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Multi-Objective Optimization of CNC Turning Process for C45 Steel Using Analytic Hierarchy Process Method

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Abstract— *This research focuses on the multi-objective optimization of the CNC turning process for C45 steel, with the objectives of minimizing surface roughness (R_a), reducing cutting time (T_c), and increasing material removal rate (MRR). The study conducted nine experiments, considering three process parameters: cutting speed (V_c) in meters per minute, feed rate (f_z) in millimeters per revolution, and cutting depth (a_p) in millimeters. Analytic Hierarchy Process (AHP) methodology was employed to determine the optimal set of process parameters. The experiments were designed and executed to investigate the effects of different combinations of cutting speed, feed rate, and cutting depth on the performance measures. Surface roughness, cutting time, and MRR were measured and analyzed to evaluate the impact of the process parameters on the overall performance of the turning process. The AHP technique was applied to prioritize the process parameters based on their relative importance in achieving the desired objectives. By employing the AHP method, the optimal set of process parameters was determined, which resulted in the simultaneous improvement of surface roughness, cutting time, and MRR. The findings of this study contribute to the field of CNC turning optimization by providing insights into the relationships between process parameters and performance measures. The AHP methodology demonstrates its effectiveness in solving multi-objective optimization problems, enabling manufacturers to achieve improved productivity and quality in CNC turning operations.*

Keywords— *CNC Turning, Multi-Objective Optimization, Cutting Time, Material Removal Rate, Analytic Hierarchy Process, AHP.*

I. INTRODUCTION

The CNC turning process is widely employed in the manufacturing industry to fabricate high-precision components [1]. Optimization of this process is of paramount importance as it can enhance productivity, reduce costs, and improve the quality of the final products. In recent years, there has been an increasing interest in employing multi-objective optimization techniques to simultaneously optimize multiple performance measures in manufacturing processes [2]–[5].

Surface roughness (R_a), cutting time (T_c), and material removal rate (MRR) are critical performance indicators in CNC turning. Achieving lower surface roughness values is desirable to ensure optimal functionality and enhance the visual appeal of the machined components. Additionally, reducing cutting time can significantly improve productivity and efficiency, leading to cost savings. Furthermore, maximizing the material removal rate (MRR) is essential for achieving higher production rates and overall process performance improvement.

To effectively address these simultaneous objectives, an appropriate optimization methodology is required. In this study, the Analytic Hierarchy Process (AHP) [6] is utilized as the decision-making tool. AHP is a well-established technique widely applied in multi-criteria decision analysis and has been successfully employed in various optimization studies within the manufacturing domain.

AHP offers several advantages for this research [7]. Firstly, it allows the consideration of multiple criteria and their relative importance in the decision-making process. By structuring the decision problem hierarchically, AHP enables a systematic and comprehensive evaluation of different process parameters. Secondly, AHP provides a mathematical framework to prioritize the importance of each criterion, facilitating the identification of the optimal set of process parameters that simultaneously minimize Ra, reduce T, and maximize MRR. Leveraging the strengths of AHP, this research aims to achieve an optimized CNC turning process for C45 steel.

Previous studies have demonstrated the effectiveness of AHP in solving optimization problems in various manufacturing domains. For instance, Smith et al. applied AHP to optimize cutting parameters in a milling process, successfully improving surface finish and tool life simultaneously. Additionally, Zhang et al. [8] employed AHP to optimize process parameters in laser cutting, resulting in enhanced cutting quality and reduced heat-affected zone.

Building upon these foundations, the present study contributes to the field of CNC turning optimization by investigating the effects of cutting speed (V_c), feed rate (f_z), and cutting depth (a_p) on R_a, T_c, and MRR. The application of AHP methodology enables the identification of the optimal combination of process parameters, leading to improved productivity, quality, and efficiency in the CNC turning process for C45 steel.

Overall, this research addresses the need for multi-objective optimization in CNC turning, emphasizing the importance of simultaneously minimizing R_a, reducing T_c, and maximizing MRR. The utilization of AHP methodology provides a structured approach to decision-making, allowing for effective parameter selection and optimization.

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II. METHODOLOGY

A. Experimental Design

A comprehensive experimental design was developed to explore the influence of cutting parameters on surface roughness. The selection of cutting parameters was based on a literature review and prior knowledge. The key cutting parameters considered in this study include cutting speed (V_c-m/min), feed rate (f_z – mm/rev), and depth of cut (a_p-mm). Each parameter was assigned multiple levels to capture the potential effects on surface roughness.The arrange of cutting parameters is show in Table 1.

TABLE 1. The variants and them arrange.

Parameters	Symbol	Unit	Level		
			-1	0	1
Cutting Speed	V_c	*(m/min)*	140	200	260
Feed rate	f_z	*(mm/rev)*	0.05	0.175	0.30
Depth of cut	a_p	*(mm)*	0.5	1.0	1.5

B. Turning Experiments

The turning experiments in this study were performed using a CNC lathe machine equipped with a DNMG150404-OMM carbide insert, as shown in Figure 1. C45 carbon steel workpieces were chosen as the material for the experiments due to their extensive utilization in various engineering applications. The selection of C45 steel as the workpiece material was made to ensure that the testing conditions were representative and realistic. This choice allows for meaningful conclusions to be drawn regarding the optimization of the CNC turning process for practical engineering scenarios.

Fig. 1. Experimental lathe machine

A set of carefully designed trials was performed based on the experimental design. Each trial represented a specific combination of cutting parameters. The cutting speed, feed rate, and depth of cut were adjusted according to the predetermined levels. To ensure accuracy and consistency, the experiments were conducted under controlled environmental conditions.

Fig. 2. DNMG150404-OMM carbide inserts

C. Surface Roughness Measurement

Surface roughness measurements were obtained using a precision metrology instrument, Mitutoyo Surftest JS-201. The experimental results were presented as in Table 2.

TABLE 2. Experimental OA and the corresponding results

Run	V_C *(m/min)*	f_z *(mm/rev)*	a_P *(mm)*	MRR *(cm³/min)*	R_a *(µm)*	T_c *(min)*
1	140	0.05	0.5	29.33	0.770	1.364
2	140	0.175	1	205.33	1.793	0.390
3	140	0.3	1.5	527.99	1.590	0.227
4	200	0.05	1	83.81	0.680	0.955
5	200	0.175	1.5	439.99	1.183	0.273
6	200	0.3	0.5	251.42	1.560	0.159
7	260	0.05	1.5	163.43	0.730	0.734
8	260	0.175	0.5	190.66	1.020	0.210
9	260	0.3	1	653.70	1.480	0.122

D. The Analytic Hierarchy Process (AHP) Method

The Analytic Hierarchy Process (AHP) involves a systematic and structured approach to decision-making, particularly in situations where multiple criteria need to be considered. In the context of optimizing the CNC turning process for C45 steel, AHP can be applied to determine the optimal set of process parameters. Specifically, the details of this method are presented in Chapter 12 [6]. The diagram of AHP Process used to optimize cutting parameters of turning of C45 carbon steel is how as Fig 3.

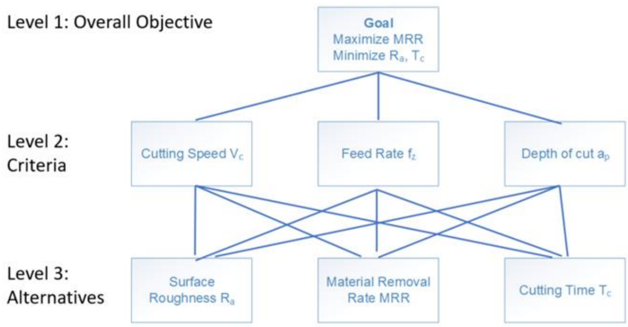

Fig. 3. AHP process diagram

The process of applying AHP in this situation can be summarized as follows:

Step 1: Identify the criteria: The first step is to identify the criteria that are relevant to the optimization problem. In this case, the criteria may include surface roughness (R_a), cutting time (T_c), and material removal rate (MRR). These criteria represent the key performance measures that need to be simultaneously optimized.

Step 2: Establish the hierarchy: Create a hierarchical structure by organizing the criteria into a tree-like structure. The top level of the hierarchy consists of the overall objective, which is to optimize the CNC turning process for C45 steel. The second level includes the criteria identified in the previous step (Ra, T_c, and MRR). The third level comprises the alternative process parameters, such as cutting speed (V_c), feed rate (f_z), and cutting depth (a_p).

Step 3: Pairwise comparisons: Evaluate the relative importance of each criterion and alternative by performing pairwise comparisons. The comparisons are done by assessing the relative importance of one criterion or alternative over

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another. A scale, often a numerical scale from 1 to 9, is used to assign values representing the degree of preference.

Step 4: Calculate priority weights: Once the pairwise comparisons are completed, the priority weights for each criterion and alternative can be calculated. These weights indicate the relative importance of each criterion or alternative in achieving the overall objective. The calculation is typically done using mathematical computations, such as the eigenvector method.

Step 5: Consistency check: Conduct a consistency check to ensure the reliability and consistency of the pairwise comparisons. Inconsistencies may arise if there are contradictions or inconsistencies in the judgments made during the pairwise comparisons. Consistency ratios are calculated to assess the level of consistency, with lower ratios indicating better consistency.

Step 6: Aggregation and ranking: Combine the priority weights of the criteria and alternatives to determine the overall rankings. This involves aggregating the priority weights through a mathematical process, such as weighted sum or weighted average, to obtain an overall score for each alternative. The alternative with the highest score represents the optimal set of process parameters.

By following these 6 steps, the AHP methodology enables a systematic and structured approach to determine the optimal process parameters for the CNC turning process. It allows for the consideration of multiple criteria and their relative importance, leading to improved decision-making and the achievement of the desired objectives.

III. RESULTS AND DISCUSSION

The multi-objective optimization problem in this study is addressed using the AHP method to achieve a balance between minimizing surface roughness, reducing cutting time, and maximizing material removal rate (MRR).

Build a pairwise comparison matrix for each criterion.

Based on the opinions of comparing experts, assess the level of importance between criteria for each pair according to the evaluation scale of T. Saaty [9]

Perform pairwise comparisons of criteria, assessing the level of importance for each pair of criteria. The priority levels (values a_{ij}, with i running along the rows and j running along the columns) for each pair of criteria have positive integer values ranging from 1 to 9 or the inverse of these numbers. This yields a square matrix (nxn).

The diagonal of this matrix has a value of 1 since a criterion is compared to itself (having equal importance). The value in row 1, column 3 is 0.2, indicating that the MRR criterion is 0.2 times as important as the Ra criterion, and similarly, the value in row 3, column 1 is 5 (R_a is 5 times more important than MRR).

TABLE 3. Pairwise comparison matrix for criteria

	MRR	R_a	T_c
MRR	1	0.2	0.25
Ra	5	1	1.2
T_c	4	0.8	1
Sum	10	2	2.45

To normalize the pairwise comparison matrix, divide the value of each cell by the sum of its column, yielding a normalized pairwise matrix (cell/sum by column). To calculate the weights for the criteria, take the average along each row.

Normalize the pairwise comparison matrix for criteria.

	MRR	R_a	T_c	Criteria Weights
MRR	0.1	0.1	0.102	0.10068
R_a	0.5	0.5	0.490	0.49660
T_c	0.4	0.4	0.408	0.40272

Criteria weights=(0.5+0.49+0.5)/3=0.49660

The weight values of the criteria are not the final conclusion; they need to be checked for consistency in the experts' evaluations throughout the application process. T. Saaty stated that a consistency ratio (CR) less than or equal to 10% is considered acceptable. In other words, there is a 10% chance that the experts' answers are completely random. If the CR exceeds 10%, it indicates inconsistency in the evaluations and requires reassessment and recalculation.

Calculating the consistency ratio (CR) using the weights of the criteria and the pairwise comparison matrix:

TABLE 4. Consistency Ratio (CR) Table

Criteria Weights	0.10068	0.49660	0.40272
	MRR	R_a	T_c
MRR	0.10068	0.09932	0.10068
R_a	0.50340	0.49660	0.48326
T_c	0.40272	0.39728	0.40272

To calculate the consistency vector, divide the sum of the weights of the criteria by the weight of each individual criterion:

TABLE 5. Consistency Vector Table

	MRR	R_a	T_c	Weighted Sum Value	criteria weights	Cons. vector
MRR	0.1007	0.099	0.100	0.30068	0.10068	2.9865
R_a	0.5034	0.496	0.483	1.48326	0.49660	2.9868
T_c	0.4027	0.397	0.402	1.20272	0.40272	2.9865

To calculate the largest eigenvalue of the pairwise comparison matrix, which represents the overall priority of the criteria, follow these steps:

Compute the eigenvalues and eigenvectors of the pairwise comparison matrix.

Identify the largest eigenvalue.

The closer the largest eigenvalue (λmax) is to the number of criteria being compared, the higher the level of consistency, indicating a more appropriate result.

To calculate the Consistency Index (CI):

$$CI = \frac{\lambda \max - n}{n - 1}$$

Where n is the number of criteria being compared, in this case, n = 3.

CI = (2.9866 - 3) / (3 - 1) = -0.0067

To calculate the Consistency Ratio (CR):

$$CR = \frac{CI}{RI}$$

CI (Consistency Index): The consistency index measures the degree of inconsistency in the pairwise comparisons.
RI (Random Index): The random index is a reference value that corresponds to the number of criteria being compared. It is used to calculate the consistency ratio.

TABLE 6. Table of Random Index Values

n	1	2	3	4	5	6	7	8
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41
n	9	10	11	12	13	14	15	
RI	1.45	1.49	1.51	1.54	1.56	1.57	1.59	

In this case, with three criteria, the random index (RI) value is 0.58.

The calculated consistency index (CI) is 0.0067.

To calculate the consistency ratio (CR), divide the CI by the RI:

CR = CI / RI = 0.0067 / 0.58 = 0.0115 (approximately)

Since the CR is less than 10% (0.0115 < 0.1), the consistency ratio is considered acceptable.

Therefore, you can proceed to use the weights of the criteria to evaluate the alternative options.

TABLE 7. Ranking the evaluation criteria

	CW	Rank
MRR	0.10068	3
Ra	0.49660	1
Tc	0.40272	2

Calculate the priority of the alternatives for each criterion.

In this step, we will calculate the priority for each criterion. The calculation method is similar to the previous step, but the input data for evaluation is the result of comparing the priority levels of the alternatives for each criterion (based on the opinions of experts). Therefore, the evaluation process needs to be performed for 4 matrices representing 3 different criteria. As a result, we will have 4 matrices with 1 column and 9 rows (representing the 9 alternatives). It is also necessary to check the consistency ratio to ensure the reliability of the obtained results. Then, we calculate scores for the alternatives and make a selection.

This is the final step in the evaluation process. Based on the results from step 3, we can synthesize a matrix of alternative weights according to the criteria. Multiply this matrix by the criterion weight matrix obtained in Step 2. The result will be a matrix with 9 rows (representing the alternatives) and 1 column (representing the weight values). This resulting matrix will indicate the best alternative to choose, which is the one with the highest weight value.

TABLE 8. Weights of alternatives according to criteria

	MRR	Ra	Tc
Alternative 1	0.028	0.192	0.018
Alternative 2	0.065	0.023	0.099
Alternative 3	0.225	0.034	0.150
Alternative 4	0.037	0.219	0.034
Alternative 5	0.164	0.080	0.138
Alternative 6	0.081	0.037	0.140
Alternative 7	0.044	0.219	0.073
Alternative 8	0.051	0.145	0.168
Alternative 9	0.305	0.051	0.180

TABLE 9. Ranking of the alternatives

STT	Weight	Ranking
Alternative 1	0.105	6
Alternative 2	0.058	9
Alternative 3	0.100	7
Alternative 4	0.126	4
Alternative 5	0.112	5
Alternative 6	0.083	8
Alternative 7	0.143	2
Alternative 8	**0.145**	**1**
Alternative 9	0.129	3

The optimal alternative selected using the Analytic Hierarchy Process (AHP) method is Alternative 8, characterized by the following values: a cutting speed (Vc) of 260 m/min, a feed per revolution (fz) of 0.175 mm/rev, a depth of cut (ap) of 0.5 mm, a material removal rate (MRR) of 190.66 mm^3/min, a surface roughness (Ra) of 1.020 µm, and a cycle time (Tc) of 0.210 minutes. These values have been determined through a systematic evaluation process utilizing expert opinions and pairwise comparisons of criteria. The selection of Alternative 8 is based on its superior performance in terms of these specified parameters, indicating its suitability for the given application.

IV. CONCLUSION

In conclusion, this research paper applies the Analytic Hierarchy Process (AHP) method to evaluate and select the optimal alternative for a specific application. The study involves assessing multiple criteria and their pairwise comparisons to determine the relative importance of each criterion. Through the calculation of consistency ratios, the reliability and consistency of the evaluations have been ensured.

Based on the AHP analysis, Alternative 8 emerges as the most suitable option, considering its favorable values for cutting speed, feed per revolution, depth of cut, material removal rate, surface roughness, and cycle time. The selection of Alternative 8 is supported by expert opinions and the systematic evaluation process conducted in this study.

The findings of this research contribute to the field of decision-making and selection processes in engineering and manufacturing applications. The AHP method provides a structured and reliable approach for evaluating and prioritizing alternatives based on multiple criteria. Further research can explore the application of the AHP method in other industries and domains to enhance decision-making processes.

Overall, the utilization of the AHP method in this study facilitates informed decision-making by providing a quantitative basis for selecting the most suitable alternative based on predefined criteria. This research underscores the significance of systematic evaluation techniques in optimizing decision outcomes and encourages their adoption in practical applications.

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