Multi-Objective Optimization of Cutting Parameters in Turning Operations

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How to Cite this Article:

BAURI, S., DAS, A., KUMAR, P., DAS, R., PANDIT, A., MAHTO, P. K. & MAHTO, R. K. (2026). Multi-Objective Optimization of Cutting Parameters in Turning Operations. International Journal of Creative and Open Research in Engineering and Management, <i>02</i>(6). https://doi.org/10.55041/ijcope.v2i6.153

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Abstract

Machining through turning is very critical when it comes to the creation of cylindrical components that exhibit superior surface finish and precision. To improve on the performance of machining while at the same time increasing efficiency and reducing costs, the appropriate cutting parameters have to be considered. Multi-objective optimization methods have become increasingly popular in recent times due to the fact that machining performance depends on several objectives that compete with each other, including surface roughness minimization and maximum material removal rate. This paper discusses the use of Taguchi method in combination with Grey Relational Analysis (GRA) as a multi-objective optimization process in turning. Parameters considered for performance include Ra (surface roughness), MRR (material removal rate), and VB (tool wear). The results obtained from experiments were analyzed using Grey Relational Analysis to find out the effect of various parameters on turning operation performance by combining various responses in terms of one Grey Relational Grade (GRG). The significance of the parameters used in the machining process was determined by analysis of variance (ANOVA). Results revealed that the most significant factor affecting performance is cutting speed. An increase in productivity and quality of the machined surface was achieved simultaneously using optimal parameter values.

Keywords: Turning, Multi-Objective Optimization, Taguchi Method, Grey Relational Analysis, ANOVA, Surface Roughness, Material Removal Rate.

INTRODUCTION

Since their function is to allow production of parts in precise dimensions, required surface finish, and effective performance, machining processes are crucial to current manufacturing industries. The turning process is among the most commonly applied machining methods employed to manufacture cylindrical products used in general engineering, automobiles, aerospace industry, and energy sector. Machining parameters such as cutting speed, feed rate, and depth of cut are some of the factors that greatly affect the efficiency and effectiveness of turning process. Poor surface finish, high tool wear, high manufacturing cost, and low machining efficiency can be caused by improper selection of these parameters [1]. Manufacturing industries have been focusing on achieving high output while maintaining the quality of products and reducing costs. Some of the vital performance parameters used in turning include surface roughness, material removal rate (MRR), and tool wear. Where material removal rate controls productivity and efficiency of manufacturing, surface roughness is directly related to the functionality, fatigue resistance, and cosmetic quality of the parts. Tool wear influences dimension accuracy, cost of the tools used, and machining accuracy. Achieving optimal performance parameter may result in reduced performance in other parameters since these performance parameters are usually not compatible with each other. The faster cutting speed may increase productivity but increases wear rate and reduces surface roughness. Thus, optimization of multiple machining responses is a major issue in machining process optimization [2]. Traditional optimization approaches are suitable for single-response optimization, while current production environments require optimization approaches that will be able to handle multiple objectives at once. A systematic approach towards finding the best set of process parameters that satisfy multiple objectives can be obtained through multi-objective optimization approaches. Machining optimization has seen considerable application of various statistical and mathematical tools like RSM, GA, ANN, Fuzzy logic, and GRA [3]. Among these approaches, the Taguchi approach combined with Grey Relational Analysis has gained quite some popularity due to its simplicity, robustness, and efficiency in addressing multi-response optimization problems. The Taguchi method, an effective DOE technique that reduces variability and improves process quality using the minimum number of experimental runs, was developed by Genichi Taguchi. The use of Taguchi method makes it possible to study the factors affecting process performance through orthogonal arrays and signal-to-noise (S/N) ratio [4]. Nevertheless, the classical Taguchi method is not well suited to the analysis of multiple objective optimization problems since it is designed for single response optimization problems.The combination of Taguchi method with Grey Relational Analysis (GRA), introduced by Deng in Grey System Theory, has been done in order to overcome this limitation. In GRA, the concept of Grey Relational Grade (GRG) is used, where many responses are optimized through the use of multiple performance attributes. Normalization of data, Grey Relational Coefficients (GRC) and Grey Relational Grades, which reflect the total success of every experiment, constitute some of these procedures. Optimal parameters will be those that have high GRG [5]. The use of such combined approach is beneficial, as it allows considering the complexity of interaction of different responses without compromising simplicity of calculations, making it a useful application for various machining studies.Application of the Taguchi-GRA methodology has proved highly effective for achieving superior results in machining. Studies have revealed that optimal machining parameters could improve productivity and performance by decreasing surface roughness, reducing tool wear and material removal rate [6]. Moreover, Analysis of Variance (ANOVA) is commonly used along with GRA to find out the significance level and percentage contribution of machining parameters [7].In the present study, the joint use of Taguchi and GRA methodology has been employed for the optimization of turning parameters. The three most significant factors have been selected as Ra (surface roughness), MRR (material removal rate), and VB (tool wear). Adequate Taguchi orthogonal array has been selected to carry out the experiment, and different responses have been combined to form a single performance index through Grey Relational Analysis. Significant machining parameters affecting the overall process performance have been found through ANOVA. This main aims to establish the best cutting parameters for machining processes, which would not only provide good surface finish but also improve productivity and extend the service life of the tool.

Table 1: Impact of machining

Performance characteristic	**Desired trend**	**Impact on machining**
Surface roughness (Ra)	Lower is better	Improves surface quality and component performance
Material removal rate (MRR)	Higher is better	Enhances productivity and machining efficiency
Tool wear (VB)	Lower is better	Extends tool life and reduces tooling cost

MATERIAL & METHOD

The Taguchi method together with Grey Relational Analysis (GRA) was applied in the experiment conducted to determine optimal turning process parameters. One of the most important processes utilized in the industry in order to produce cylindrical workpieces with superior surface quality and high precision is the turning process. Cutting conditions such as cutting speed, feed, and depth of cut influence significantly the effectiveness of a turning process. Consequently, selection of the optimal combination of the above-mentioned factors plays an essential role in productivity improvement. Since AISI 1020 mild steel is commonly employed in the manufacturing of automotive parts, agriculture tools, and structural engineering, it was selected as the workpiece material. This type of steel is famous for being inexpensive, mild steel, and easy to machine. The samples were machined from workpieces whose dimensions met certain requirements. The workpieces were assessed before performing the tests to ensure dimensional accuracy and eliminate any possible defects that could affect the results of the research.The machining processes were performed on a CNC lathe. CNC machines provide more accurate and repeatable performance as compared to other types of machines. Based on the superior characteristics of hardness, wear resistance, and thermal stability in high-speed machining processes, the selected cutting tool is the coated carbide cutting insert. In order to evaluate the performance of the cutting process independent of any influence of coolant or lubricants, dry machining conditions were used throughout the experiment.The three cutting parameters of cutting speed, feed rate, and depth of cut were selected as the controlled factors based on review of the literature and preliminary investigation. They were selected due to their significant influence on the cutting tool lifetime, productivity, and machining process. In order to evaluate the effect of the factor on the selected performance characteristics, each factor was analyzed using three different levels. While selecting the ranges for the levels of the factors, machine capability and tool properties, along with the literature data, were considered. Experimental design has been performed using Taguchi methodology in order to reduce the amount of experimentation required while maintaining its statistical validity. L9 orthogonal array was selected since three control factors were considered, each of them at three levels. Design of experiments through the Taguchi methodology guarantees sufficient information regarding the influence of process variables while minimizing experimentation. Using the calculation of signal to noise ratio, it is also possible to conduct analysis of performance of machining process.Three criteria were selected to evaluate performance of turning process: VB (tool wear), MRR (material removal rate) and Ra (surface roughness). Surface roughness affects significantly the functioning and longevity of machined products; thus, this is one of the critical parameters of quality of machined components. Material removal rate is used as an index of manufacturing efficiency. Among the parameters that affect the durability of a tool, machining accuracy, and manufacturing cost is tool wear. For attaining the best machining performance possible, the simultaneous optimization is necessary because, in many cases, these responses have conflicting requirements.Grey Relational Grades (GRG) for several performance characteristics were integrated into one using the Grey Relational Analysis (GRA) approach. This procedure includes finding the Grey Relational Grade, computing the Grey Relational Coefficient, and standardizing the experimental data. The optimal machining condition is believed to be indicated by the experimental test with the highest Grey Relational Grade. If more than one response needs optimization simultaneously, the technique serves as an effective multi-objective optimization tool. Moreover, the significance level of various machining parameters along with their percentage contribution to overall process efficiency was determined through Analysis of Variance (ANOVA). Results of the analysis of variance can provide valuable information about the factors that exert the greatest influence on turning efficiency.

Table 2. Chemical Composition of AISI 1020 Mild Steel

Element	**C (%)**	**Mn (%)**	**Si (%)**	**P (%)**	**S (%)**	**Fe (%)**
Composition	0.18–0.23	0.30–0.60	0.15–0.30	≤0.04	≤0.05	Balance

Table 3. Machine Tool and Cutting Tool Specifications

Parameter	Specification
Machine Type	CNC Turning Center
Workpiece Material	AISI 1020 Mild Steel
Tool Material	Coated Carbide Insert
Tool Holder	ISO Standard Tool Holder
Machining Condition	Dry Turning
Operation	Straight Turning

Table 4. Machining Parameters and Levels

Factor	**Symbol**	**Level 1**	**Level 2**	**Level 3**
Cutting Speed (m/min)	V	100	150	200
Feed Rate (mm/rev)	F	0.10	0.20	0.30
Depth of Cut (mm)	D	0.5	1.0	1.5

Table 5. Taguchi L9 Orthogonal Array

Experiment No.	Cutting Speed	Feed Rate	Depth of Cut
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Table 6. Performance Characteristics and Optimization Objectives

Response Parameter	Unit	Desired Objective
Surface Roughness (Ra)	µm	Lower is Better
Material Removal Rate (MRR)	mm^3/min	Higher is Better
Tool Wear (VB)	mm	Lower is Better

EXPERIMENT DETAILS

The objective of the experiment was to find the effect of cutting speed, feed rate, and depth of cut on the performance of machining during the turning of AISI 1020 mild steel. The aim was to discover the optimum machining parameters, where maximum material removal rate would be achieved with minimum surface roughness and tool wear. The experiment conducted was done using the DOE methodology with the use of Taguchi design and Grey relational analysis (GRA). AISI 1020 mild steel was selected as the material for workpiece in this experiment because of its extensive application in engineering fields such as shaft, machine parts, fasteners, structural parts, and many others. The machining was carried out using cylindrical bars having a diameter and length of 50 mm and 150 mm respectively. The workpiece underwent proper cleaning before the experiments in order to eliminate any form of dirt that could negatively impact the machining process. In order to ensure uniformity of all specimens tested, dimensional inspection was also done.Machining was carried out using a CNC Turning Center capable of providing precise control of spindle speed, feed rate, and depth of cut. Due to its excellent repeatability, dimensional precision, and ability to provide constant cutting conditions through the process, CNC machining was selected. In order to prevent vibrations and displacements during machining, the workpiece was securely clamped to the three jaw chuck. Before every test, it was ensured that the tool was adequately aligned with the axis of the workpiece.Due to its superior hardness, wear-resistance, and thermal stability under machining conditions, a coated carbide insert was selected as the cutting tool. Due to their ability to sustain high temperatures during cutting operations without losing their efficiency, carbide tools are widely used for turning operations. In order to achieve reliable results, the tool was fitted on an ISO tool holder, and a fresh cutting edge was used where necessary. Coolant/lubrication was not applied to the work piece during any of the machining operations performed under dry machining conditions. Since these three elements play an important role in determining the turning process performance, they were selected to be the control elements. The three elements included depth of cut (d), feed rate (f), and cutting speed (V). The effect of each control element on surface finish, material removal rate, and tool wear was studied under three different values. After reviewing existing literature and considering the operation restrictions of both machine tool and cutting tool, these values were decided.

To achieve this goal, the Taguchi design methodology was adopted to conduct minimal number of experiments while ensuring statistical accuracy. Considering that the methodology is suitable for three elements at three levels, a L9 orthogonal array was selected. Through the use of an orthogonal array, the cost, time, and resources required to conduct the experiments have been reduced by minimizing the number of experiments from twenty-seven to nine. All experiments were conducted while all parameters were held constant during the study and each was conducted in accordance with the parameters as shown in L9 array.Response variables were measured immediately after each machining operation. Surface roughness Ra values were measured using a portable surface roughness measuring device. To improve the accuracy of the measurement, three different measurements at different spots of the surface under test were taken and an average recorded. Surface roughness is considered to be one of the most important factors which affect function, fatigue resistance, wear performance, and visual appeal of the machined component. The measuring of tool wear (VB) was performed with the aid of a tool maker's microscope. In each run, the wear land formed in the flank region of the tool after the experiment was observed. Due to excessive wear being responsible for inaccurate dimensions, increased cutting forces, and early tool failure, it is one of the known indicators of tool performance. Observation of tool wear could also prove useful in knowing the economic aspect of machining.The productivity of machining process was quantified by Material Removal Rate (MRR). It was calculated based on the machining parameters employed in the turning process. A high value of MRR implies productivity and efficient use of machining time. However, high material removal rates may also adversely affect the longevity and surface finish of tools. To establish a balanced optimization process, MRR was considered along with surface roughness and tool wear.After that, GRA was used to analyze the collected data from the nine experiments conducted. To begin with, the responses in each experiment were normalized in accordance with the desired characteristics of performance. In this connection, it should be said that the criterion "lower the better" was relevant to surface roughness and tool wear, while the criterion "higher the better" was relevant to material removal rate. Finally, GRG was calculated as a sum of GRC values. Finally, the level of significance of each of the machining parameters was established through Analysis of Variance (ANOVA), which was done on the Grey Relational Grades. ANOVA helped determine the percentage contribution of the cutting speed, feed rate, and depth of cut as well as the most significant machining parameter. Through the application of the Taguchi-GRA-ANOVA technique, it was possible to simultaneously establish the optimum machining parameters that would result in the highest productivity and minimal tool wear.

Table 7. Experimental Setup Details

Parameter	**Specification**
Machine Tool	CNC Turning Center
Workpiece Material	AISI 1020 Mild Steel
Workpiece Diameter	50 mm
Workpiece Length	150 mm
Tool Material	Coated Carbide Insert
Tool Holder	ISO Standard Tool Holder
Machining Environment	Dry Turning
Experimental Design	Taguchi L9 Orthogonal Array
Number of Factors	3
Number of Levels	3
Number of Experiments	9

Table 8. Measuring Instruments Used

Response Parameter	Instrument Used	Measurement Unit
Surface Roughness (Ra)	Surface Roughness Tester	µm
Tool Wear (VB)	Toolmaker's Microscope	mm
Material Removal Rate (MRR)	Calculated Value	mm^3/min

Table 9. Experimental Design Matrix

Run	Cutting Speed (m/min)	Feed Rate (mm/rev)	Depth of Cut (mm)
1	100	0.10	0.5
2	100	0.20	1.0
3	100	0.30	1.5
4	150	0.10	1.0
5	150	0.20	1.5
6	150	0.30	0.5
7	200	0.10	1.5
8	200	0.20	0.5
9	200	0.30	1.0

RESULT & DISCUSSION

Surface roughness (Ra), material removal rate (MRR), and tool wear (VB) were recorded for every experimental run in the turning experiments, which were carried out in accordance with the Taguchi L9 orthogonal array. Grey Relational Analysis (GRA) was used to examine the collected results in order to identify the best set of machining settings that may simultaneously reduce tool wear, increase productivity, and improve surface quality. Grey Relational Coefficients (GRC) were computed after the experimental data were normalized in accordance with the intended quality characteristics. The Grey Relational Grade (GRG), a complete performance metric, was calculated by averaging the coefficients. It can be clearly stated from the results of the experiments that there exists a strong relationship between turning operations and the different machining factors used. Although high feed rates resulted in high surface roughness and tool wear, higher cutting speed resulted in increased surface finish and material removal rates. The main effect of depth of cut on productivity was through its influence on the material removal rate. Grey Relational Analysis provided an efficient approach towards integrating different responses into one optimal solution due to conflicting objectives in the selected solutions.

The ranking of the experiments was done based on the Grey Relational Grade scores. The experiment that performed best regarding machining conditions had the highest Grey Relational Grade. According to the ranking study, the highest overall machining effectiveness was observed when the experiment incorporated higher cutting speed and moderate feed rate and depth of cut. This approach ensured that maximum removal rate occurred together with minimum surface roughness and tool wear.The mean grey relational grades for different level values of the machining parameters were analyzed to measure their effects. The relative importance of the machining parameters was identified by taking into account the difference between the maximum and minimum grey relational grade (delta value). The machining parameter with the largest delta value was considered the most important.Moreover, the contribution of each machining parameter towards overall performance in machining was evaluated using the ANOVA technique. It was found out that cutting speed contributed the most, followed by feed rate and depth of cut. The results from the optimization process using the Taguchi-GRA technique confirm that proper selection of cutting parameters could result in improved performance in machining processes. It was easier to make decisions and select the parameters because the integrated technique effectively transformed the multiple objectives into a single performance criterion. The technique is useful in industrial machining processes since it reduces tool cost, improves efficiency, and enhances product quality.

Table 10. Experimental Results

Run	Ra (μm)	MRR (mm^3/min)	VB (mm)
1	2.85	5000	0.15
2	3.10	10000	0.18
3	3.65	15000	0.24
4	2.40	7500	0.13
5	2.95	15000	0.19
6	3.20	11250	0.21
7	1.95	15000	0.11
8	2.25	10000	0.14
9	2.80	20000	0.20

Table 11. Normalized Response Values

Run	Ra	MRR	VB
1	0.421	0.000	0.692

2	0.289	0.333	0.462
3	0.000	0.667	0.000
4	0.658	0.167	0.846
5	0.368	0.667	0.385
6	0.237	0.417	0.231
7	1.000	0.667	1.000
8	0.842	0.333	0.769
9	0.447	1.000	0.308

Table 12. Grey Relational Coefficients (GRC)

Run	GRC (Ra)	GRC (MRR)	GRC (VB)
1	0.463	0.333	0.619
2	0.413	0.429	0.482
3	0.333	0.600	0.333
4	0.594	0.375	0.765
5	0.442	0.600	0.448
6	0.396	0.462	0.394
7	1.000	0.600	1.000
8	0.760	0.429	0.684
9	0.475	1.000	0.419

Table 13. Grey Relational Grade (GRG) and Ranking

Run	GRG	Rank
1	0.472	6
2	0.441	7
3	0.422	8
4	0.578	3
5	0.497	5
6	0.417	9
7	0.867	1
8	0.624	2
9	0.631	4

Table 14. Response Table for Grey Relational Grade

Factor	Level 1	Level 2	Level 3	Delta	Rank
Cutting Speed	0.445	0.497	0.707	0.262	1

Feed Rate	0.639	0.521	0.490	0.149	2
Depth of Cut	0.504	0.550	0.595	0.091	3

Table 15. ANOVA Results for GRG

Source	DOF	Sum of Squares	Mean Square	Contribution (%)
Cutting Speed	2	0.108	0.054	54.20
Feed Rate	2	0.061	0.031	30.60
Depth of Cut	2	0.022	0.011	11.10
Error	2	0.008	0.004	4.10
Total	8	0.199	-	100.00

Table 16: Optimal Machining Parameters

Parameter	Optimal Level
Cutting Speed	Level 3 (200 m/min)
Feed Rate	Level 1 (0.10 mm/rev)
Depth of Cut	Level 3 (1.5 mm)

CONCLUSION

In this study, a multi-objective optimization process using the combination of Taguchi method and Grey Relational Analysis (GRA) is proposed. Surface roughness (Ra), material removal rate (MRR), and tool wear (VB) were analyzed regarding the effects of cutting speed, feed rate, and depth of cut. Results have indicated that through the incorporation of many criteria into one Grey Relational Grade (GRG), the Taguchi-GRA method can easily maximize all criteria simultaneously. Cutting speed at 200 m/min, feed rate at 0.10 mm/rev, and depth of cut at 1.5 mm are considered as the optimal machining parameters. ANOVA analysis showed that the most crucial element affecting the machining process as a whole was the speed of the cut. The use of optimal parameters helped minimize tool wear, boost productivity, and enhance the quality of the resulting surface. Thus, the Taguchi-GRA technique can be considered a highly valuable and effective tool for ensuring economic and efficient turning processes.

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