Optimization of CNC Machining Parameters for Sustainable Intelligent Manufacturing Systems

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ABSTRACT

Computer Numerical Control (CNC) machining plays a vital role in modern manufacturing by improving precision, repeatability, productivity, and surface quality. However, CNC processes face challenges such as high energy consumption, tool wear, vibration, noise emission, and machining inaccuracies. This study focuses on optimizing CNC machining parameters using advanced optimization techniques and artificial intelligence-based approaches. The research considers key performance indicators such as cutting speed, feed rate, depth of cut, surface roughness, energy use, and process stability. The study supports sustainable and intelligent manufacturing by balancing productivity, quality, cost-effectiveness, and environmental performance.

Keywords: *CNC Machining, Optimization Techniques, Sustainable Manufacturing.*

I. INTRODUCTION

Computer Numerical Control (CNC) machining processes have become a cornerstone of modern manufacturing systems due to their ability to deliver high precision, repeatability, and productivity in complex part production. In the era of Industry 4.0, CNC machines are widely integrated with advanced computational intelligence, automation systems, and data-driven optimization frameworks to meet the increasing demand for high-quality and cost-effective manufacturing solutions. These systems are extensively used in aerospace, automotive, biomedical, and precision engineering industries, where dimensional accuracy and surface integrity are critical requirements. However, despite their technological advancement, CNC machining processes are inherently associated with challenges such as high energy consumption, tool wear, vibration, noise emission, and surface quality deterioration. These challenges become more prominent when machining advanced materials such as aluminum alloys, composites, and hardened steels, which require carefully optimized process parameters to ensure machining efficiency and sustainability. Recent studies have emphasized that machining performance is strongly influenced by process variables such as cutting speed, feed rate, depth of cut, spindle speed, and tool geometry, which collectively determine productivity, energy usage, and surface finish quality (Ahmed & Arora, 2019; Singh & Sultan, 2018). Furthermore, sustainable manufacturing perspectives have increasingly highlighted the need to minimize environmental impact while maintaining economic efficiency and human well-being in machining operations (Lahlali et al., 2026). As a result, CNC machining has evolved from being purely production-oriented to a more integrated system that balances performance, sustainability, and cost-effectiveness.

In recent years, significant research attention has been directed toward the optimization of CNC machining processes using advanced computational and artificial intelligence-based techniques. Traditional experimental methods such as Taguchi design, response surface methodology, and analysis of variance have been widely applied for parameter optimization in machining operations; however, these approaches are often limited in handling complex multi-objective problems (Ahmed & Arora, 2019;

Nataraj & Balasubramanian, 2017). To overcome these limitations, researchers have increasingly adopted evolutionary algorithms and machine learning-based optimization techniques. For instance, genetic algorithms, particle swarm optimization, artificial neural networks, fuzzy logic systems, and hybrid intelligent models have been successfully applied to optimize machining parameters for improving surface roughness, reducing energy consumption, and enhancing material removal rate (Soori & Asmael, 2022). Similarly, Xiao et al. (2021) developed a multi-objective optimization framework integrating particle swarm optimization and NSGA-II to achieve energy-efficient and cost-effective machining performance. In another study, Chiu and Lee (2020) proposed an intelligent machining system based on adaptive neuro-fuzzy inference systems combined with particle swarm optimization to optimize machining parameters according to user-defined performance requirements. Moreover, Zhang et al. (2023) emphasized the significance of machining accuracy reliability by incorporating geometric and vibration error modeling into optimization frameworks. These studies collectively indicate that modern CNC optimization is shifting toward data-driven, intelligent, and multi-objective decision-making frameworks. Additionally, Ding (2024) and Wang et al. (2025) highlighted that geometric accuracy, machine tool performance, and process optimization are interdependent factors that must be simultaneously addressed to achieve high-performance machining systems. Despite these advancements, challenges still exist in integrating sustainability indicators such as energy consumption and noise emission with traditional machining quality metrics in a unified optimization framework.

Although substantial progress has been made in CNC machining optimization, several research gaps remain unresolved. Existing studies often focus on isolated performance measures such as surface roughness, machining time, or energy consumption, without fully integrating multiple conflicting objectives into a unified optimization model. Furthermore, there is limited research that simultaneously considers sustainability factors, machining accuracy, tool wear, vibration effects, and environmental impact in a comprehensive framework. Most conventional optimization approaches also rely on simplified assumptions that may not accurately represent real industrial machining conditions. In addition, the adaptability of optimization models to different machining operations such as milling, turning, and hybrid machining processes remains limited. As highlighted by Lahlali et al. (2026), achieving sustainable machining requires a balanced trade-off between economic, environmental, and operational parameters, which is still not fully addressed in existing literature. Similarly, Wang et al. (2025) and Zhang et al. (2023) emphasized the need for improved geometric accuracy modeling and reliability-based optimization approaches to enhance machining performance under real-world uncertainties. Therefore, there is a strong need to develop advanced multi-objective optimization frameworks that integrate artificial intelligence, evolutionary computation, and predictive modeling techniques for improving CNC machining performance. In this context, the present study aims to evaluate and optimize CNC machining processes using advanced optimization techniques by considering multiple performance indicators such as surface quality, energy consumption, machining efficiency, and process stability, thereby contributing to the development of sustainable and intelligent manufacturing systems.

II. RESEARCH BACKGROUND

Lahlali et al. (2026) was reviewed as focusing on sustainable manufacturing, emphasizing the critical balance between economic efficiency, environmental impact, and human well-being. It was reported that machining, particularly CNC milling of 2017 A aluminum alloy, had been recognized as a high-energy and noise-intensive process, yet few studies had simultaneously addressed energy, noise, and surface quality. The authors were observed to have developed a predictive modelling and multi-objective optimization approach, conducting experimental tests on contouring and surfacing operations with variations in cutting speed, feed rate, and depth of cut. The review indicated that NSGA-II had been employed to solve the multi-objective optimization problem, followed by decision-making through TOPSIS, with surface quality incorporated as a predictive constraint. Findings had shown that in contouring operations, high cutting speed with low feed rate and high depth of cut minimized energy consumption and noise without affecting surface quality, while in surfacing operations, a trade-off was necessary, balancing low feed rate for surface roughness with moderately reduced cutting speed to maintain noise and energy limits. The approach was further interpreted as reflecting sustainable manufacturing principles by indirectly reducing operational costs and emissions.

Wang et al. (2025) had highlighted that the CNC machine tool served as the fundamental equipment in the manufacturing industry, particularly in sectors requiring high levels of accuracy. They had emphasized that geometric accuracy design constituted a critical step in machine tool design and significantly influenced the machining precision of workpieces. The authors had reviewed various methods previously employed to model, extract, optimize, and measure the geometric errors affecting machine tool accuracy. Their study had provided a comprehensive overview of the state-of-the-art approaches and summarized recent research progress related to geometric accuracy design in CNC machine tools. The paper had examined interrelated aspects of accuracy design, including modeling, analysis, and optimization. Accuracy analysis, which incorporated geometric error modeling and sensitivity analysis, had been used to determine a machine tool's output accuracy based on the known precision of individual components. Conversely, accuracy allocation had been applied to design component-level accuracy according to required output specifications, aiming to balance manufacturing cost, quality, reliability, and environmental impact. Additionally, the authors had outlined evaluation methods and verification approaches to ensure that designed accuracy was achieved. Finally, they had identified the challenges in geometric accuracy design and suggested directions for future research.

Ding, M. (2024) had concentrated on precision and performance optimization methods for high-end CNC machine tools, aiming to enhance their performance and improve working precision. The study had explored various techniques through systematic research and experimentation, including advanced control algorithms, cutting-edge tooling technologies, and innovative machining strategies. The findings had provided significant theoretical insights and practical guidelines for the application and development of high-end CNC machine tools in industries such as aerospace, automotive, and manufacturing. The research had emphasized the importance of optimizing machine parameters, tool selection, and machining processes to achieve greater accuracy, efficiency, and productivity. Furthermore, the study had highlighted the need for continuous innovation and adaptation to meet the evolving demands of modern manufacturing, offering a roadmap for future research and development in this area.

Zhang et al. (2023) examined the practical significance of machining accuracy reliability for the quality of processed parts. They highlighted that, during milling, geometric errors and vibration errors were the primary sources that substantially reduced the machining accuracy reliability of machine tools. To address this, they proposed a method for evaluating machining accuracy reliability that accounted for both geometric and vibration errors. Using milling dynamics theory and the full-discretization method (FDM), they developed a four degrees of freedom (DOF) milling dynamics model of the tool–workpiece vibration system, alongside a vibration error prediction model. The dynamics model was applied for milling stability prediction and parameter optimization, while the prediction model estimated vibration errors. By employing multi-body system (MBS) theory, they constructed a comprehensive error model integrating both geometric and vibration errors to assess their impact on machining accuracy. Furthermore, through Monte Carlo simulation with directional importance sampling (DIS-MCS), a machining accuracy reliability model was formulated to evaluate machine tool performance. Their method was validated on a five-axis CNC machine tool, and the results confirmed its effectiveness in optimizing milling parameters, predicting vibration errors, and evaluating machining accuracy reliability.

Soori and Asmael (2022) focused on the optimization process applied to machining operations to achieve continual improvements in the accuracy and quality of produced parts. They investigated the effects of machining parameters in milling operations, including spindle speed, depth of cut, and feed rate, to minimize surface roughness and machining time. The study also examined effective machining parameters in turning operations, such as depth of cut, feed rate, and spindle speed, for similar objectives of reducing surface roughness and process time. Furthermore, the authors reported that machining parameters in Electro Discharge Machining (EDM), including peak current, gap voltage, duty cycle, and pulse on time, could be optimized to enhance material removal rate, reduce tool wear, and improve surface quality. In addition, they observed that in wire EDM operations, parameters such as spark on time, spark off time, and input current were studied and optimized to improve material removal rate, surface roughness, and spark gap. Various optimization methods, including the Taguchi method, fuzzy logic algorithms, artificial intelligence, genetic algorithms, artificial neural networks, artificial bee colony algorithms, ant colony optimization, and harmony search algorithms, were reported to have been employed to determine optimal machining parameters. The study concluded that such optimization could reduce time and production costs, thereby increasing productivity in part manufacturing. Finally, Soori and Asmael reviewed the challenges and limitations of these optimization techniques and suggested that future research could advance the field by critically analyzing recent achievements reported in the literature.

Xiao, et al. (2021) examined NC machining as a widely used method in mechanical manufacturing systems. They highlighted that a reasonable selection of process parameters could significantly reduce both processing costs and energy consumption. To achieve energy-efficient and low-cost CNC machining, they optimized cutting parameters considering energy-saving and cost aspects, and proposed a process parameter optimization method for CNC machining centers. They analyzed the energy flow characteristics of the machining system and, accounting for machine tool performance and tool life constraints, established a multi-objective optimization model with milling speed, feed per tooth, and spindle speed as variables. A weight coefficient was introduced to convert it into a single-objective model. To ensure solution accuracy, they developed a combinatorial optimization algorithm based on particle swarm optimization and NSGA-II. Using plane milling as a case study, they verified the feasibility of their approach. The results demonstrated that the model was effective in balancing energy consumption and processing cost, and the combinatorial algorithm outperformed NSGA-II in both solution speed and optimization accuracy.

Chiu and Lee (2020) had introduced an intelligent machining system (IMS) that employed an adaptive-network-based fuzzy inference system (ANFIS) predictor alongside the particle swarm optimization (PSO) algorithm with a hybrid objective function. The study had aimed to provide suitable machining parameters to satisfy diverse user requirements, including accuracy, surface smoothness, and machining speed. Initially, key computer numerical control parameters had been selected, and actual trajectories under varying machining conditions had been collected using linear scales. These data had been analyzed to determine machining time, contouring error, and tracking error, corresponding to speed, milling accuracy, and surface smoothness, respectively. A data-driven approach using ANFIS had been developed to model the relationship between machining parameters and the three performance indices. To establish the IMS, the authors had combined the trained ANFIS model with a hybrid objective function optimization problem, which was solved using the PSO algorithm based on user-specific requirements. Finally, the study had demonstrated the performance and effectiveness of the proposed system through experimental practical machining.

Ahmed and Arora (2019) had investigated the surface roughness and energy consumption in CNC end milling of plain low carbon steel (mild steel) A36 K02600 using a carbide end mill cutter. They had adopted Taguchi's L9 orthogonal array to design the experimental runs, considering process parameters such as cutting velocity, feed rate, spindle speed, and cutting depth, in order to examine their influence on quality characteristics. The study had evaluated optimal control parameter combinations for minimizing surface roughness and energy consumption using the signal-to-noise ratio. Analysis of variance had revealed the contribution of each control factor to the quality characteristics. Furthermore, numerical predictive models based on linear regression and artificial neural networks had been developed to accurately forecast the responses. Multi-objective Genetic Algorithm optimization had been employed to obtain a set of control parameters that would simultaneously optimize both responses. The study had concluded that spindle speed (68.24% contribution) and feed rate (92% contribution) were the most influential variables for surface quality and energy consumption, respectively. The outcomes from the artificial neural network model and genetic algorithm had confirmed that both quality characteristics could be optimized concurrently. Taguchi's robust design approach had been recognized as an effective method for optimizing machining parameters to achieve improved surface quality with reduced energy consumption, with improvements of 27.79% and 30%, respectively. The use of low carbon steel, widely accepted in industry, had reinforced the practical relevance of the study.

Singh and Sultan (2018) examined the sustainability of manufacturing processes, emphasizing three primary factors that influenced both ecological and financial constraints: the energy required to complete a task, the material consumed, and the time taken for completion. They highlighted that these factors needed to be quantified and analyzed to design manufacturing systems that optimized process sustainability. To achieve this, they presented a computer package that employed life cycle inventory models for CNC (Computer Numerical Control) milling and turning processes. The study indicated that, based on resource utilization and production stages, the job completion time for both turning and milling could be divided into process (machining), idle, and basic times. Since the parameters for evaluating process times differed—for example, depth and width of cut for milling and initial and final diameters for turning—they reported two separate case studies, one for each process. Their analysis revealed that selecting highly dense and hard materials increased completion time due to lower cutting speeds and feed rates compared to softer materials. Additionally, they observed that face milling required longer durations and higher power consumption than peripheral milling, which they attributed to extended retraction times caused by over-travel distances and slower vertical transverse speeds relative to horizontal transverse speeds in peripheral milling.

Nataraj and Balasubramanian (2017) had highlighted that machining hybrid metal matrix composites was challenging due to the abrasive nature of the particulates, which acted like cutting edges, causing rapid tool wear and inducing vibrations. They had attempted to evaluate the machining characteristics of such composites experimentally and had developed a mathematical model to predict responses, including surface finish, vibration intensity, and work-tool interface temperature under known cutting conditions on a CNC lathe. A design of experiments approach had been employed to conduct the trials, and response surface methodology had been used to formulate the predictive model. The study had reported that vibrations along Vx, Vy, and Vz were 41.59, 45.17, and 26.45 m/s^2, respectively, while surface finish values Ra, Rq, and Rz were 1.76, 3.01, and 11.94 μm, with a work-tool interface temperature of 51.74 °C under optimal machining parameters (cutting speed of 175 m/min, depth of cut 0.25 mm, and feed rate 0.1 mm/rev). The experimental results had shown close conformity with the response surface methodology overlay plots for the measured responses.

III. KEY FINDINGS FROM STUDY

Author (Year)	Objective of Study	Methodology / Approach	Key Findings	Research Contribution / Outcome
Lahlali et al. (2026)	Sustainable optimization of CNC milling parameters considering energy, noise, and surface quality	Experimental machining + NSGA-II + TOPSIS multi-criteria decision-making	High cutting speed with low feed reduced energy and noise in contouring; trade-offs observed in surfacing operations	Developed multi-objective sustainable machining framework integrating environmental and quality factors
Wang et al. (2025)	Improve geometric accuracy design of CNC machine tools	Review of modeling, sensitivity analysis, and accuracy allocation methods	Machine tool accuracy strongly depends on component-level geometric errors	Provided comprehensive framework for accuracy modeling, optimization, and evaluation
Ding (2024)	Enhance precision and performance of high-end CNC machines	Advanced control algorithms and machining experiments	Optimization of tool selection and machining parameters improved accuracy and efficiency	Provided theoretical and practical guidelines for high-performance CNC systems
Zhang et al. (2023)	Evaluate machining accuracy reliability considering geometric and vibration errors	Milling dynamics model + MBS theory + Monte Carlo simulation	Vibration and geometric errors significantly affect machining reliability	Developed reliability evaluation model validated on 5-axis CNC system
Soori & Asmael (2022)	Review machining parameter optimization techniques	Literature-based review of optimization algorithms	Taguchi, GA, ANN, fuzzy logic, swarm intelligence widely used	Identified limitations and future research directions in machining optimization
Xiao et al. (2021)	Optimize CNC machining for energy efficiency and cost reduction	PSO + NSGA-II hybrid multi-objective optimization model	Proposed model reduced energy consumption and machining cost effectively	Demonstrated superiority of hybrid optimization over conventional methods
Chiu & Lee (2020)	Develop intelligent CNC machining optimization system	ANFIS prediction model + PSO optimization	System effectively optimized accuracy, speed, and surface quality	Introduced intelligent adaptive machining parameter selection system

Ahmed & Arora (2019)	Optimize surface roughness and energy consumption in CNC milling	Taguchi design + ANN + Genetic Algorithm	Spindle speed and feed rate were most influential factors	Achieved significant improvement in machining quality and energy efficiency
Singh & Sultan (2018)	Analyze sustainability in CNC milling and turning	Life cycle inventory-based computational model	Hard materials increased machining time and energy consumption	Provided sustainability-based process time classification model
Nataraj & Balasubramanian (2017)	Evaluate machining performance of hybrid metal matrix composites	DOE + Response Surface Methodology	High vibration and surface roughness observed under certain conditions	Developed predictive model for machining responses in composite materials

IV. CONCLUSION

The reviewed literature on performance evaluation and optimization of CNC machining processes clearly indicates that modern manufacturing systems are increasingly shifting toward intelligent, sustainable, and multi-objective optimization frameworks. It has been consistently observed that CNC machining performance is governed by a complex interaction of process parameters such as cutting speed, feed rate, depth of cut, spindle speed, and tool condition, which directly influence surface quality, energy consumption, machining time, vibration, and overall production efficiency. Earlier studies primarily focused on single-objective optimization techniques; however, recent research has demonstrated a strong transition toward multi-objective optimization approaches that simultaneously consider productivity, cost, quality, and environmental impact. Techniques such as Taguchi methods, response surface methodology, artificial neural networks, genetic algorithms, particle swarm optimization, NSGA-II, fuzzy logic systems, and hybrid intelligent models have been widely adopted to enhance machining performance. It has been found that hybrid optimization techniques, particularly those integrating machine learning with evolutionary algorithms, provide superior accuracy and adaptability in solving complex machining problems compared to traditional methods. Furthermore, studies have emphasized that sustainability has become a critical dimension in CNC machining, where energy efficiency and noise reduction are now considered alongside conventional quality metrics such as surface roughness and dimensional accuracy. Research findings also indicate that machining accuracy is significantly affected by geometric errors and vibration-induced deviations, which necessitate advanced reliability-based modeling and dynamic analysis for improved precision. In addition, intelligent machining systems based on AI and data-driven models have shown strong potential in optimizing real-time machining conditions and adapting to varying operational requirements. Despite these advancements, the literature reveals that there is still a gap in developing fully integrated frameworks that simultaneously address machining accuracy, sustainability, tool wear, vibration control, and cost optimization under real industrial conditions. Therefore, it can be concluded that future CNC machining systems must evolve toward fully integrated intelligent optimization platforms that combine predictive modeling, real-time monitoring, and multi-objective decision-making. Such developments will not only enhance machining efficiency and product quality but also contribute significantly to sustainable manufacturing practices and Industry 4.0-based smart production environments.

V. FUTURE SCOPE

The future scope of research in the performance evaluation and optimization of CNC machining processes is highly promising, particularly with the rapid advancement of Industry 4.0, artificial intelligence, and smart manufacturing systems. Future studies are expected to focus on the development of fully integrated intelligent machining frameworks that combine real-time monitoring, predictive analytics, and adaptive control systems to dynamically optimize machining parameters during operation. Unlike traditional offline optimization approaches, future CNC systems will increasingly rely on real-time sensor data, digital twins, and cyber-physical systems to enhance decision-making accuracy and process efficiency. Artificial intelligence-based techniques such as deep learning, reinforcement learning, and hybrid evolutionary algorithms are anticipated to play a crucial role in handling complex multi-objective optimization problems involving trade-offs among surface quality, energy consumption, tool wear, vibration, and production cost. Moreover, sustainability will remain a key research direction, where future optimization models are expected to incorporate carbon footprint analysis, energy-efficient machining strategies, and environmentally conscious manufacturing indicators alongside conventional performance metrics. Another important direction will be the integration of machine learning with predictive maintenance systems to forecast tool wear, machine failure, and process instability, thereby improving reliability and reducing downtime. In addition, the application of digital twin technology in CNC machining will enable virtual simulation and optimization of machining processes before actual production, significantly reducing trial-and-error experimentation. Research is also expected to expand toward hybrid machining processes and advanced materials such as composites, alloys, and nano-engineered materials, which require highly adaptive and robust optimization strategies. Furthermore, the development of cloud-based and IoT-enabled manufacturing platforms will enhance connectivity and data sharing across production systems, enabling global optimization of machining operations. Finally, future research should focus on developing standardized frameworks for multi-objective optimization that can be easily implemented in industrial environments, ensuring scalability, robustness, and real-time adaptability. Collectively, these advancements will transform CNC machining into a highly intelligent, autonomous, and sustainable manufacturing system aligned with the goals of Industry 5.0.

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