*M*3	–1	0	0	0	–1	–1	–1	–1	1	1	1	–1
*M*4	–1	0	0	0	–1	–1	–1	–1	1	1	1	–1
*M*5	0	1	1	1	0	0	0	0	1	1	1	0
*M*6	0	1	1	1	0	0	0	0	1	1	1	0
*M*7	0	1	1	1	0	0	0	0	1	1	1	0
*M*8	0	1	1	1	0	0	0	0	1	1	1	0
*M*9	–1	–1	–1	–1	–1	–1	–1	–1	0	–1	0	–1
*M*10	–1	–1	–1	–1	–1	–1	–1	–1	1	0	1	–1
*M*11	–1	–1	–1	–1	–1	–1	–1	–1	0	–1	0	–1
*M*12	0	1	1	1	0	0	0	0	1	1	1	0

Table 8

Scoring for each machine type for criterion *C*5

M*/*P	***P*1**	***P*2**	***P*3**	***P*4**	***P*5**	***P*6**	***P*7**	***P*8**	***P*9**	***P*10**	***P*11**	***P*12**
*M*1	0	–1	–1	–1	0	0	–1	–1	1	–1	1	–1
*M*2	1	0	0	0	1	1	1	1	1	1	1	1
*M*3	1	0	0	0	1	1	1	1	1	1	1	1
*M*4	1	0	0	0	1	1	1	1	1	1	1	1
*M*5	0	–1	–1	–1	0	0	–1	–1	1	–1	1	–1
*M*6	0	–1	–1	–1	0	0	–1	–1	1	–1	1	–1
*M*7	1	–1	–1	–1	1	1	0	0	1	1	1	0
*M*8	1	–1	–1	–1	1	1	0	0	1	1	1	0
*M*9	–1	–1	–1	–1	–1	–1	–1	–1	0	–1	0	–1
*M*10	1	–1	–1	–1	1	1	–1	–1	1	0	1	–1
*M*11	–1	–1	–1	–1	–1	–1	–1	–1	0	–1	0	–1
*M*12	1	–1	–1	–1	1	1	0	0	1	1	1	0

Table 9
Scoring for each machine type for criterion *C*6

M/*P*	*P*1	*P*2	*P*3	*P*4	*P*5	*P*6	*P*7	*P*8	*P*9	*P*10	*P*11	*P*12
*M*1	0	1	1	1	0	0	1	1	1	1	1	1
*M*2	–1	0	0	0	–1	–1	0	0	–1	0	1	0
*M*3	–1	0	0	0	–1	–1	0	0	–1	0	1	0
*M*4	–1	0	0	0	–1	–1	0	0	–1	0	1	0
*M*5	0	1	1	1	0	0	1	1	1	1	1	1
*M*6	0	1	1	1	0	0	1	1	1	1	1	1
*M*7	–1	0	0	0	–1	–1	0	0	–1	0	1	0
*M*8	–1	0	0	0	–1	–1	0	0	–1	0	1	0
*M*9	–1	1	1	1	–1	–1	1	1	0	1	1	1
*M*10	–1	0	0	0	–1	–1	0	0	–1	0	1	0
*M*11	–1	–1	–1	–1	–1	–1	–1	–1	–1	–1	0	–1
*M*12	–1	0	0	0	–1	–1	0	0	–1	0	1	0

Table 10
Scoring for each machine type for criterion *C*7

M/*P*	*P*1	*P*2	*P*3	*P*4	*P*5	*P*6	*P*7	*P*8	*P*9	*P*10	*P*11	*P*12
*M*1	0	0	0	0	0	1	0	0	1	1	1	0
*M*2	0	0	0	0	0	1	0	0	1	1	1	0
*M*3	0	0	0	0	0	1	0	0	1	1	1	0
*M*4	0	0	0	0	0	1	0	0	1	1	1	0
*M*5	0	0	0	0	0	1	0	0	1	1	1	0
*M*6	–1	–1	–1	–1	–1	0	–1	–1	0	0	0	–1
*M*7	0	0	0	0	0	1	0	0	1	1	1	0
*M*8	0	0	0	0	0	1	0	0	1	1	1	0
*M*9	–1	–1	–1	–1	–1	0	–1	–1	0	0	0	–1
*M*10	–1	–1	–1	–1	–1	0	–1	–1	0	0	0	–1
*M*11	–1	–1	–1	–1	–1	0	–1	–1	0	0	0	–1
*M*12	0	0	0	0	0	1	0	0	1	1	1	0

Table 11
Scoring for each machine type for criterion *C*8

M/*P*	*P*1	*P*2	*P*3	*P*4	*P*5	*P*6	*P*7	*P*8	*P*9	*P*10	*P*11	*P*12
*M*1	0	0	–1	–1	–1	–1	–1	–1	1	1	–1	0
*M*2	0	0	–1	–1	–1	–1	–1	–1	1	1	–1	0
*M*3	1	1	0	–1	1	1	1	1	1	1	1	1
*M*4	1	1	1	0	1	1	1	1	1	1	1	1
*M*5	1	1	–1	–1	0	1	1	1	1	1	1	1
*M*6	1	1	–1	–1	–1	0	0	1	1	1	1	1
*M*7	1	1	–1	–1	–1	0	0	1	1	1	1	1
*M*8	1	1	–1	–1	–1	–1	–1	0	1	1	0	1
*M*9	–1	–1	–1	–1	–1	–1	–1	–1	0	1	–1	–1
*M*10	–1	–1	–1	–1	–1	–1	–1	–1	–1	0	–1	–1
*M*11	1	1	–1	–1	–1	–1	–1	0	1	1	0	1
*M*12	0	0	–1	–1	–1	–1	–1	–1	1	1	–1	0

Step 2 of the CURLI method has been applied, the result was the *Q* matrix as in **Table 12**.

Step 3 of the *CURLI* method has been applied to rearrange the *Q* matrix. After moving the positions of the rows and columns, there is a new matrix as in **Table 13**.

Table 12

Q matrix

M/*P*	*P*1	*P*2	*P*3	*P*4	*P*5	*P*6	*P*7	*P*8	*P*9	*P*10	*P*11	*P*12
*M*1	0	4	3	3	–1	0	2	2	8	6	6	3
*M*2	–4	0	–1	1	–5	–4	–3	–2	6	6	6	–1
*M*3	–3	1	0	1	–3	–2	–1	0	6	6	8	0
*M*4	–3	–1	–1	0	–3	–2	–2	–2	6	6	8	–2
*M*5	1	5	3	3	0	2	4	4	8	6	8	4
*M*6	0	4	2	2	–2	0	2	3	7	5	7	3
*M*7	–2	3	1	2	–4	–2	0	4	6	7	8	4
*M*8	–2	2	0	2	–4	–3	–4	0	6	7	7	1
*M*9	–8	–6	–6	–6	–8	–7	–6	–6	0	–3	3	–6
*M*10	–6	–6	–6	–6	–6	–5	–7	–7	3	0	5	–7
*M*11	–6	–6	–8	–8	–8	–7	–8	–7	–3	–5	0	–6
*M*12	–3	1	0	2	–4	–3	–4	–1	6	7	6	0

Table 13

Q matrix after rearranging

M/*S*	*P*11	*P*9	*P*10	*P*2	*P*4	*P*12	*P*8	*P*3	*P*7	*P*6	*P*1	*P*5
*M*11	0	–3	–5	–6	–8	–6	–7	–8	–8	–7	–6	–8
*M*9	3	0	–3	–6	–6	–6	–6	–6	–6	–7	–8	–8
*M*10	5	3	0	–6	–6	–7	–7	–6	–7	–5	–6	–6
*M*2	6	6	6	0	1	–1	–2	–1	–3	–4	–4	–5
*M*4	8	6	6	–1	0	–2	–2	–1	–2	–2	–3	–3
*M*12	6	6	7	1	2	0	–1	0	–4	–3	–3	–4
*M*8	7	6	7	2	2	1	0	0	–4	–3	–2	–4
*M*3	8	6	6	1	1	0	0	0	–1	–2	–3	–3
*M*7	8	6	7	3	2	4	4	1	0	–2	–2	–4
*M*6	7	7	5	4	2	3	3	2	2	0	0	–2
*M*1	6	8	6	4	3	3	2	3	2	0	0	–1
*M*5	8	8	6	5	3	4	4	3	4	2	1	0

According to the data in **Table 13**, it is possible to see that almost every cells which lie above the main diagonal of the matrix are non-negative. On the contrary, almost every cells that lie below the main diagonal of the matrix are non-positive. Which means the rearrangement of the rows and columns of the *Q* matrix was successful. Accordingly, *M*11 is considered to be the best alternative. In other words, OKAMOTO 700×1500 is the best grinding machine among the twelve surveyed machines.

Table 14 presents the ranking results of grinding machine types using the *FUCA* method and the *CURLI* method:

Table 14

Ranking the grinding machine types using different methods

Grinding machine	*M*1	*M*2	*M*3	*M*4	*M*5	*M*6	*M*7	*M*8	*M*9	*M*10	*M*11	*M*12
FUCA	10	4	8	5	11	9	12	7	2	3	1	6
CURLI	11	4	8	5	12	10	9	7	2	3	1	6

Observing **Table 14**, it can be seen that the results of ranking the grinding machine types by the two methods *FUCA* and *CURLI* are quite similar. 8/12 ranks of machines are completely the same when using the two methods *FUCA* and *CURLI*. The most important thing is that both *FUCA* method and *CURLI* method show that *M*11 is the best machine type. That means both methods are confirmed to be equally effective in this case. *M*11 is the best alternative. In other words, OKAMOTO 700×1500 is the best grinding machine.

3. 2. Case 2: Selecting drilling machine

Thirteen different types of drilling machine are considered in this case, which are Z3032X7, Z3032X7P, Z3040X8/1, Z3040X10/1, Z3063×25A, Z3080×25, Z3050X16/1, FRD-1700H, ZWB3050X16, FRD-1100S, FRD-1300H, FRD-750S, and FRD-900S. They are denoted as *M*1, *M*2, …, *M*13, respectively. The data of thirteen drilling machine types is provided by the supplier as in **Table 15** [28]:

Table 15

Drilling machine types [28]

M/*C*	*C*1	*C*2	*C*3	*C*4	*C*5	*C*6	*C*7	*C*8	*C*9	*C*10	*C*11
*M*1	31.5	16	750	130	400	8	3	150	700	300	65
*M*2	31.5	16	750	130	400	8	3	150	700	300	68
*M*3	40	27	1500	240	500	6	3	200	820	120	72.5
*M*4	40	30	1500	240	700	6	doomsday	200	1020	320	90
*M*5	63	36	5500	400	1600	16	doomsday	450	2050	450	105
*M*6	80	42	7500	450	2000	16	doomsday	550	2500	500	120
*M*7	50	36	4000	315	1250	16	doomsday	350	1600	350	100
*M*8	55	50	7500	250	1310	12	doomsday	336	1700	400	95
*M*9	55	30	4000	315	1250	doomsday	doomsday	350	1600	350	135
*M*10	50	25	3000	250	810	12	3	300	1145	330	90
*M*11	55	50	5000	250	920	12	doomsday	300	1240	330	100
*M*12	38	25	2000	200	500	6	3	210	775	290	55
*M*13	38	25	2000	200	650	6	3	210	920	290	60
Unit	mm	mm	W	mm	mm	–	–	mm	mm	mm	million
Type	max	max	max	max	max	max	max	max	max	min	min

Eleven criteria have been used to describe for each machine type. The units and types of the criteria are summarized in the last two rows in **Table 15**. The detailed explanation of each criterion is as follows:

*C*1: is the maximum diameter of a hole machined in a workpiece that the machine can drill;

*C*2: is the maximum diameter of a threaded hole in a workpiece that the machine can tap;

*C*3: is the capacity of the machine;

*C*4: is the maximum stroke of the main shaft. This parameter decides the maximum depth of hole machined in a workpiece that can be machined in the machine;

*C*5: is the maximum horizontal stroke of the drill head. This parameter decides the maximum size of a workpiece that can be machined in the machine;

*C*6: is the number of spindle speed levels. The bigger this parameter is, the more flexible the machine can be adjusted;

*C*7: is the number of feed rate levels. This is also a parameter that effects the ability to adjust the flexibility of the machine;

*C*6 and *C*7 are the two criteria that are different from all the other criteria. These two criteria are qualitative criteria while all the other criteria are quantitative criteria;

*C*8: is the diameter of the cylinder. The bigger the cylinder diameter of the machine is, the higher the rigidity of the machine is;

*C*9: is the maximum distance from the center of the main shaft to the cylinder of the machine. This is also a parameter that decides the maximum size of a workpiece that can be machined in the machine;

*C*10: is the minimum distance from the center of the main shaft to the cylinder of the machine. This parameter decides the number of hole can be drilled in a workpiece in one placement. Which means the smaller this parameter is, the more holes can be drilled in one placement;

*C*11: is the price of the machine. Of course, this is a the-smaller-the-better parameter.

The task of selecting the drilling machine in this example is to choose the one that is considered to be the best of the thirteen available machines. The drilling machine that is considered the best is the one in which the criteria *C*1, *C*2, *C*3, *C*4, *C*5, *C*6, *C*7, *C*8, *C*9 are considered «largest» and *C*10 and *C*11 are considered the «smallest».

Ranking the drilling machine types by the two methods *FUCA* and *CURLI* has also been performed in the same way in case 1. **Table 16** presents the results of ranking the drilling machine types by two different methods:

Table 16
Ranking the drilling machine type by different methods

Drill machine	*M*1	*M*2	*M*3	*M*4	*M*5	*M*6	*M*7	*M*8	*M*9	*M*10	*M*11	*M*12	*M*13
FUCA	12	13	10	8	2	1	4	3	5	7	6	11	9
CURLI	12	13	10	8	2	1	4	3	5	7	6	11	9

Observing **Table 16**, it can be seen that all the ranks of the thirteen machines are the same when using the two methods *FUCA* and *CURLI*. That means the efficiency of these two methods is also confirmed to be equal in this case. *M*6 is the best alternative, in other words, *Z*3080×25 is the best drilling machine among the thirteen surveyed drilling machines.

3. 3. Case 3: Selecting milling machine

In this case, nine milling machine types have been taken into consideration. Nine machine types are denoted as *M*1, *M*2, ..., *M*9, respectively, which correspond to the machine types *ZX*7016, *ZX*7025, *ZX*7032, *ZX*7040B, *ZX*7040B1, *ZX*7045, *ZX*7045*B*, *ZX*7045*B*1, and *ZX*7045*C*. The data of these machine types is also introduced by the supplier as in **Table 17** [29]:

Table 17
Milling machine types [29]

M/*C*	*C*1	*C*2	*C*3	*C*4	*C*5	*C*6	*C*7	*C*8	*C*9	*C*10	*C*11	*C*12	*C*13
*M*1	40	10	16	80	12	550	63840	320	120	360	182	100	12.5
*M*2	63	13	25	110	5	750	108225	240	140	510	240	190	25
*M*3	80	22	31.5	130	12	1500	153300	450	170	460	202	285	40
*M*4	80	22	40	110	6	1100	153300	450	170	450	261.5	340	63
*M*5	80	22	40	110	12	1100	153300	450	170	450	261.5	340	65
*M*6	80	28	45	120	6	1110	196800	540	170	475	260	318	57
*M*7	80	28	32	110	6	1500	153300	450	170	475	260	405	68
*M*8	80	28	32	110	12	1500	196800	540	170	475	260	405	70
*M*9	80	28	45	110	6	1500	196800	540	170	475	260	375	82
Unit	mm	mm	mm	mm	–	W	mm^2	mm	mm	mm	mm	kg	million
Type	max	max	max	max	max	max	max	max	max	max	max	max	min

Thirteen criteria have been used to describe each machine type. The units and types of each criterion have also been summarized in the last two rows of **Table 17**. In detail, they are:

*C*1: is the maximum size of the surface of a workpiece that the machine can milled when using face milling cutter;

*C*2: is the maximum size of the groove that the machine can mill when using end mill;

*C*3: is the maximum diameter of the hole that can be machined when using the machine in drill mode;

*C*4: is the maximum stroke of the main shaft of the machine. This parameter decides the maximum depth that can be drilled by the machine;

*C*5: is the number of speed levels, this is the parameter that decides the flexibility in changing cutting speed;

*C*6: is the capacity of the engine;

*C*7: is the size of the table. The larger the size of the working Table is, the larger the size of the part that can be machined, and vice versa;

*C*8: is the vertical stroke of the table. This parameter decides the maximum length of the working surface that can be milled in a single feed;

*C*9: is the horizontal stroke of the table. This parameter decides the maximum width of the surface that can be milled in a single feed;

*C*10: is the distance from the spindle to the table. This parameter decides the maximum height of a workpiece that can be placed on the table;

*C*11: is the distance from the shaft to the cylinder. This parameter decides the maximum width of a workpiece that can be placed on the table;

*C*12: is the weight of the machine. A machine with higher weight, the higher the rigidity;

*C*13: is the price of the machine.

The task of selecting the milling machine in this example is to choose the one that is considered to be the best of the nine available machines.

The milling machine that is considered the best is the one in which the criteria *C*1, *C*2, *C*3, *C*4, *C*5, *C*6, *C*7, *C*8, *C*9, *C*10, *C*11 and *C*12 are considered «largest» and C13 is considered the «smallest».

The two methods *FUCA* and *CURLI* have also been used in the same way as in case 1 to rank the milling machine in this case. **Table 18** shows the results of ranking the machine types by two different methods:

Table 18
Ranking the milling machines by different methods

Milling machine	***M*1**	***M*2**	***M*3**	***M*4**	***M*5**	***M*6**	***M*7**	***M*8**	***M*9**
FUCA	9	8	5	7	6	1	4	2	3
CURLI	9	8	5	7	6	1	4	2	3

Observing **Table 18**, it can be seen that all the ranks of the machine types are the same when using the two methods *FUCA* and *CURLI*.

One more time, it is possible to confirm that the two methods *FUCA* and *CURLI* are equally effective in this case. *M*6 is the best alternative. In other words, among the nine considered milling machines, *ZX*7045 is the best machine type.

From the achieved results above, it is possible to see that:

– the two methods *FUCA* and *CURLI* are confirmed to be equally effective in selecting the best machine tool;

– among the twelve machines, including KURODA 110×315, NAGASE 300×600, NAGASE 300×600-1998, NAGASE 400×600, NICCO 110×315, NICCO 110×315, NICCO 200×500, OKAMOTO 200×500, OKAMOTO 500×1200, OKMAMOTO 500×600, OKAMOTO 700×1500, and KURODA 200×500, OKAMOTO 700×1500 is the best grinding machine type;

– among the thirteen drilling machine, including *Z*3032X7, *Z*3032X7P, *Z*3040X8/1, *Z*3040X10/1, *Z*3063x25A, *Z*3080x25, *Z*3050X16/1, FRD-1700H, *ZWB*3050*X*16, FRD-1100S, FRD-1300H, FRD-750S, and FRD-900S, Z3080×25 is the best machine;

– *ZX*7045 is the best milling machine among the nine machine type including *ZX*7016, *ZX*7025, *ZX*7032, *ZX*7040B, *ZX*7040B1, *ZX*7045, *ZX*7045B, *ZX*7045B1, and *ZX*7045C.

3. 4. Limitations of the study and development prospects

Ranking the machines will be more completed if more criteria are taken into consideration, such as safety in use, level of environmental pollution, noise when operating, etc. This is the work to be done in the near future.

In this study, the weights of the criteria were chosen to be equal. However, the ranks of the machine types can be changed when using the *FUCA* method if the weights of the criteria are determined by other methods. This is also a content that needs to be done in other specific cases.

4. Conclusions

The ranking to select the best machine tool has a great influence on the efficiency of the machining process. Two different *MCDM* methods, *FUCA* and *CURLI*, were used to select grinding machine, drilling machine and milling machine. The results have shown that these two methods are equally effective in determining the best alternative in all three cases.

With the information provided by the three suppliers, the best product code for the grinding machine is OKAMOTO 700×1500, the best drilling machine is the machine with the product code *Z*3080×25, the milling machine with the product code *ZX*7045 is the best machine type.

Use the *FUCA* method for machine tool selection when weighting of criteria needs to be considered. Conversely, when the weight of the criteria is not considered, the recommended *CURLI* method is used.

Conflict of interest

The authors declare that there is no conflict of interest in relation to this paper, as well as the published research results, including the financial aspects of conducting the research, obtaining and using its results, as well as any non-financial personal relationships.

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Data availability

Manuscript has data included as electronic supplementary material.

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