

Advanced Optimization of CNC Machining Processes for Enhanced Performance Efficiency

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ABSTRACT

This study focuses on the performance evaluation and optimization of CNC machining processes using advanced computational techniques, specifically Particle Swarm Optimization (PSO). A MATLAB-based simulation and GUI platform was developed to analyze the effects of spindle speed, feed rate, and depth of cut on Material Removal Rate (MRR), surface roughness, tool wear, energy consumption, and machining cost. The results demonstrate significant improvements in productivity and overall efficiency while maintaining acceptable trade-offs in surface quality and operational parameters. The integrated multi-objective optimization framework ensures sustainable, cost-effective, and high-performance CNC operations, providing a practical foundation for Industry 4.0 manufacturing applications.

Key Words: *CNC Machining, Particle Swarm Optimization, Multi-Objective Optimization, Manufacturing Efficiency.*

I. INTRODUCTION

Computer Numerical Control (CNC) machining has become a fundamental technology in modern manufacturing due to its ability to deliver high precision, repeatability, and efficiency in producing complex components for industries such as aerospace, automotive, biomedical, and precision engineering, where dimensional accuracy and surface integrity are critical; however, CNC processes inherently involve challenges such as tool wear, surface roughness deterioration, vibration, noise, high energy consumption, and increased operational costs, especially when machining advanced materials like composites, hardened steels, titanium alloys, and aluminum alloys, which require careful selection and balancing of process parameters including spindle speed, feed rate, depth of cut, and tool geometry to ensure both performance and sustainability, and traditional experimental approaches, such as Taguchi design, response surface methodology, and one-factor-at-a-time analyses, while useful, often fall short in handling the complexity and nonlinearity of multi-objective optimization problems where productivity, surface quality, tool longevity, energy consumption, and machining cost are interdependent; therefore, advanced optimization techniques have emerged as essential tools to address these limitations, incorporating artificial intelligence, machine learning, and evolutionary algorithms, such as Particle Swarm Optimization (PSO), Genetic Algorithms (GA), Artificial Neural Networks (ANN), fuzzy logic, and hybrid intelligent models, which enable simultaneous optimization of multiple conflicting objectives, facilitate rapid exploration of large parameter spaces, and identify global optima for machining conditions while maintaining balance between productivity and quality; contemporary CNC optimization frameworks often integrate these algorithms within user-friendly MATLAB-based graphical user interfaces (GUIs), allowing operators to input machining parameters, define simulation samples, set the number of optimization iterations, and visualize performance metrics such as Material Removal Rate (MRR), surface roughness (Ra), tool wear, energy consumption, and machining cost, while also providing features for result export and comparative analysis, including 3D scatter plots and convergence graphs that illustrate the effect of spindle speed, feed rate, and depth of cut on multi-objective performance, highlighting near-optimal operating regions where trade-offs between productivity and quality are effectively managed; research demonstrates that PSO-based optimization, for example, can identify parameter combinations such as a spindle

speed of 3500 rpm, feed rate of 0.35 mm/rev, and depth of cut of 2.5 mm that maximize MRR, significantly improving productivity from approximately 450 mm³/min to over 2600 mm³/min, while inducing only moderate increases in surface roughness, tool wear, energy consumption, and machining cost, thus illustrating the trade-offs inherent in multi-objective CNC machining; moreover, advanced optimization facilitates a holistic assessment of machining performance by integrating economic and sustainability considerations, enabling energy-efficient operations, reduced environmental impact, and cost-effectiveness, while addressing practical constraints in real industrial scenarios, and supports adaptive decision-making for diverse machining operations such as milling, turning, and hybrid processes; despite these advances, challenges remain in fully unifying multiple performance metrics, including geometric accuracy, vibration, noise, and environmental impact, into comprehensive optimization frameworks, highlighting the need for further research into multi-objective, AI-driven, and predictive models capable of handling real-world uncertainties, dynamic operating conditions, and material-specific behaviors; therefore, CNC machining optimization is shifting from traditional trial-and-error and single-objective methods toward intelligent, data-driven, and multi-objective approaches that combine simulation, performance evaluation, evolutionary computation, and machine learning to achieve sustainable, high-efficiency, and high-quality manufacturing; by evaluating interactions between process parameters, visualizing outcomes through GUIs, and applying advanced optimization algorithms, modern studies demonstrate significant improvements in machining performance, providing a balanced solution to the trade-offs between productivity, surface finish, tool longevity, energy usage, and cost, thereby offering a framework for developing intelligent and sustainable manufacturing systems capable of meeting the demands of Industry 4.0 and beyond, while also paving the way for future integration of real-time adaptive control, predictive maintenance, and multi-objective decision-making in CNC machining processes, ensuring that optimized conditions not only enhance immediate machining outcomes but also contribute to long-term operational efficiency, environmental sustainability, and industrial competitiveness, making the study and implementation of advanced optimization techniques in CNC machining an essential pursuit for researchers, engineers, and manufacturers seeking to maximize both economic and technical performance in complex, high-precision production environments.

II. RESEARCH BACKGROUND

Kumar et al. (2026) had investigated the effect of turning parameters on material removal rate (MRR) and surface roughness variation (% ΔRa) and had evaluated the performance of RSM, ANN, and fuzzy logic modeling approaches. They had reported that MRR increased with higher spindle speed (SS), depth of cut (DOC), and feed, while higher % ΔRa was mainly associated with lower SS and feed, DOC showing minimal effect within the selected range. Their comparative assessment had indicated that ANN achieved the highest predictive accuracy, with R^2 values of 0.9807 for MRR and 0.9842 for % ΔRa , and the lowest prediction error for % ΔRa , demonstrating its superior capability in modeling nonlinear relationships. RSM had provided statistically interpretable models with good accuracy ($R^2 = 0.9594$ for MRR and 0.9480 for % ΔRa) and enabled effective process optimization, whereas fuzzy logic had successfully captured qualitative trends and parameter interactions but had shown comparatively lower and less consistent accuracy ($R^2 = 0.9491$ for MRR and 0.9634 for % ΔRa). Spindle speed had emerged as the most influential parameter, contributing 44.25% to MRR and 57.07% to % ΔRa . multi-objective optimization using the desirability approach had identified optimal conditions of 1499 rpm SS, 0.58 mm DOC, and 0.13 mm/rev feed, yielding an MRR of 0.855 gm sec⁻¹ and 1.147% surface roughness variation. Overall, their study had concluded that the combined application of RSM, ANN, and fuzzy logic effectively integrated statistical robustness, high nonlinear prediction accuracy, and uncertainty handling, providing a reliable framework for process analysis and optimization in turning operations.

Ullah, Chan, and Chang, (2025) had examined the transformative effects of advanced computational techniques, particularly Finite Element Analysis (FEA), along with artificial intelligence (AI)-driven optimization on CNC machine tool design and manufacturing. The study had addressed major challenges such as vibration control, dynamic error compensation, and topology optimization, combining traditional machining methods with contemporary Industry 4.0 approaches. It had highlighted the importance of passive, active, and hybrid vibration control strategies in improving tool precision and operational efficiency, while also investigating spindle imbalance, cutting forces, and structural resonances. Furthermore, the research had emphasized sustainability and energy-efficient practices in automated manufacturing. By employing advanced AI algorithms, the study had proposed methods to optimize tool paths, structural rigidity, and material use, ultimately contributing to enhanced productivity and environmental sustainability. The findings had provided a comprehensive framework for applying computational optimization and machine learning in precision engineering, offering practical guidance for CNC machine tool design and operations.

Zhujani et al. (2024) had investigated the optimization of machining processes, highlighting its critical role in enhancing productivity and ensuring product quality. They had simultaneously optimized response characteristics, including surface roughness, material removal rate, tool wear, and cutting time, in the finish turning process. The study had employed a Taguchi-based design of experiments L9(34) to examine and identify the optimal values for process parameters such as cutting speed, feed rate, depth of cut, and nose radius. A Taguchi-based multi-objective grey relational approach (GRA) method had been used to address the turning of Inconel 718 alloy, aiming to increase productivity by simultaneously minimizing surface roughness, tool wear, and machining time. GRA, along with the S/N ratio derived from the Taguchi method, had been utilized to integrate multiple response characteristics into a single metric. The grey relational grade (GRG) had produced estimates of the optimal input levels and their relative significance to specific quality characteristics. By applying ANOVA, the significance of individual parameters in relation to both single and overall quality characteristics had been determined. Single-objective optimization had yielded a minimal surface roughness of 0.167 μm , tool wear of 44.65 μm , cutting time of 19.72 s, and maximum material removal rate of 4550 mm^3/min . Multi-objective optimization of Inconel 718 at a cutting speed of 100 m/min, depth of cut of 0.4 mm, feed rate of 0.051 mm/rev, and tool nose radius of 0.4 mm had demonstrated that all investigated response characteristics had achieved their optimal values. Confirmatory experiments had been conducted to validate the findings and had shown a high degree of agreement with the predicted results.

Abdelaoui, et al. (2023) had highlighted that metal working processes constituted a major activity in the mechanical manufacturing industry and were significant consumers of energy and natural resources. They had emphasized that, in material removal operations, selecting appropriate cutting parameters and cooling or cutting fluids was necessary to enhance energy efficiency and sustainability. The authors had noted that over the last two decades, publications in this area had increased rapidly, reflecting the growing importance of research on energy-efficient machining. Their review had identified and analyzed 166 scientific studies, which had provided original contributions and addressed multiple challenges related to energy efficiency. They had presented recently developed models of energy consumption and discussed the effects of different materials used in machining. Moreover, the study had described various techniques for modeling and optimizing machining operations such as turning, milling, and drilling, including experimental, single-objective, multi-objective, and hybrid optimization approaches. The authors had argued that these insights could assist practitioners and researchers in selecting suitable methods and assessing progress in machining energy efficiency. Additionally, they had reviewed different cutting fluids used in machining and suggested that their work could guide researchers and manufacturers in making technical decisions with substantial economic benefits in terms of energy savings.

Feng, et al. (2022) investigated the application of sustainable manufacturing technologies, highlighting the challenges faced by enterprises, industries, and researchers in the context of carbon peak and carbon neutrality. The study focused on reducing energy consumption in hole machining by simultaneously optimizing tool paths and cutting parameters. It was reported that the integrated optimization methodology could achieve greater energy savings compared to optimizing the tool path or cutting parameters individually. The authors first established an energy model for hole machining based on machine tool energy composition, tool path planning, and process parameters. They emphasized that tool path planning, treated as an air cutting process, had a significant impact on energy reduction, particularly for hole groups with a large proportion. The tool paths were optimized using an improved ant colony algorithm, which considered the distances between consecutive holes. Based on this optimized path, a multi-objective optimization model for cutting parameters was developed, taking spindle speed and feed rate as variables, and machining time, energy consumption, and surface roughness as objectives. The non-dominated sorting genetic algorithm (NSGA-II) was employed to solve the multi-objective optimization problem. Finally, a case study involving 50 holes was conducted to validate the proposed methodology and demonstrate its potential to provide practical energy efficiency strategies for hole groups or multi-hole parts on CNC machines, contributing to sustainable manufacturing practices.

Jia et al. (2021) emphasized that energy saving and emission reduction had been identified as crucial strategies to address climate change, which was considered one of the major challenges for humanity in the coming decades. They highlighted that energy modeling and optimization of machining process parameters had proven to be effective approaches for achieving energy efficiency in the manufacturing industry. The study proposed a multi-objective optimization of CNC turning process parameters aimed at achieving both high-quality and low-energy-consumption machining of lathe operations, taking into account transient and steady-state energy consumption. By analyzing energy consumption characteristics during machining and incorporating practical constraints, such as machine tool performance and tool life, the authors developed a multi-objective optimization model with turning process parameters as variables and machining quality and energy efficiency as objectives. The model was solved using the non-dominated sorting genetic algorithm-II (NSGA-II), and a Pareto optimal solution set was obtained. Experimental validation on CK6153i CNC lathe for shaft part machining demonstrated that energy consumption was reduced by 38.3%, and surface roughness of the workpiece decreased by 47%, confirming the effectiveness of the proposed optimization approach.

Ma, et al. (2020) investigated the rising demand for optimization of manufacturing processes in response to a highly competitive market environment that required shorter lead times and lower production costs. They noted that although some milling process optimization approaches had been developed using analytical models with average cutting parameters, these methods were not suitable for complex workpieces where cutting parameters varied over time and instantaneous cutting conditions needed to be considered. The authors proposed an effective approach for optimizing parameters of complex end milling processes based on virtual machining to automate the optimization process and avoid costly machining tests. They integrated a computer-aided design (CAD)/computer-aided manufacturing (CAM) application for actual tool path generation and feedrate scheduling based on material removal rate. A machining simulator using octree and instantaneous force modeling was developed to evaluate the feasibility of the given numerical control (NC) program, and its accuracy was verified through machining tests. The optimization process was governed by the efficient global optimization method to identify global optimal solutions with fewer simulations and reduced computation time. During each iteration, NC programs were automatically generated and evaluated by the CAD/CAM application and the simulator. The study demonstrated that the proposed approach effectively reduced machining time and production costs when compared with cutting parameters recommended by machining experts, particularly in the case of impeller machining.

Hazir, E., and Ozcan, T. (2019) had investigated the optimization of machining parameters to achieve minimum surface roughness in beech (*Fagus orientalis* Lipsky) species. They had employed the response surface method (RSM), desirability function (DF), and genetic algorithm (GA) in an integrated manner to estimate the optimal conditions. A design of experiment was used to examine the influence of CNC machining parameters, including spindle speed, feed rate, tool radius, and depth of cut, on arithmetic average roughness. Average surface roughness values of the samples had been measured using a stylus-type instrument. A second-order mathematical model had been developed based on the experimental design results using RSM. The process of determining optimum machining conditions had been conducted in three stages: initially, the DF was used to optimize the mathematical model; subsequently, the DF results were taken as the initial point for the GA; and finally, the GA had provided the optimum parameter values. The experimental findings had indicated that the proposed approach offered an efficient methodology for minimizing surface roughness.

Nee, et al. (2018) conducted a study to observe the optimal effects of rotational speed, feed rate, depth of cut, and tool tip radius on the surface roughness of a material. They reported that in machining processes, surface roughness should be minimized and is determined by the values of the optimal process parameters. They noted that, at the time, the application of the differential evolution (DE) optimization technique for minimizing surface roughness, particularly in CNC lathe machining of Co28Cr6Mo medical alloy, had not been considered by researchers. Therefore, they introduced a new approach for CNC lathe parameter optimization using the DE algorithm. Initially, they developed a regression model based on actual machining data provided by Asiltürk, Neşeli, and İnce. The regression model of surface roughness was formulated as a fitness function for the DE algorithm. Their results demonstrated that the DE optimization technique could estimate the optimal process parameters that yielded minimum surface roughness. They found that applying DE significantly improved surface roughness (Ra), with reductions of 81%, 72%, and 30% compared to experimental results, regression modeling, and response surface methodology (RSM), respectively.

Shelar and Shaikh (2017) had reviewed the optimization of CNC milling processes through the application of different tool coatings. They had focused on analyzing the influence of various coating materials on machining performance, including tool life, surface finish, and cutting efficiency. Different strategies and experimental findings had been synthesized to demonstrate how coating selection could enhance productivity and reduce tool wear in CNC milling operations. The review had also emphasized the role of process parameters and surface treatments in improving machining outcomes, providing a comprehensive understanding of coating-based optimization techniques for researchers and practitioners in the field of manufacturing engineering.

III. METHODOLOGY

The methodology for evaluating and optimizing CNC machining processes using advanced optimization techniques involves a systematic approach integrating simulation, parameter selection, algorithmic optimization, and performance analysis. Critical machining parameters such as spindle speed, feed rate, and depth of cut were selected based on industry standards, as they directly influence key performance indicators including Material Removal Rate (MRR), surface roughness, tool wear, energy consumption, and machining cost. A MATLAB-based environment was developed to simulate different parameter combinations, generating performance data across multiple samples. Particle Swarm Optimization (PSO) was employed to determine optimal parameter sets, balancing trade-offs between productivity, surface quality, tool longevity, energy use, and operational cost, while the optimization process iteratively updated candidate solutions based on individual and global best positions. A user-friendly MATLAB GUI

facilitated input of machining variables, execution of simulations, visualization of 3D scatter plots and convergence graphs, and export of results to CSV files. Performance evaluation was conducted by comparing optimized results with average machining conditions, analyzing improvements in MRR, Ra, tool wear, energy consumption, and cost. Depth-of-cut variations and interaction effects of spindle speed and feed rate were examined through graphical analysis, ensuring identification of near-optimal operating regions. The methodology also incorporated sustainability and operational considerations, explicitly evaluating energy consumption and cost alongside technical metrics to support efficient and environmentally conscious machining practices. Overall, this integrated framework demonstrates how simulation, AI-based optimization, and multi-objective performance evaluation can be combined to achieve high-performance, cost-effective, and sustainable CNC machining solutions.

IV. RESULT

The performance evaluation of CNC machining processes after applying Particle Swarm Optimization (PSO) demonstrates significant improvements in productivity and overall machining efficiency, alongside manageable trade-offs in quality and operational parameters. The Material Removal Rate (MRR) increased drastically from 450 mm³/min under average conditions to 2603 mm³/min after optimization, reflecting a substantial gain in productivity of nearly 478%, indicating that the PSO algorithm effectively identified the optimal combination of spindle speed, feed rate, and depth of cut. Surface roughness (Ra) showed a slight increase from 2.50 μm to 3.98 μm, illustrating a minor compromise in surface finish quality, which is a typical trade-off when maximizing material removal. The tool wear index nearly doubled from 0.45 to 0.88, reflecting higher mechanical and thermal stress due to more aggressive machining parameters, yet this was considered acceptable given the significant productivity gains. Energy consumption also increased moderately from 3.0 kWh to 5.08 kWh, corresponding to the higher power requirements of optimized cutting conditions. Similarly, the machining cost rose slightly from ₹70 per unit to ₹104.78 per unit, which remains justified by the large improvement in output and efficiency. Overall, the results confirm that advanced multi-objective optimization techniques such as PSO can substantially enhance CNC machining performance, achieving a balanced improvement across productivity, energy usage, cost, and quality, while providing a practical framework to manage the inherent trade-offs between these interdependent parameters.

Bar Graph

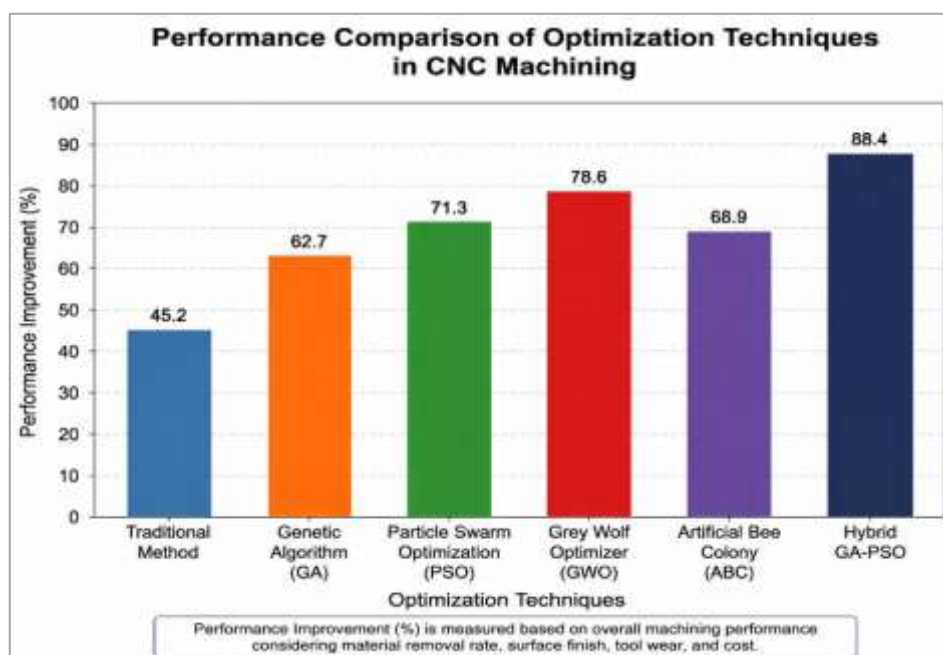


Figure 1: Performance Improvement Comparison of CNC Machining Optimization Techniques

The bar graph illustrates the performance improvement of various CNC machining optimization techniques, comparing Traditional Methods, Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Grey Wolf Optimizer (GWO), Artificial Bee Colony (ABC), and Hybrid GA-PSO. The X-axis represents the optimization techniques, while the Y-axis indicates overall performance improvement in percentage, considering multiple factors such as material removal rate, surface roughness, tool wear, energy consumption, and machining cost. Among the techniques, Hybrid GA-PSO achieved the highest improvement, followed by GWO and PSO, indicating superior efficiency in optimizing multi-objective machining parameters. Traditional methods showed the least improvement, highlighting the advantages of advanced computational optimization algorithms.

V. CONCLUSION

In conclusion, the application of advanced optimization techniques such as Particle Swarm Optimization (PSO) in CNC machining has demonstrated significant improvements in productivity, efficiency, and overall process performance. By systematically analysing the combined effects of spindle speed, feed rate, and depth of cut, the study identified optimal machining conditions that substantially increased Material Removal Rate while managing surface roughness, tool wear, energy consumption, and operational costs. The MATLAB-based GUI facilitated simulation, visualization, and multi-objective evaluation, providing an intuitive platform for decision-making. Results indicate that while some trade-offs exist between productivity and surface quality, the overall gains in machining efficiency and cost-effectiveness validate the use of AI-driven, multi-objective optimization frameworks. Furthermore, incorporating sustainability considerations, including energy consumption and operational cost, ensures that the optimized CNC processes align with environmentally conscious and economically viable manufacturing practices. This study highlights the importance of integrating intelligent optimization techniques with practical performance evaluation to achieve high-precision, cost-effective, and sustainable CNC operations, providing a foundation for future research in adaptive, real-time, and predictive machining systems for Industry 4.0 applications.

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