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Automated green innovation for computerized numerical-controlled machining design

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Abstract

With the development of manufacturing technology and strict international environmental regulations, green production has become an imperative research topic in the manufacturing industry. Because cutting is affected by several factors, the development of green processes is vital for automated cutting using machines. These factors are often subjective and are set up merely based on the manual and experience of engineers, reducing tool life and deteriorating tool precision; ultimately, this approach increases production costs and reduces production efficiency. Moreover, the ecological environment can be seriously affected. Furthermore, the parameters must be adjusted according to variations in the processing state, which is a considerable drawback for the automated cutting industry. In this study, we investigated the precision computerized numerical-controlled cutting process as an example. We first assessed the literature and investigated tool wear and cutting noise as quality standards for green computerized numerical-controlled cutting. The cutting depth, cutting speed, feed rate, and the tip of the center were selected as control parameters. The consistency of the results was verified through an expert questionnaire conducted using analytic hierarchy process, and the weighted values of the control parameters were obtained. Simultaneously, seven environmental efficiency elements of the World Business Council for Sustainable Development and TRIZ 39 engineering parameters of the CSI project were used to establish the engineering parameters for the green production design. Furthermore, 40 inventive principles from a contradiction matrix were used to design an optimization strategy to develop and verify an innovation strategy of singular quality. Finally, the experimental results revealed that implementing the analytic hierarchy process coupled with the TRIZ innovative thinking mode and green production concept enables enterprises to reduce their consumption of raw materials and waste production during the design process. This approach effectively reduces the burden on the environment and thus facilitates industry competitiveness and sustainability.

Keywords

Automation, green innovation, green production, TRIZ, analytic hierarchy process

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Introduction

Nowadays, industrialized countries have proposed progressive strategies for the manufacturing industry, such as the "Made in China 2025" project and Germany's "Industry 4.0," indicating the return of the global core industry to the manufacturing industry. Precision mechanics is crucial in the manufacturing industry, which is a central industry for powerful industrial

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nations. With an increasingly stringent demand for high assembly quality, the tolerance for component errors is diminishing, and processing accuracy is becoming particularly significant.

For metal and nonmetallic cutting manufacturing, the turning process is a widely used processing method. The production process generally consumes a large amount of energy. In particular, a computerized numerical-controlled (CNC) turning tool can process high-precision metal parts. However, several factors must be considered during the turning process, such as tool size, feed rate, cutting speed, cutting depth, and differences in workpiece quality. These factors make parameter setting more challenging. Therefore, in the turning process, turning tests are often conducted directly on machine tools through trial and error or the parameters are set up on the basis of empirical experience. However, this approach not only consumes extensive resources but also increases costs and delays the delivery dates. Moreover, the noise caused by the turning process affects the surrounding environment and results in environmental problems.

Green production (GP) is a unanimous goal of global industrialized countries. However, the domestic industry focuses on process improvement through internal experiences, which are not released. Consequently, relevant knowledge and experience cannot be accumulated, resulting in manufacturing technology that does not comply with the concept.

This research focused on tool wear and cutting noise because the two qualities play a central role in the empirical precision cutting process. Besides, the analysis between various control factors and the qualities is effectively analyzed for the empirical industry.

Literature review

To study the optimal turning parameters, Bagaber and Yusoff[1] used uncoated carbide tools to perform machine cutting of stainless 316 under dry conditions and used the response surface methodology of an experimental design method and multiobjective optimization process parameters. The experimental results revealed that the minimal power consumption was 14.94%, and the surface roughness and tool wear decreased to 4.71% and 13.98%, respectively. This approach effectively reduced the cost and amount of energy consumed and avoids the use of cutting fluid that causes pollution. Li et al.[2] used a back-propagation neural network and considered spindle speed, feed rate, cutting depth, path spacing, and processing time as cutting parameters. They set energy consumption and surface roughness as targets, attempting to construct a multiobjective optimization cutting-parameter prediction model. The experiments verify that this method can effectively predict the parameters.

To investigate GP and other innovative methods to mitigate the burden of the cutting process on the environment, Deif[3] used engineering activities and design to intervene in product development and system operation. Kobayashi[4] proposed that the combination of quality function development and an eco-specification matrix can determine the development point of products. This combination was converted into TRIZ engineering parameters to further examine the inventive principles of products.

Regarding studies on tool wear, cutting noise, and GP, Anderberg et al.[5] demonstrated that CNC processing can increase production yields, reduce costs, save energy, and therefore enhance corporate competitiveness. Moreover, such processing facilitates a transition toward a sustainable and environmentally friendly manufacturing scheme, encouraging manufacturers to research model construction and conduct experiments on the processing costs through monitoring tool wear and energy consumption. The increasing environmental demands from governmental bodies and customers demonstrates the need for companies to improve their environmental performance. The research presented here shows that improvements in productivity and cost efficiency can be achieved alongside energy savings in a CNC machine environment. This improves company profitability and promotes more sustainable and environmentally friendly manufacturing, whereby the relationship between machining parameters, machining costs, and energy consumption is evaluated. From this perspective, it is pertinent that production planners understand the methodological possibilities for ensuring improvements in cost and energy efficiency. This study is based on a machining cost model. Experiments were conducted to monitor energy consumption and tool wear. Schultheiss et al.[6] stated that increasing the utilization rate of cutting tools to reduce the need for new tools can reduce the resources and energy required for producing new tools, thereby alleviating the overall effect of the processing operation on the environment. Schultheiss et al.[6] also conducted experiments on turning and milling processes, which revealed that reducing tool wear shortened the production cycle time by approximately 15% and lowered energy consumption by 12%. Several articles have discussed different approaches for improving sustainability during machining operations. However, effectively utilizing cutting tools is an approach that has been overlooked. Utilizing cutting tools not only decreases the need for new tools but also reduces the resources and energy used to produce new tools. The aim of this study was to maximize cutting tool utilization during machining operations without adversely affecting product quality, thus decreasing the environmental impact of machining operations. This was achieved by determining to what extent it is possible to increase total tool life using previously worn tools in a secondary machining operation. For both the milling and turning cases investigated in this study, the experimental results showed that it is possible to increase total tool life by 50%–100% compared with equivalent conventional machining operations. This increase in tool life could decrease the production cycle time by approximately 15% and reduce energy consumption by 12% as compared with conventional machining processes. Lin et al.[7] claimed that tool wear is an essential factor that affects the surface quality of a workpiece. Their study employed an artificial neural network to construct an estimation model using data collected from experiments. The model was used to explore the relationship between tool wear and cutting noise. Subsequently, noise testing was conducted during high-speed milling to establish an automatic tool wear monitoring system for determining the conditions of a cutting tool. Moreover, a polynomial network for predicting tool wear and cutting noise under different scenarios was applied to the manufacturing of thin ribs, conforming to the principles of environmentalism and reducing processing costs. Tool wear is a crucial factor that affects the quality of a machined surface. An abductive network was applied to synthesize the datasets measured from the experiments, and prediction models were established for tool-life estimation and over-worn situation alert under various tool geometries. Through the identification of tool wear and the related cutting noise, we hope to construct an automatic tool wear monitoring system using noise detection during a high-speed cutting process to examine whether a tool can be used or not to reduce the cost of milling. Hence, thin-ribbed components can be machined with consideration to environmental protection. In this study, several types of polynomial nodes were used in the polynomial network for predicting tool wear and cutting noise under different conditions. Zhang et al.[8] asserted that GP has received attention from academia and industry. They optimized cutting parameters to evaluate the balance between the three essential factors of GP, namely, energy, noise, and cost. They adopted analysis of variance (ANOVA) to explore the effects of cutting parameters on cutting noise. The results identified the depth of cut as the main factor affecting cutting noise, and a cutting cost model was constructed accordingly. In addition, the cutting speed, feed rate, and depth of cut were used as decision variables to propose a multiobjective optimization model to save energy, reduce noise, and lower costs. Green manufacturing has attracted considerable attention from the academic and industrial sectors under with respect to current environmental circumstances. The purpose of this study was to evaluate the trade-offs between the main factors in green manufacturing, namely, energy, noise, and cost, through cutting parameter optimization. Moreover, ANOVA results were employed to analyze the influence of cutting parameters on noise. The results showed that the depth of cut was the dominant factor influencing noise. Based on the results, a multiobjective optimization model for saving energy, reducing noise, and saving costs is proposed, which uses the cutting speed, feed fate, and depth of cut as decision variables.

The aforementioned studies have indicated the importance of tool wear and cutting noise for environment protection during a CNC cutting process. Accordingly, this study selected these two factors as quality standards for green processing. The above-mentioned studies demonstrate the importance of tool wear and cutting noise for environmental protection in the numerical-controlled (NC) machining process; therefore, tool wear and cutting noise are selected as the cutting quality of this study.

GP

GP is mainly an organized production process that is based on the principle of protecting the ecological environment.[9,10] It meets green consumption through the output of products. The purpose of GP is as follows: (1) in the entire production process, the generation and emission of pollutants are minimized, so that resources can be effectively used. Thus, both the production stage and the consumption process can meet the requirements of environmental protection and reduce the harm to humans and the environment. (2) Mitigating resource depletion by increasing resource utilization, mutual replacement of scarce resources, and reuse of resources can then be achieved.

Analytic hierarchy process

The analytic hierarchy process (AHP) was proposed by Thomas L Saaty, a professor at the University of Pittsburgh in 1971. AHP is mainly applied to uncertain situations and decision-making problems that include multiple evaluation criteria.[11] Decision-makers set the final target against the problems. In accordance with the target, the criteria are repeatedly extended to the next criteria and subcriteria until the fulfillment of the last criterion. An eigenvector is then calculated by comparing evaluation scales to obtain the weighted values for all criteria, and these criteria are then prioritized through comprehensive weighting.

TRIZ theory

TRIZ is a theoretical method that was regulated by Altshuller when researching national patent cases. The name "TRIZ" comes from a Russian synonym for the theory of inventive problem-solving, that is, "innovative invention problem-solving theory."

After 70 years of research and empirical validations, TRIZ has been established as a set of highly efficient and reliable innovative thinking and systematic approaches that provide complete and abundant creative production tools and help identify innovative directions and solutions for projects. TRIZ is used to enhance the characteristics and efficiency of invented products.[12]

Green innovation

Green innovation is an enterprise that considers the environmental effects of the product design and development stages to achieve environmental friendliness. Furthermore, corporate social responsibility is considered a key factor.[13]

Green innovation includes five characteristics: (1) energy-saving; (2) extending the product life cycle; (3) avoiding waste production, reducing the amount of waste, and subsequent problem-solving; (4) recycling, continual usage, and protecting limited resources; and (5) avoiding the use of hazardous substances to maintain ecosystem balance.[14]

Regarding studies on TRIZ theory and integrated applications of green innovation, Chen and Liu[15] integrated the following seven eco-efficiency factors proposed by the World Business Council for Sustainable Development (WBCSD) (i.e. (1) reduce the material intensity of its goods and services; (2) reduce the energy intensity of its goods and services; (3) reduce the dispersion of any toxic materials; (4) enhance the recyclability of its materials; (5) maximize the sustainable use of renewable resources; (6) extend the durability of its products; and (7) increase the service intensity of its goods and services) with the parameters of the TRIZ contradiction matrix, allowing research and development personnel to quickly identify adequate parameters for the preset categories according to the intended development trend. This helps identify problems and resolve contradictions in relevant processes. Chen and Liu[15] used the seven environmental efficiency factors of WBCSD (environmental efficiency factor projects including: (1) reduce the material intensity of its goods and services; (2) reduce the energy intensity of its goods and services; (3) reduce the dispersion of any toxic materials; (4) enhance the recyclability of its materials; (5) maximize the sustainable use of renewable resources; (6) extend the durability of its products; and (7) increase the service intensity of its goods and services) In combination, R&D designers can rapidly identify the proposed classification based on trends they want to develop and identify appropriate engineering parameters to help identify problems and resolve conflicts. Chen[16] applied green trends of evolution and ideal final results of TRIZ to green innovation, which assists designers in developing new products and estimating future product trends.

The aforementioned studies have identified the inextricable relationship between TRIZ theory and green innovation, and have suggested that problems concerning green innovation can be identified and resolved using parameters derived from TRIZ theory. Therefore, this study was conducted by employing green innovation and TRIZ theory. The abovementioned studies show that the relationship between TRIZ theory and green innovation is inextricably linked. The exploration and processing of the green innovation scheme problem can be solved by the engineering parameters in TRIZ theory; therefore, this study adopted a combination of these two methods.

Research design

In this study, through the relevant literature review and AHP method, the expert questionnaire was constructed to verify the consistency of the results. After obtaining the weight values of the quality criteria, the top two weighted qualities were selected, which were tool wear and cutting, respectively. The tool wear and noise are then selected as the quality criterion of green CNC cutting. The cutting depth, cutting speed, feed rate, and tool nose runoff are used as control parameters.

After establishing the green CNC cutting hierarchy structure, a combination of TRIZ theory and seven environmental efficiency elements proposed by the WBCSD was implemented. In this approach, a new green design matrix was established, and the contradiction matrix was consequently completed. Finally, by combining the one-parameter method with the inventive principles, the innovative principles were calculated and ordered in accordance with their occurrence in the contradiction matrix. Furthermore, this study investigated the "individual quality of the precision CNC turning process" of the green innovative program by selecting the principles that appear most frequently in the contradiction matrix.

Establishment of AHP hierarchy structure

To establish the evaluation criteria of green CNC cutting and study the characteristics of application level analysis, three evaluation criteria and nine evaluation subcriteria were compiled using relevant literature and interviews from experts and scholars. Consequently, a hierarchical structure for green CNC cutting was established, as shown in Figure 1.

Evaluation criteria

The two principle criteria and four assessment subcriteria received from the results by AHP questionnaire are described as follows:

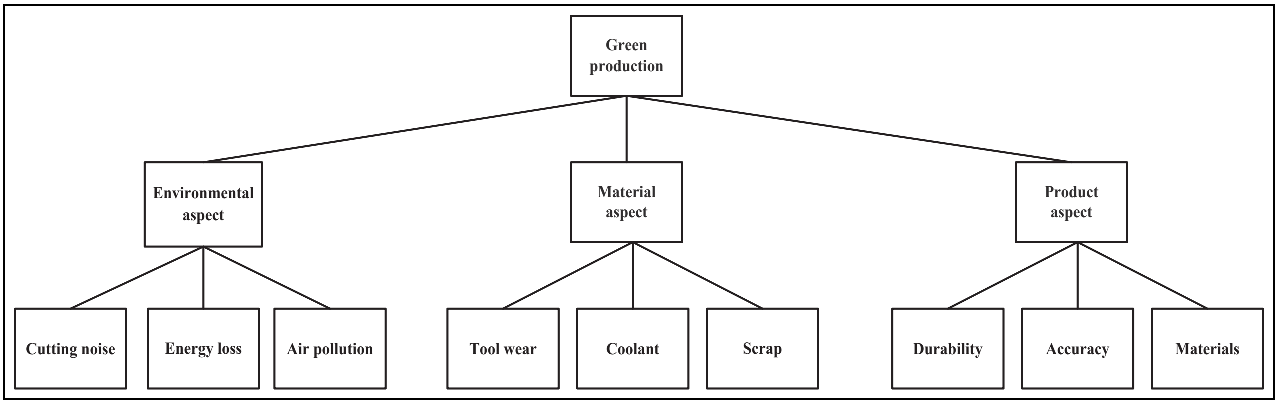

Figure 1. Green CNC cutting hierarchy structure.

1. Tool wear.

Tool wear is a result of physical and chemical effects of the heat and mechanical friction that occur during cutting. Tool wear occurs on the backside of the tool wear belt, notch, and collapse. The abrasion area is crescent-shaped, and the back of the flank undergoes oxidation pit and ditch during abrasive wear of the pattern.

2. Cutting noise.

Noise is one of the factors contributing to industrial pollution. Replacing manpower with machinery and equipment can enable mass production; however, it also produces noise problems and affects the surrounding environment. Long-term exposure to high-decibel noise leads to permanent hearing damage. Therefore, suppressing the noise source properly is necessary to sustain industrial development and environmental quality.

3. Depth of cut.

The pressure on the tool should be increased to increase the cutting depth; however, this increases the possibility of metal deformation at the front of the tool. Such deformation increases the size of the adhesive layer and makes the surface less smooth. This is permissible in roughing cut operations, but to obtain a smooth surface, it is necessary to reduce the cutting depth and maintain the adhesive layer at the smallest possible size.

4. Cutting speed.

Cutting speed is the most common factor that affects cutting conditions. Cutting speed substantially affects multiple factors, such as tool wear, surface roughness, machining efficiency, cutting vibration, work safety, and cutting power. The surface roughness improves with an increase in the cutting speed, and the processing efficiency improves as well. However, an increase in the cutting speed accelerates tool tear. Therefore, increasing the cutting speed should not be considered the only solution for increasing productivity. In general, references exist for each tool, based on the model number, that specify the optimal range of cutting speeds for different processing materials.

5. Feed rate.

Because of the limited output power of machine tools, the feed rate increases as the cutting efficiency increases. For a certain range, an increase in the feed rate can reduce the amount of tool wear; however, it can cause surface roughness or chip disposal problems. The surface roughness is geometrically determined by the feed rate and nose radius of the cutting edge, and increasing the feed rate roughens the processing surface.

6. Tool nose runoff.

Within factories, gaskets of different thicknesses are used to adjust the turning tool height while attempting to maintain the rotation center of the tool nose and turning workpiece at the same level. The adjustment of the turning tool is quite cumbersome and finicky, and the height affects the tool life and processing accuracy. To analyze the effects of the tool installation point on the processing angle, consider the external diameter of the turning rod: If the feed motion is ignored when the installation point of the tool nose is higher or lower than the workpiece axis, it causes variations in the front clearance angle before processing and in the rake angle after processing.

Table 1. Pairwise comparison matrix of principal criteria.

Principal criteria factors	Environmental aspect	Material aspect	Product aspect
Environmental aspect	1	1.067	1.333
Material aspect	0.938	1	1.400
Product aspect	0.750	0.714	1
Sum	2.688	2.781	3.733

Table 2. Weight analysis of principal criteria.

Principal criteria factors	Environmental aspect	Material aspect	Product aspect	Weight
Environmental aspect	0.372	0.384	0.357	0.371
Material aspect	0.349	0.360	0.375	0.361
Product aspect	0.279	0.257	0.268	0.268
Sum	1	1	1	1

Table 3. Pairwise comparison matrix of environmental aspect.

Environmental aspect	Cutting noise	Energy loss	Air pollution
Cutting noise	1	1.667	0.920
Energy loss	0.600	1	1.320
Air pollution	1.087	0.758	1
Sum	2.687	3.424	3.240

Table 4. Weights of environmental criteria.

Environmental aspect	Cutting noise	Energy loss	Air pollution	Weight
Cutting noise	0.372	0.487	0.284	0.381
Energy loss	0.223	0.292	0.407	0.308
Air pollution	0.405	0.221	0.309	0.311
Sum	1	1	1	1

Questionnaire result analysis

The overall criteria weighting and consistency were assessed based on the results of the research questionnaire, with the analysis of individual weights and consistency conducted in Microsoft Excel. The pairwise comparison matrix and weight analysis of the two principal criteria factors are shown in Tables 1 and 2, respectively.

Table 2 indicates that the eigenvalue (λ) = 3.001, consistency index (CI) = 0.001, and consistency ratio (CR) = 0.001. These data and values are less than 0.1, which is in accordance with Saaty's requirements. To analyze green CNC cutting, the priority vector of main criteria factor was considered. Environmental aspect, material aspect, and product aspect were the primary, secondary, and tertiary criteria, respectively. A pairwise comparison matrix and weight analysis of subcriterion factors are shown in Tables 3–8.

Table 4 indicates that λ = 3.094, CI = 0.047, and CR = 0.081. These values are less than 0.1, which is in accordance with Saaty's requirements. The analysis of green CNC cutting indicated the priority vector of subcriterion factors for environmental aspect and showed that the cutting noise is the most significant subcriterion, followed by the air pollution and energy loss.

Table 6 indicates that λ = 3.019, CI = 0.01, and CR = 0.17. These values are less than 0.1, which is in accordance with Saaty's requirements. The analysis of green CNC cutting considered the priority vector of subcriterion factors for the material aspect. The analysis showed that the tool wear is the most significant subcriterion, followed by the coolant and scrap.

Table 5. Pairwise comparison matrix of material aspect.

Material aspect	Tool wear	Coolant	Scrap
Tool wear	1	1.387	1.133
Coolant	0.721	1	1.120
Scrap	0.882	0.893	1
Sum	2.604	3.280	3.253

Table 6. Weights of material aspect criteria.

Material aspect	Tool wear	Coolant	Scrap	Weight
Tool wear	0.384	0.423	0.348	0.385
Coolant	0.277	0.305	0.344	0.309
Scrap	0.339	0.272	0.307	0.306
Sum	1	1	1	1

Table 7. Pairwise comparison matrix of product aspect.

Product aspect	Durability	Accuracy	Materials
Durability	1	0.653	0.920
Accuracy	1.531	1	1.533
Materials	1.087	0.652	1
Sum	3.618	2.306	3.453

Table 8. Weights of product aspect criteria.

Product aspect	Durability	Accuracy	Materials	Weight
Durability	0.276	0.283	0.266	0.275
Accuracy	0.423	0.434	0.444	0.434
Materials	0.300	0.283	0.290	0.291
Sum	1	1	1	1

Table 8 indicates that $\lambda = 3.101$, CI = 0.051, and CR = 0.087. These values are less than 0.1, which is in accordance with Saaty's requirements. The analysis of green CNC cutting considered the priority vector of subcriterion factors for the product aspect. The analysis showed that the accuracy is the most significant subcriterion, followed by the materials and durability.

This study uses the results obtained from the AHP method and the expert questionnaire to find out the key factors that will be considered in practical processing of green CNC cutting and their corresponding impacts (Table 9).

Green design matrices

The inventive principles for tool wear and cutting noise were collated to establish green design matrices, as displayed in Tables 10 and 11.

Innovation strategies

The problem identified in this study was associated with technical contradiction. Therefore, a technical contradiction process was adopted to improve the two quality standards in the turning process, thereby optimizing these standards. The single quality innovation strategy of TRIZ was used to divide the quality standards into three groups, which were the three factors explored in this study (cutting depth, cutting speed, and feed rate). The problem identified in this study was associated with technical contradiction. Therefore, the technical contradiction process in the turning process was used to improve the two quality goals and then to optimize the quality objectives. Using the TRIZ single quality innovation strategy, the two quality objectives were divided into three groups, which were the three factors exaimined in this study (cutting depth, cutting speed, and feed rate). By analyzing the 39 engineering parameters

Table 9. Green CNC cutting and their corresponding impacts.

Principle criteria	Principle weight	Subcriteria	Subweight	Subpriority	Overall weight	Overall priority
Environmental aspect	0.371	Cutting noise	0.381	1	0.141	1
		Energy loss	0.308	3	0.114	5
		Air pollution	0.311	2	0.116	4
Material aspect	0.361	Tool wear	0.385	1	0.139	2
		Coolant	0.309	2	0.111	6
		Scrap	0.306	3	0.111	7
Product aspect	0.268	Durability	0.275	3	0.074	9
		Accuracy	0.434	1	0.116	3
		Materials	0.291	2	0.078	8

Table 10. Green design matrix for tool wear.

Improving parameter	Worsening parameter					
	Stability of object	Tension/ pressure	Force	Waste of energy	Speed	Waste of time
Reduce the energy intensity of its goods and services				14,20,19,35,2,36,25		
Reduce the dispersion of any toxic materials	28,33,1,18,4,35,2,40					
Enhance the recyclability of its materials		6,18,38,40, 34,15,10,14			35,15,34, 18,6,36	
Extend the durability of its products	28,33,1,18,4,35,2,40					
Increase the service intensity of its goods and services					35,15,34, 18,6,36	14,10,34, 17,37,36,4

Table 11. Green design matrix for cutting noise.

Improving parameter	Worsening parameter			
	Tension/pressure	Stability of object	Strength	Temperature
Reduce the material intensity of its goods and services			8,3,26,14,9,18,40	
Reduce the energy intensity of its goods and services				28,30,36,2,10, 40,35,39,19
Reduce the dispersion of any toxic materials		28,33,1,18,13, 17,35,2,40		
Enhance the recyclability of its materials	6,18,38,40,10,3			
Maximize the sustainable use of renewable resources			8,3,26,14,9,18,40	
Extend the durability of its products		28,33,1,18,13, 17,35,2,40	8,3,26,14,9,18,40	

and the green matrices integrated with the 40 inventive principles, the following innovation strategies were derived: (1) to achieve the target of tool wear, increasing the cutting speed and cutting depth and reducing the feed rate can enhance the recyclability of materials and increase the service intensity of goods and services; this strategy is particularly effective for enhancing the recyclability of tool materials. (b) To achieve the target of cutting noise, reducing the cutting speed, cutting depth, and feed rate can reduce the energy intensity of goods and services, enhance the recyclability of materials, and extend the durability of products. Table 12 briefly details the innovation strategies.

Experimental verification

Cutting was performed according to the definition of three control variables. In this study, S45C mild carbon

Table 12 Design strategy based on identified TRIZ solution principles.

Tool wear innovation strategy

TRIZ solution principles	Solution descriptions	Innovation strategy descriptions
#14. Spheroidality	1. Use curve instead of straight line, surface instead of plane, sphere instead the cube 2. Use roller, ball, spiral, and semicircle 3. Change linear motion to rotation 4. Use centrifugal force	When the cutting speed is high, the depth of cut should be increased. By rotating the machining, the contact area between the tool and the workpiece is reduced. Furthermore, the probability of chipping and tool wear is reduced, which extends tool life. Thus, the recyclability of the materials is enhanced, which is environmentally efficient (innovation strategy: increase the cut depth)
#18. Mechanical vibration	1. Let the object or system vibrate 2. Increase the vibration frequency of object or system 3. Use the resonant frequency of an object or system 4. Use piezoelectric vibrators to replace mechanical vibrations 5. Use vibration that combines ultrasonic and electromagnetic fields	When increasing the cutting speed, the vibration and resonance frequency of the workpiece and the tool itself enable the tool to be evenly stressed. Avoiding a single point of force wear on the tool will prolong its life, which enhances the recyclability of its materials and is environmentally efficient (innovation strategy: increase the cutting speed)
#35. Change parameters	1. Change the physical state of an object or system 2. Change the concentration or density 3. Change the degree of flexibility 4. Change the temperature 5. Change other parameters	When the cutting speed and feed rate are slow, the factor parameters should be changed to reduce tool wear and avoid harmful smoke generated by low-speed friction. Doing so prolongs tool life, enhances the recyclability of its materials, and increases the service intensity of goods and services, which is environmentally efficient. (Innovation strategy: reduce the feed rate)

Cutting noise innovation strategy

TRIZ solution principles	Solution descriptions	Innovation strategy descriptions
#35. Change parameters	1. Change the physical state of an object or system 2. Change the concentration or density 3. Change the degree of flexibility 4. Change the temperature 5. Change other parameters	Changing factor parameters, reducing the depth of cut, or reducing the contact pressure between a workpiece and tool will reduce the turning noise and avoid deformation of the workpiece. Doing so reduces the dispersion of toxic materials and extends the durability of products, which is environmentally efficient (innovation strategy: reduce the cutting depth)
#18. Mechanical vibrations	1. Let the object or system vibrate 2. Increase the vibration frequency of object or system 3. Use the resonant frequency of object or system 4. Use piezoelectric vibrators to replace mechanical vibrations 5. Using vibrations that combine ultrasonic and electromagnetic fields	By using the resonant frequency of the object, when the cutting speed is reduced, the friction between the tool and the workpiece as well as the noise can be reduced. Doing so enhances the recyclability of its materials, which is environmentally efficient (innovation strategy: reduce cutting speed)
#35. Change parameters	1. Change the physical state of an object or system 2. Change the concentration or density 3. Change the degree of flexibility 4. Change the temperature 5. Change other parameters	By changing the factor parameters and reducing the feed rate, the contact pressure between the workpiece and the tool is reduced, which reduces the noise. Doing so reduces the energy intensity of its goods and services, which is environmentally efficient (innovation strategy: reduce the feed rate)

Table 13. Tool wear from suggested parameters by machining handbook.

Cutting speed (m/min)	Depth of cut (mm)	Feed rate (mm/rev)	Tool nose runoff (mm)	Tool wear (mm^{-2})
200	1	0.06	± 0.03	4.38E−0.7

Table 14. Cutting noise from suggested parameters by machining handbook.

Cutting speed (m/min)	Depth of cut (mm)	Feed rate (mm/rev)	Tool nose runoff (mm)	Cutting noise (dB)
200	1	0.06	± 0.03	82.83

Table 15. Optimal values for the innovation strategies with a single quality characteristic.

	Cutting speed (m/min)	Depth of cut (mm)	Feed rate (mm/rev)	Tool nose runoff (mm)	Tool wear (mm^{-2})
Cutting speed (m/min)	**250**	1	0.06	± 0.03	3.87E−0.7
Depth of cut (mm)	200	**1.5**	0.06	± 0.03	2.97E−0.7
Feed rate (mm/rev)	200	1	**0.02**	± **0.03**	**4.55E−0.7**
	200	1	**0.02**	**0.1**	**3.87E−0.7**
Suggested parameters by machining handbook	**200**	**1**	**0.06**	± **0.03**	4.38E−0.7

	Cutting speed (m/min)	Depth of cut (mm)	Feed rate (mm/rev)	Tool nose runoff (mm)	Cutting noise (dB)
Cutting speed (m/min)	**150**	1	0.06	± 0.03	81.73
Depth of cut (mm)	200	**0.5**	0.06	± 0.03	82.61
Feed rate (mm/rev)	200	1	**0.02**	± 0.03	82.55
Suggested parameters by machining handbook	**200**	**1**	**0.06**	± **0.03**	82.83

steel was cut using an ECOCA PC-3807 CNC lathe (manufactured by Shengjie). The dimension of the turning material, which clamped the 100-mm-long S45C mild carbon steel, was ϕ45 mm × 250 mm. A NX2525 discarded blade (Mitsubishi) was installed on the TJNR2020K16 tool holder (Toshiba).

This study analyzed and compared the experiment result from median parameters adopted by the CNC turning industry. The tool wear and cutting noise from median parameters is 4.38E−0.7 mm^{-2} (Table 13) and 82.83 dB (Table 14), respectively.

The values of the innovation strategy parameters with a single quality characteristic were obtained using the TRIZ. Table 15 indicates the optimized values of these parameters. Due to an error in the measured tool wear, to determine the optimization strategy for a single quality characteristic, the tool nose runoff was adjusted for turning. When the tool nose runoff was ± 0.03 mm, the amount of tool wear exceeded that from suggested parameters by handbook. Therefore, the tool nose runoff was adjusted to 0.1 mm, and the amount of tool wear was 3.87E−0.7 mm^{-2}, which corresponded with that from suggested parameters by handbook commonly used in practice. This result indicated that the TRIZ-based innovation strategy for a single quality characteristic is feasible. The eco-efficiency goals proposed by the WBCSD can be achieved using such a strategy for production.

Two quality targets for tool wear and cutting noise were compared and analyzed, indicating that the values obtained in this study were superior to those obtained from the suggested parameters by handbook. This comparison verifies that innovation strategies developed using the TRIZ for these two quality targets were successfully optimized.

Conclusion

Industrial product design is becoming increasingly complex. More demanding processing requirements necessitate the set conditions of cutting parameters to be extremely rigorous, to prevent situations where other qualities are affected by modifications in partial parameters. In the CNC turning process, the greatest challenge is that the set conditions of the cutting parameters are extremely stringent. Because of cost and time factors, several quality characteristics are assessed using the expert experience as well as trial and error methods during processes. However, the improper usage of such indicators rather than quality measurements is a concern.

Furthermore, with an increase in environmental awareness and the constraints of international laws, reducing environmental damage during the production design stage of the product has become necessary to avoid being labeled as a high-pollution industry and consequently being forced to relocate or close factories. Therefore, an easy-to-use quality improvement analysis procedure is necessary for the automated CNC turning industry.

Considering the failure of traders to explicitly choose numerical conditions for achieving turning quality optimization, this research used CNC turning to integrate seven environmental efficiency factors, particularly the factors of tool wear and cutting noise, to establish engineering parameters for GP design.

This study used an expert questionnaire designed by AHP combined with the TRIZ innovative thinking model and GP concept. According to the experimental results, tool wear decreased to $0.51\mathrm{E}{-}0.7\,\mathrm{mm}^{-2}$ and cutting noise decreased to 1.1 dB, which can effectively help enterprises to reduce the burden on the environment when designing and producing products. Compared with existing optimization methods, this approach provides a set of simple and effective analytical methods to solve the process optimization problem.

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