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A proposed multi-criteria analysis model for evaluating the optimum turning parameters and tool inserts in machining operation

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ABSTRACT

Metal machining is defined as the process of removing unwanted materials to achieve the desired dimensional accuracy of products. Several complicated factors must be considered in this process based on knowledge judgment, the expert/technician's experience, and standard engineering handbook, survey and literature. This study presents a multi-criteria analysis model that evaluates the optimum cutting parameters and appropriate tool inserts for the turning process based on surface roughness and material removal rate. This decision support model aids suppliers of cutting tools in developing a technical module to help their customers select optimal turning parameters. A hierarchical structure of these factors is implemented to evaluate desirable values, which are a trade-off among multiple criteria. In this paper, the combination of the AHP (Analytical Hierarchy Process) and VIKOR (Vlse Kriterijumska Optimizacija i Kompromisno Rešenje) is proposed to conduct a hybrid multi-criteria decision model. First, the AHP is used to determine the weights of the selected factors/criteria. Second, the VIKOR is used to assess the suitability of optimal parameters and the tool inserts. Finally, a numerical example is carried out to validate the developed model. The results demonstrate that the model is practical and can be applied to small and medium-sized enterprises in the manufacturing technology.

1. Introduction

Metal cutting is defined as an industrial operation involving the removal of unwanted material to form the finished product based on technical drawings. In the domain of metalworking, the quality of the final product stands as the paramount consideration, particularly with regard to the quality of the machining surface of the component. The quality of output is contingent upon the selection of machine tools, machining tools and cutting modes. The cutting tool's inserts, which are of paramount importance, exert a significant influence on the quality of the surface of the machined product and the cost of the production process. Consequently, the suitable combination of inserts and machining modes constitutes a multifaceted process of making a decision, entailing the consideration of numerous criteria, including but not limited to machining modes, cutting speed, feed rate, cutting depth and geometric parameters of tool inserts such as nose radius, clearance angle, approach angles, rake angle and angle of inclination.

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The turning parameters are chosen according to the supplier and manufacturer and supplier's catalog, the experience judgments from the experts, machine operators/technicians, engineering handbooks and literatures. The appropriate operating parameters will reduce the manufacturing cost and improve the machining quality of finished products. Therefore, the most suitable combination of machining parameters and inserts plays a vital role in enhancing the efficiency, quality and cost of the turning process.

The turning process involves the rotation of the workpiece simultaneously combined with the cutting tool's motion. This results in two vertical cutting movements and one horizontal movement. Lathes account for approximately 25% to 35% of the total devices presented in the machining/mechanical workshop. Lathes are capable of machining various surfaces, including internal and external turning threads, conical surfaces, rings and shaping faces, among others. The precision of machining operations is contingent upon several primary factors. The following factors must be considered in order to ensure machine tool accuracy and precision, such as spindle inversion and parallelism of the slider with the centerline of the spindle. In addition, the status of the cutting tool must be taken into account, as well as the qualification of the workers and technicians. In the context of CNC machining, the turning-process quality is less contingent on the experienced operator compared to conventional machine tools.

The quality of a surface is determined by two primary factors: a surface roughness and microhardness. The surface roughness of finished products has been demonstrated to affect their fatigue strength, chemical corrosion resistance and abrasion resistance. The efficacy of machining processes is contingent upon the cutting mode, which exerts a substantial influence on the MRR (material removal rate). Therefore, the objective is to obtain the desired effectiveness in the turning operation by selecting the appropriate inserts in the cut mode.

2. Literature review

Patel et al. [1] presented a novel methodology for the evaluation and selection of tool inserts in CNC turning processes. This methodology is based on SAW (simple additive weighting) and WPM (weighted product method). A particular emphasis was placed on the attributes of cutting tool inserts, which were considered in terms of the geometric parameters of the insert. Subsequently, the SAW method was used to ascertain the weights of attributes, and the priorities of cutting tool inserts were appraised through the implementation of the WPM technique. Balasubramaniyan and Selvaraj [2] developed a multi-criteria decision aided model based on the TOPSIS (technique for order preference by similarity to ideal solution) and AHP methods. Their model was utilized to determine the suitable parameters for the turning of EN25 steel. Their research objective was to minimize microhardness and surface roughness, and maximize MRR. The machining parameters that were utilized included the type of coated tool, cutting speed, cutting depth, and feed rate. The weights of the components were calculated based on the AHP. Subsequently, 18 experimental runs were conducted, incorporating the aforementioned parameters and the incorporation of micro hardness, surface roughness, and MRR. The final step entailed the application of the TOPSIS technique to determine the ranking of the experiments. Madic et al. [3] evaluated the machining process conditions in laser cutting employing the WASPAS (the weighted aggregated sum product assessment), Taguchi, operational competitiveness rating analysis (OCRA), and AHP. Asjad and Talib [4] have determined the optimum machining condition in the CNC milling based on the criteria of table speed, feed, and cutting depth using the Taguchi, TOPSIS, MOORA (multi-objective optimization on the basis of ratio analysis), and PCA (principal component analysis) to evaluate their impact on MRR and surface roughness. Khan and Maity [5] combined the TOPSIS and ANOVA (analysis of variance) for multi-criteria assessment for turning pure titanium with the consideration of three objective functions, such as minimization of the surface roughness, cutting force, and machining temperature, and maximization of MRR. Majumder and Saha [6] have presented the combination of MOORA with PCA and TOPSIS with PCA to determine the most suitable parameters (i.e., spindle speed, cutting depth, and feed rate) to obtain the performance index in the turning of ASTM A588 material. Besides, Saha [7] selected the process parameters in turning ASTM A36 Mild Steel Bar using multi-objective Taguchi approach. Gangil and Pradhan [8] have combined the response surface method and VIKOR to select the optimum processing parameters of EDM (electrical discharge machining). Suresh, Krishnaiah, and Venkataramaiah [9] have proposed the decision model based on WAPAS and ANOVA for multiple criteria optimal hard turning. Next, Singaravel, Shankar, and Prasanna [10] have employed the ARAS (Additive Ratio Assessment) technique to identify the appropriate parameters of coated cutting tools for turning AISI 4340 steel. Their considered parameters included cutting mode and the use of coated tools. The primary objectives were to minimize surface roughness, microhardness, and maximum MRR. Palanisamy, Selvaraj, and Sivasankaran [11] optimized the processing parameters in turning INCOLOY 800H, based on the multilayer CVD-coated tool. The input factors in this equation include the cutting mode. The responses under consideration are microhardness, surface roughness, MRR, and degree of work hardening. The optimal parameters were identified through the utilization of Taguchi L27 and TOPSIS methodologies. Singaravel and Selvaraj [12] developed a decision model based on AHP to identify the optimal turning parameters for EN25 steel. The factors that are to be analyzed include the cutting mode. The simultaneous outputs that will be considered are minimizing surface roughness, feed rate, and maximizing MRR. Balasubramaniyan and Selvaraj [2] combined the Taguchi and TOPSIS methodologies to ascertain the processing parameters for turning EN25 steel to ensure dimensional accuracy. As with the aforementioned study, the parameters considered in their research were cutting modes. The objectives of minimizing circularity and cylindricity were to be achieved simultaneously. Nayak and Rana [13] selected an appropriate multi-response optimization method for turning using multiple response optimization, grey number, and VIKOR. The independent variables in this experiment included cutting mode, and coolant flow rate. A circular bar of mild steel with a diameter of 32 mm and a length of 500 mm was utilized for the experimental design on the turret turning machine with a high-speed steel (HSS) cutting tool. Thirumalai et al. [14] implemented multi-response optimization of the turning process parameters for Inconel 718. AHP and TOPSIS were used to select the optimum set of given finite numbers of alternatives of machining of Inconel 718 using carbide cutting tools. Krishna et al. [15] used the Entropy, MOORA and COPRAS methods for turning Nimonic C263 with the aim of minimizing force and flank wear. Khelfaoui et al. [16] evaluated the effects of input parameters such as cutting speed, depth of cut, tool nose radius, feed rate on surface roughness, tangential cutting force, motor power consumption, cutting power, and material removal rate during intermittent turning of AISI D3 tool steel. Adil, Krishnaiah and Rao [17] proposed a mathematical model and optimized cutting conditions in turning operations on MDN 350 steel with carbide inserts. Their cutting inputs were speed and tool feed rate, rake angle, cutting angle and nose radius of the tool inserts. The roughness of the machine components was measured output. In a similar manner, Solanki and Jain [18] optimized bi-objectives of MRR and surface roughness using MCDM model based on Taguchi approach for turning Aluminium Alloy AL-6082. They also used ANOVA, TOPSIS and GRA to evaluate the optimization process for turning operation of AL-6082. Moreover, TOPSIS and GRA also provided a suitable solution for optimizing the machining parameters that lead to improved product quality by examining surface roughness parameters, hardness variations, and microstructure with a spindle speed, a feed rate, and a depth of cut [19]. Pasic et al.

[20] analyzed the impact of input parameters (cutting speed, feed rate, depth of cut, and insert radius) on surface roughness and cutting forces during the machining of 90MnCrV7.

AHP is a multi-criteria decision analysis, employed to determine the weights of attributes. The AHP method facilitates the organization of the hierarchical structure of complex problems for decision-makers. The decision-making process is comprised of three sequential steps. First, a hierarchical structure is developed across three levels, incorporating the goal, the criteria, and the alternatives [12, 21]. Second, a pair-wise comparison matrix is established. Third, the ranking of the alternatives is determined. The VIKOR method plays a significant role in evaluating the priorities of the alternatives in machining process planning [22].

3. Research method

C45 steel is utilized in construction and industrial applications due to its mechanical properties, including durability, hardness, and plasticity. The machine, bridge construction, steel frame, and other elements can be readily quenched and tempered to achieve the desired degree of hardness. Furthermore, C45 round steel is frequently utilized in the fabrication of various components, including threading, bolts, machine parts, axles, gear wheels, sickles, drills, woodworking drills, and knives.

The objective of this research is to examine the shaft turning of a diameter of 30mm in C45 with roughness of Ra2.5. The following pieces of hard alloy (inserts) can be used for processing:
This alloy group is capable of processing materials CT3 and C45 at a cutting speed of 350 meters per minute. The shaft, composed of C45 steel with a diameter of 30 mm, can be machined using the following inserts of T14K8, T5K10, T10K8, T7K12, T5K12, and TT7K12, T5K12 can be machined with a cutting depth and large cutting feed. Furthermore, the following inserts are compatible with the system: T30K4, T15K6, and T15K10. Three distinct groups of alloys can be utilized for processing: tungsten carbide, carbide, titanium, and titanium carbide. This alloy exhibits a strength that is 1.5 to 2 times greater than that of TK. The software is referred to as TTK. The fabrication of hard alloys entails the production of components with predetermined dimensions and geometries, ensuring compatibility with the handle. The hardness of the alloy will increase as it is plated on a thin layer of titanium, borite, nitrite, etc. (5-15 µm). The cutting speed has been demonstrated to be capable of attaining a rate of 800 meters per minute.

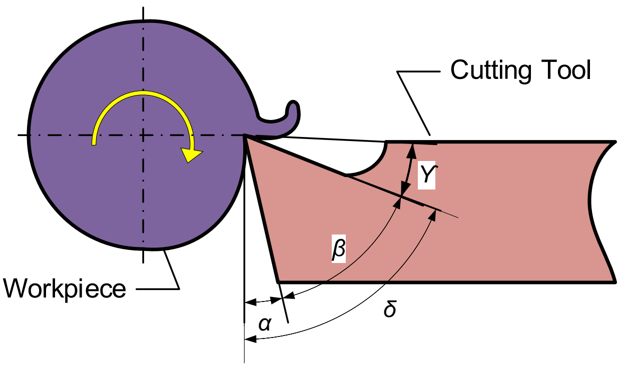

Fig. 1. Illustration of angles of cutting tool.

Source: "Turning inserts and grades" Sandvik, link: https://www.sandvik.coromant.com/en-us/tools/inserts-grades/insert-grade-information/turning-inserts-grades

Fig. 2. The inserts of cutting tools.

The selection of cutting tools is contingent upon the specific angle of the task, with the primary angle, designated as α, and the front angle, denoted as γ, requiring meticulous consideration (see Figure 1). Geometrical parameters of the tool inserts are illustrated in [16, 17]. In the process of preparing materials for the front angle, a specific procedure is followed. Initially, the front edge is sharpened to a smaller size. This is done in preparation for the subsequent steps of turning and hardening. In the case of finished machining and flexible/soft machining materials, the front angle is sharpened to a greater extent. The front angle typically assumes values such as: $\gamma = 0°$ or $\pm 5°$.

In this research, we develop a multiple criteria decision model to select the most suitable inserts for cutting tools. The methods employed are founded on the AHP and VIKOR, with the support of multiple criteria. The inserts of the cutting tool are illustrated in Figure 2.

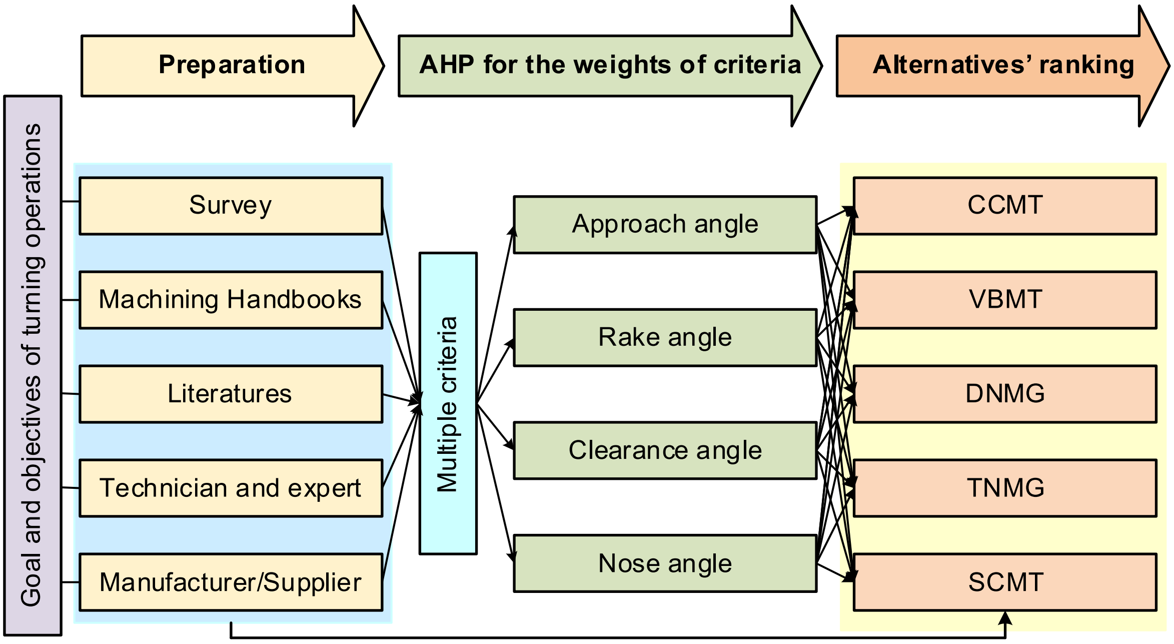

Fig. 3. The structure of a proposed multi-criteria analysis model

The structure of multiple criteria decision-making is constructed based on three levels. The initial stage involves the execution of a survey to assess the pertinent criteria. The second level encompasses the selected criteria of approach angle, clearance angle, rake angle and nose radius. The third level involves alternative inserts of cutting tools, including CCMT, VBMT, DNMG, TNMG, and SCMT, manufactured by Sandvik. As illustrated in Figure 3, the following procedure is to be followed in order to reach a decision.

4. Results and Discussion

The weights of the criteria of approach angle, clearance angle, rake angle and nose radius are calculated using the AHP method. This method can be solved in the Expert Choice software. The construction of these comparison matrices is predicated on the expert's assessments or the technician's evaluations. The company boasts a wealth of experience in the domain of CNC turning and operation within a mechanical workshop setting. Subsequent to this, the ranking of alternatives is evaluated based on the VIKOR, a method capable of determining the weights of alternatives for each cutting tool insert. The results of this study are depicted in Table 1.

Table 1
The weights of criteria utilizing AHP and alternatives' ranking from VIKOR

Alternative	Approach angle (degree)	Rake angle (degree)	Nose radius (mm)	Clearance angle (degree)	VIKOR ranking
Weights (AHP)	0.375	0.25	0.28	0.1	
1	91	-6	0.8	0	2
2	45	0	0.4	7	5
3	107.5	-6	1.2	0	1
4	93	0	0.2	7	4
5	95	0	0.2	5	3

The ranking of inserts is indicated as follows: 3 > 1 > 5 > 4 > 2. Following the selection of the appropriate inserts for the cutting tools, experiments are conducted for shaft turning with a diameter of 30 mm with consideration of two objectives: roughness and MRR. The experiment data are illustrated as Table 2 based on a full factorial design of eight experiments for three considered factors.

Table 2
Experimental planning

No.	Feed rate (mm/rev)	Depth of cut (mm)	Cutting speed (m/min)	Roughness (µm)	MRR (cm^3/min)
1	0.1	0.6	113	1.02	6.77
2	0.1	1.8	113	1.77	20.33
3	0.1	0.6	245	2.32	27.93
4	0.1	1.8	245	2.33	44.2
5	0.26	0.6	113	2.19	29.4
6	0.26	1.8	113	2.11	35.3
7	0.26	0.6	245	2.47	25.46
8	0.26	1.8	245	2.43	24.41

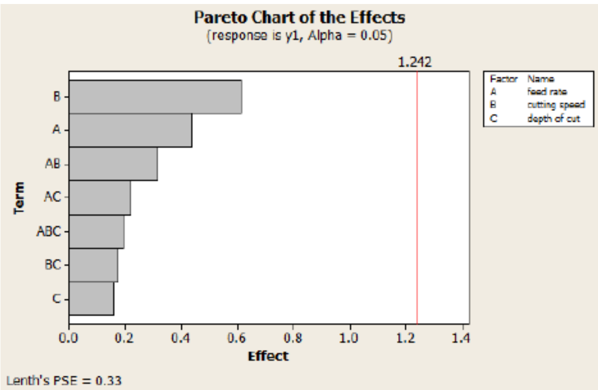

Fig. 4. Effects of factors to roughness

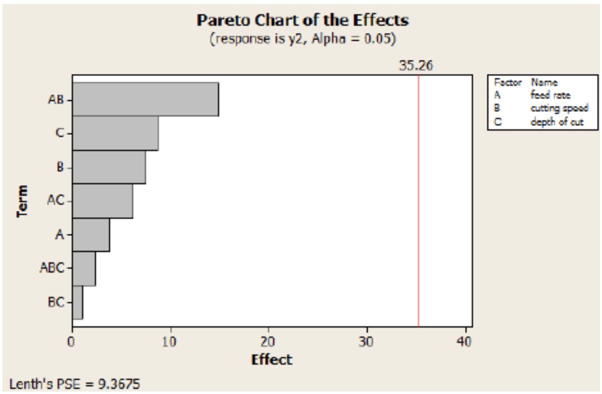

Fig. 5. Effects of factors to MRR

A thorough examination of the full factorial design, as illustrated in Figures 4 and 5, revealed that the cutting speed exerts a substantial impact on the roughness of turning the 30-mm diameter shaft. The cutting depth and the interaction of feed rate and cutting speed are paramount to the effectiveness of MRR. To ascertain the optimum parameters of the CNC turning process from the collected data, the module of optimizer analysis of Minitab was utilized, yielding the desired results as depicted in Figure 6.

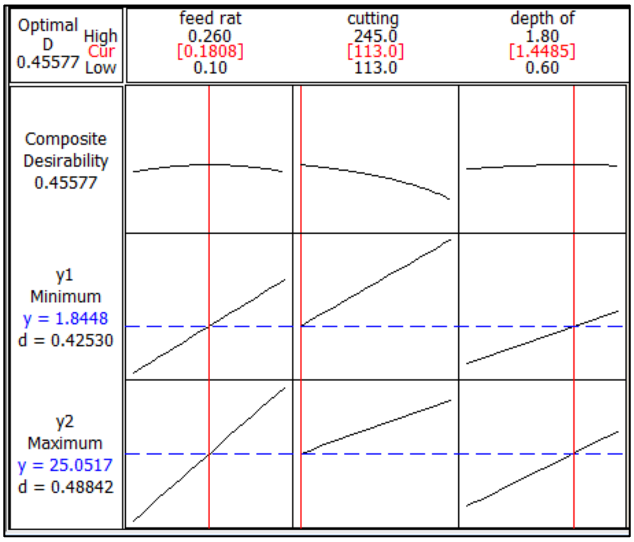

Fig. 6. The optimum parameters of three factors for CNC turning process

It is evident that the optimal parameters for these three factors are 113, 0.1808, and 1.4485, respectively.

5. Conclusions

The metal-cutting process of CNC turning entails the removal of superfluous metal volumes to obtain the desired dimensional accuracy and precision of machined parts. In this study, a multi-criteria analysis model was proposed to select the optimum processing parameters and tool inserts in the turning process based on two objectives of minimizing surface roughness and maximizing the material removal rate. Specifically, the decision support system is formulated through the implementation of the AHP and VIKOR. Subsequently, an experimental design for the CNC turning process was developed, incorporating a full factorial design with three factors of feed rate, cutting depth, and cutting speed. This design comprises two respective levels for each factor. The findings indicated that the proposed method is more pragmatic and applicable for manufacturing suppliers in the field of cutting tools. In the future, there will be an increased focus on fuzzy decision support systems that are capable of addressing uncertain factors. These systems will serve as an extension of our current work, providing a more comprehensive and nuanced approach to decision-making in uncertain circumstances.

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