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MULTI-OBJECTIVE OPTIMIZATION OF TURNING PROCESS BY FUCA METHOD

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Abstract: A study about multi-objective optimization of turning process has been done in this paper. Twenty-five experiments of a matrix designed according to Taguchi method have been performed. In each experiment, the values of five parameters were changed, including tool nose radius, tool holder length, spindle speed, feed rate, and cutting depth. The three output parameters determined for each experiment include surface roughness, roundness deviation and material removal capacity. Four different methods were used to calculate the weights of the output parameters. The *FUCA* method was used to solve the multi-objective optimization problem. This work was repeated four times with four corresponding weight sets of the criteria. The purpose of solving the multi-objective optimization problem is determining the values of the input parameters to ensure both the surface roughness parameter and the roundness deviation parameter are the smaller the better, and the material removal capacity is the larger the better. A surprising thing happened, the optimal values of the set of input parameters were exactly the same when using four different weighting methods. Accordingly, the optimal values of tool nose radius, tool holder length, spindle speed, feed rate and cutting depth correspondingly are 0.8 (mm), 40 (mm), 587 (rev/min), 0.316 (mm/rev) and 0.6 (mm).

KEYWORDS: Turning, Optimization, FUCA method, weight method

1 Introduction

The turning method plays an important role in mechanical production [1, 2]. Normally, for each product that needs to be machined by cutting methods, the machining volumne of the turning method accounts for a large proportion [3, 4]. For the turning method in particular and the other machining methods in general, they all have the same purpose which is ensuring both economic and technical criteria. To ensure both economic and technical goals, the highest productivity, the least material consumption, the lowest labor cost, etc. To achieve multiple goals at the same time, it is a need to solve the multi-objective optimization problem [5, 6]. There are two ways to solve optimization problems. The *first one* is, using algorithms, such as Genetic Algorithm (*GA)*, Particle Swarm Optimization (*PSO)*, Ant Colony Optimization (*ACO)*, ect. The *second one* is, using mathematical methods to find out the best alternative (the optimal alternative) among the available methods. The first way has been used in many announced studies. However, this way has a limitation that the optimal values of the parameters found by solving the algorithm are difficult to apply in real production. Which means the technological equipments are not able to be adjusted to achieve the optimal values. This problem usually happens with normal lathes (not CNC lathes). Therefore, in this study, only multi-objective optimization in the second way is mentioned, which is finding the best alternative among the available alternatives. The work of finding the the best alternative among the available alternatives is called decision-making. Making a decision where each alternative is described by many criteria, it is called multi-criteria decision-making (*MCDM*) [7]. Many different *MCDM* methods were proposed by scientists, and they were applied to choose the

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optimal alternative in all fields. Talk about machining using turning method field only, *MCDM* methods have been applied widely in recent years.

There are studies which use one *MCDM* method only. The *WASPAS* method was applied for multi-objective optimization of steel turning process for bearing (bearing Steel) [8], AISI D3 steel turning [9]. The multi-objective optimiaztion of AISI 4340 steel turning process was done using the *ARAS* method [10]. The result of multi-objective optimization of ASTM A36 steel turning process was achieved by using the *COPRAS-G* method [11]. The *TOPSIS* method was used to solve the multi-objective optimization problem in many studies, such as turning AISI-D3 steel [12], turning AISI1040 steel [13], turning EN25 steel [14], turning Al7075 aluminum [15], and turning Pure Titanium material [16].

Meanwhile, there are also studies that used simultaneously multiple *MCDM* methods. The two methods *TOPSIS* and *PIV* were used simultaneously to solve the multi-objective optimization problem of 9XC steel turning process [17]. Solving multi-objective optimization problem of ASTM A588 steel turning process was done using both methods *MOORA* and *TOPSIS* [18]. The two methods *ARAS* and *CODAS* were used for multi-objective optimization of Inconel 718 steel alloy turning process [19]. The result of multi-objective optimization for turning AISI 304 steel was achieved by using simultaneously the three methods *MOORA*, *VIKOR* and *TOPSIS* [20]. All five methods including *COCOSO*, *MABAC*, *MAIRCA*, *EAMR*, *TOPSIS* were used simultaneously for multi-objective optimization of AISI 1045 steel hole turning process [21]. Recently, multi-objective optimization of 150Cr14 steel turning process has been done by using simultaneously nine methods including *R*, *CURLI*, *SAW*, *WASPAS*, *TOPSIS*, *VIKOR*, *MOORA*, *COPRA*S and *PIV* [22, 23].

The above are just a few of many studies that used different *MCDM* methods to solve multi-objective optimization problem of turning process. It can be seen that applying a new *MCDM* method for solving multi-objective optimization of turning process will also contribute deeper sights into this massive research direction.

FUCA is known to be a multi-criteria decision-making method which does not need to normalize data [24, 25]. Although it was found recently but this method has been applied to select the optimal alternatives in some different fields: selecting the best company [26], selecting the optimal solution of financial performance of companies [27-29], selecting the optimal solution for chemical production process [30]. However, this method has not been applied for multi-objective optimization of machining processes in general and machining using turning method in particular. This gap need to be fulfilled, and this is also the reason for this study.

A common feature that almost every *MCDM* methods have is that the ranking order of alternatives can be changed if the weights of the criteria is changed. An alternative can only be considered to be the best if it is always ranked first when using different weighting methods [31]. From this fact, in this study, different weighting methods will be used. Four used methods include the *EQUAL* method, the *RS* method, the *ROC* method, and the *MEREC* method. The first three methods were used because of their simplicity, there is only one formula in those methods. The fourth method was also used because it is a recommended method [32].

The paper structure of the next parts consists of six parts. The content of the four used weighting methods will be presented in the second part. The steps to find the best alternative of the *FUCA* method will be presented in the third part. A turning process for testing will be presented in the fourth part. The analysis of the experimental results will be presented in the fifth part. Using the *FUCA* method and the different weighting methods to find out the best alternative is the content presented in the sixth part. The following is the conclusions achieved in this study.

2 The used weighting methods

2.1 EQUAL weight

The *EQUAL* method has been used to calculate the weights of the criteria according to the formula (1) [33].

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

Where, w_j is the weight of criterion j, n is the number of criteria.

2.2 RS weight

The *RS* method has been used to calculate the weights of the criteria according to the formula (2) [34].

$$w_j = \frac{2\,(n+1-k)}{n(n+1)} \tag{2}$$

Where, k is the ordinal number of criteria j, $k=1 \div n$

2.3 ROC weight

The *ROC* method has been used to calculate the weights of the criteria according to the formula (3) [34].

$$w_j = \frac{1}{n}\sum_{k=i}^{n}\frac{1}{k} \tag{3}$$

2.4 MEREC weight

The steps to calculate the weights of the criteria according to the *MEREC* method include [35].

Step 1: Calculate the normalized data according to the two formulas (4) and (5).

- For the larger the better criteria.

$$n_{ij} = \frac{min y_{ij}}{y_{ij}} \tag{4}$$

- For the smaller the better criteria.

$$n_{ij} = \frac{y_{ij}}{max\ y_{ij}} \tag{5}$$

Step 2: Calculate the overall efficiency of the alternatives according to the formula (6).

$$S_i = Ln\left[1 + \left(\frac{1}{n}\sum_{j}^{n}\left|ln\left(n_{ij}\right)\right|\right)\right] \tag{6}$$

Step 3: Calculate the efficiency of the alternatives according to the formula (7).

$$S'_{ij} = Ln\left[1 + \left(\frac{1}{n}\sum_{k,k\neq j}^{n}\left|ln(n_{ij})\right|\right)\right] \quad (7)$$

Step 4: Calculate the deviations according to the formula (8).

$$E_j = \sum_{i}^{m}\left|S'_{ij} - S_i\right| \quad (8)$$

Step 5: Calculate the weights of the criteria according to the formula (9).

$$w_j = \frac{E_j}{\sum_k^m E_k} \quad (9)$$

3 The FUCA method

The *FUCA* method is used to rank the alternatives to find out the best alternative according to three steps [24, 25].

Step 1. Ranking the alternatives for each criterion (r_{ij}). Assuming that there are *m* alternatives, the best value will be ranked first, in contrast, the worst value will be *m*-ranked. If there are *n* criteria, then perform ranking *n* times for each criterion.

Step 2. Scoring for each alternative according to the formula.

$$v_i = \sum_{j=1}^{n} r_{ij}.w_j \quad (10)$$

Step 3. Ranking the alternatives according to the values of v_i. The optimal alternative will be the one with the smallest v_i value, and vice versa.

4 Experiment process

The experiments have been done on traditional lathe. The machine can only adjust the values of the cutting parameters (spindle speed, feed rate, cutting depth) which are discrete values. Tool nose radius, tool holder length, spindle speed, feed rate and cutting depth have been chosen to be the input parameters [36].

Each input parameter has been chosen with five different values, corresponding to five levels of encoding from 1 to 5. The values of the parameters at the levels have been chosen according to the ability to adjust those values of the experiment, as shown in Table 1.

Table 1. Input parameter values

Parameter	Symbol	Unit	Value at level				
			1	2	3	4	5
Tool nose radius	r_ε	mm	0.25	0.4	0.6	0.8	0.85
Tool over hang	*L*	mm	25	30	35	40	45
Cutting speed	n_w	rev/min	421	587	659	788	926
Feed rate	f_d	mm/rev	0.08	0.094	0.112	0.124	0.316
Depth of cut	a_p	mm	0.1	0.2	0.4	0.6	1

The Taguchi method has been used to design the decision matrix. With five input parameters, each parameter has five values, an orthogonal matrix of twenty-five experiments (*L25*) has been established as shown in Table 2.

Table 2. Experimental matrix and results

Exp.	Input parameter					Response		
	r_ε (mm)	L (mm)	n_w (rev/min)	f_d (mm/rev)	a_p (mm)	Ra (μm)	RD (μm)	Q (mm^3/s)
1	0.25	25	421	0.08	0.2	0.823	8.333	10.581
2	0.25	30	587	0.094	0.4	0.657	7.667	34.669
3	0.25	35	659	0.112	0.6	0.459	9.333	69.562
4	0.25	40	788	0.124	0.1	0.992	11.000	15.349
5	0.25	45	926	0.316	1	0.817	13.667	459.640
6	0.4	25	587	0.112	0.1	0.523	14.000	10.327
7	0.4	30	659	0.124	1	0.449	13.333	128.359
8	0.4	35	788	0.316	0.2	0.873	15.333	78.228
9	0.4	40	926	0.08	0.4	0.645	11.667	46.546
10	0.4	45	421	0.094	0.6	0.456	10.667	37.298
11	0.6	25	659	0.316	0.4	0.992	16.667	130.844
12	0.6	30	788	0.08	0.6	0.764	13.000	59.414
13	0.6	35	926	0.094	0.1	0.654	8.333	13.673
14	0.6	40	421	0.112	1	0.823	5.333	74.066
15	0.6	45	587	0.124	0.2	0.446	11.333	22.867
16	0.8	25	788	0.094	1	0.598	8.667	116.352
17	0.8	30	926	0.112	0.2	0.777	11.333	32.582
18	0.8	35	421	0.124	0.4	0.649	13.667	32.801
19	0.8	40	587	0.316	0.6	0.568	8.333	174.822
20	0.8	45	659	0.08	0.1	0.668	10.667	8.281
21	0.85	25	926	0.124	0.6	0.786	17.333	108.219
22	0.85	30	421	0.316	0.1	0.812	15.667	20.897
23	0.85	35	587	0.08	1	0.452	12.667	73.765
24	0.85	40	659	0.094	0.2	0.657	15.667	19.461
25	0.85	45	788	0.112	0.4	0.678	16.333	55.453

After each experiment, measuring surface roughness (*Ra*), roundness deviation (*RD*) and material removal capacity (*Q*) has been done. These are three of the parameters which are commonly used to evaluate turning process. Determining these three parameters in each experiment is much simpler than determining the others parameters (cutting heat, vibration, tool wear, etc.) [36]. The samples of steel have been washed with alcohol and left dry before measuring. This is done to clean the surface of the steel samples for the purpose of increasing the accuracy of the measuring result. The surface roughness and roundness deviation have been measured for each steel sample at least three times continuously. The values of surface roughness and roundness deviation in each experiment are the average values of the sucessive measurements. The purpose of this work is reducing the affect of random errors in measuring process to the accuracy of measuring results.

The material removal capacity is calculated according to the formula (11) [36].

$$Q = \frac{1}{60} n_w \cdot \pi \cdot d \cdot f_d \cdot a_p \quad (11)$$

Where, *d* is the diameter of the test workpiece, $d = 30$ (mm).

The output parameter values in the experiments are also summarized in Table 2.

5 Analysis of experimental results

The purpose of multi-objective optimization is determining the input parameters values to ensure that the surface roughness is the smallest, the roundness deviation is the smallest, and the material removal capacity is the largest. However, observing Table 2, we can not choose a single experiment among the twenty-five experiments that ensures this goal. In detail, the surface roughness has the smallest value at the experiment #15 ($Ra = 0.446\ \mu m$), the roundness deviation has the smallest value at the experiment #14 ($RD = 5.333\ \mu m$), meanwhile, the material removal capacity has the largest value at the experiment #5 (*Q=459.640 mm³/s*). Thus, it is obviously impossible to choose an experiment where *Ra* is the absolute smallest, *RD* is the absolute smallest and *Q* is the absolute largest. Instead, we can only find an experiment that simultaneously ensures that *Ra* is considered the smallest, *RD* is considered the smallest and *Q* is considered the largest. However, finding out an optimal experiment is also unable to achieve by observing the data in Table 2 only. An experiment which is considered to be optimal can only be found when using *MCDM* methods. The *FUCA* method has been used in this study. In the next part of this paper, four different weighting methods will be used to determine the weights of the criteria *Ra*, *RD* and *Q*, after that, the *FUCA* method will be used to find out the optimal experiment.

6 Results and discussion

The formulas (1), (2) and (3) have been used to calculate the weights of the criteria *Ra*, *RD* and *Q* according to the corresponding weighting methods which are the *EQUAL* method, the *RS* method and the *ROC* method. The formulas (4) to (9) have been used to calculate the weights of the criteria according to the *MEREC* method. The values of the weights of the criteria calculated by different methods have been presented in Table 3.

So, the weights of the criteria were calculated according to four different methods. The next thing to be done is using the FUCA method to rank the above experiments. The optimal experiment is the experiment which is ranked first.

Table 3. Weights of the criteria

Weight method	Criteria		
	Ra	RD	Q
EQUAL	1/3	1/3	1/3
RS	0.5000	0.3333	0.1667
ROC	0.6111	0.2778	0.1111
MEREC	0.1525	0.1550	0.6925

Applying step 1 of the FUCA method to rank the experiments or each criteria as shown in Table 4.

Table 4. Ranking the experiments for each criteria

Exp.	Rank		
	Ra	RD	Q
1	21.5	4	24
2	12.5	2	15
3	5	7	10
4	24.5	10	21
5	20	17	1
6	6	19	23
7	2	17	4
8	23	20	7
9	9	12	13
10	4	8.5	14
11	24.5	24	3
12	16	15	11
13	11	4	22
14	21.5	1	8
15	1	12	18
16	8	6	5
17	17	12	17
18	10	17	16
19	7	4	2
20	14	8.5	25
21	18	25	6
22	19	21.5	19
23	3	14	9
24	12.5	21.5	20
25	15	23	12
SUM	**325**	**325**	**325**

The formula (10) has been used to calulate the score v_i for each experiment. The application of the formula (10) repeatedly corresponds with four different sets of weight. The scores of the experiments have been summarized in Table 5. This table also summarized the ranking results of the experiments.

Table 5. Scores of each experiment and ranking the experiments

Exp.	Weight method							
	Equal		RS		ROC		MEREC	
	v_i	Rank	v_i	Rank	v_i	Rank	v_i	Rank
1	16.500	19	16.083	18	16.916	19	20.519	24
2	9.833	7	9.417	8	9.861	8	12.604	14
3	7.333	3	6.500	2	6.111	3	8.773	5
4	18.500	24	19.083	22	20.083	23	19.829	23
5	12.667	12	15.833	17	17.056	20	6.378	4
6	16.000	17	13.167	12	11.500	11	19.788	22
7	7.667	4	7.333	5	6.389	5	5.710	3
8	16.667	21	19.333	23	20.389	24	11.455	10
9	11.333	10	10.667	10	10.278	10	12.235	12
10	8.833	6	7.167	4	6.361	4	11.623	11
11	17.166	22	20.750	25	21.972	25	9.534	8
12	14.000	13	14.833	15	15.167	15	12.383	13
13	12.333	11	10.500	9	10.278	9	17.533	19
14	10.167	8	12.417	11	14.305	14	8.974	7
15	10.333	9	7.500	6	5.945	2	14.478	16
16	6.333	2	6.833	3	7.111	7	5.613	2
17	15.333	15	15.333	16	15.611	16	16.225	18
18	14.333	14	13.333	13	12.611	12	15.240	17
19	4.333	1	5.167	1	5.611	1	3.073	1
20	15.833	16	14.000	14	13.694	13	20.765	25
21	16.333	18	18.333	21	18.611	21	10.775	9
22	19.833	25	19.833	24	19.695	22	19.388	21
23	8.667	5	7.667	7	6.722	6	8.860	6
24	18.000	23	16.750	19	15.833	17	19.089	20
25	16.667	20	17.167	20	16.889	18	14.163	15

To make it convenient to observe, the data in Table 5 has been presented in the form of a paragraph as shown in Figure 1.

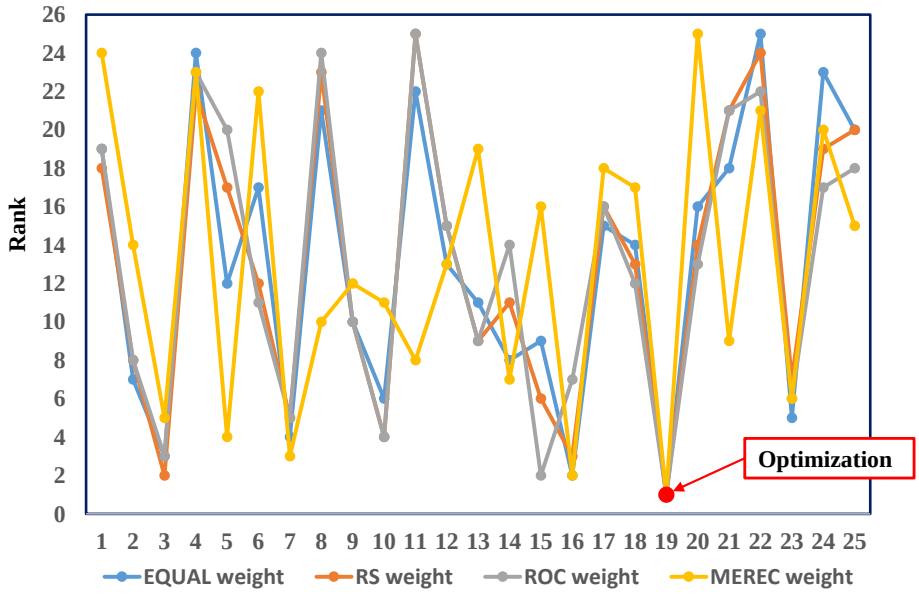


Figure 1. Ranking the experiments with different weighting methods

Observing Table 5 and Figure 1, it can be seen that the ranking results of the experiments depend a lot on the weighting methods of the criteria. This comment is also suitable with the assertion mentioned in many recently published studies [37-39]. However, the experiment #19 is always determined to be the optimal experiment corresponding with all four different sets of weight. This makes a strong belief that #19 is the true optimal experiment. Finally, we know that the optimal value of tool nose radius is 0.8 (mm), the optimal tool holder length is 40 (mm), the optimal value of spindle speed is 587 (rev/min), the optimal value of feed rate is 0.316 (mm/rev), and the optimal value of cutting depth is 0.6 (mm).

CONCLUSION

This is the first study that applies the *FUCA* method to solve the multi-objective optimization problem for turning process. Some conclusions drawn are as follows:

1. The ranks of the experiments will change when the weights of the output parameters change.

2. In this study, the optimal experiment does not depend on the weights of the criteria.

3. The optimal values of tool nose radius, tool holder length, spindle speed, feed rate and cutting depth are 8 (mm), 40 (mm), 587 (rev/min), 0.316 (mm/rev), and 0.6 (mm), respectively.

4. Further determine the optimal values of other parameters (cutting tool material, cooling lubrication, etc.) to ensure more goals (minimum cutting heat, minimum cutting force, etc.) is the work to do in the future.

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