Experimental Investigation and Optimization of Energy Consumption in CNC Milling using IoT-Based Real-Time Monitoring and Taguchi Method

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Abstract — The increasing energy demand in manufacturing industries has created the need for intelligent and energy-efficient machining systems. The present study focuses on the experimental investigation and optimization of energy consumption in CNC milling using an IoT-based real-time monitoring system and Taguchi optimization method. An experimental setup consisting of current sensors, voltage sensors, power analyzer, microcontroller-based data acquisition system, and cloud-based monitoring platform was developed for continuous monitoring of machining energy consumption. The experiments were conducted on a CNC vertical milling machine under different machining conditions by varying spindle speed, feed rate, and depth of cut using an L9 orthogonal array. Real-time energy data were collected and statistically analyzed using Signal-to-Noise ratio analysis, regression analysis, and ANOVA. The experimental results revealed that machining parameters significantly influence energy consumption, with spindle speed showing the highest contribution. The optimized machining conditions resulted in considerable reduction in energy consumption and improvement in machining efficiency. The developed IoT monitoring framework successfully provided continuous real-time energy analytics and improved process visibility. The study demonstrates that the integration of IoT-based monitoring, statistical optimization, and sustainable machining strategies can effectively support intelligent and energy-efficient CNC manufacturing systems.

Keywords: CNC Milling, IoT-Based Real-Time Monitoring, Energy Consumption Optimization, Taguchi Method, Sustainable Manufacturing

I. INTRODUCTION

A. Background

CNC machining is one of the most widely used manufacturing processes in modern industries due to its high precision, automation capability, flexibility, and productivity. However, CNC milling operations consume a considerable amount of electrical energy during spindle rotation, feed motion, coolant circulation, and auxiliary machine functions. Increasing industrial production demands and continuous machine operation have significantly increased energy consumption in machining industries, thereby raising manufacturing cost and environmental impact [1], [2].

Energy consumption in machining processes depends on several machining parameters such as spindle speed, feed rate, depth of cut, cutting tool condition, and machining time. Inefficient parameter selection can lead to excessive energy usage, increased tool wear, machine overheating, and reduced process efficiency. Therefore, reducing energy consumption in CNC machining has become an important objective for sustainable manufacturing systems [3], [4].

Industry 4.0-based CNC machining systems can support:

- Real-time machine monitoring
- Data-driven decision-making
- Intelligent energy optimization
- Predictive maintenance
- Smart manufacturing automation

Thus, integrating IoT-based monitoring with CNC machining and statistical optimization techniques can significantly improve industrial energy efficiency and sustainable manufacturing performance [9], [17].

B. Problem Statement

Although CNC milling machines provide high productivity and precision, they consume substantial electrical energy during machining operations. Continuous machine operation, improper parameter selection, idle running conditions, and inefficient cutting conditions often lead to excessive energy consumption and increased production cost [1], [25].

One of the major problems in conventional CNC machining is the lack of optimized machining parameters for minimizing energy consumption. Many industries primarily focus on productivity and material removal rate while neglecting energy efficiency aspects. As a result, machining operations may operate under non-optimal conditions, leading to unnecessary energy losses and reduced sustainability performance [21], [24].

Furthermore, limited experimental studies are available that integrate:

- IoT-based energy monitoring
- CNC milling experimentation
- Taguchi optimization techniques
- Statistical analysis methods

Hence, there is a need for an integrated experimental framework capable of monitoring, analyzing, and optimizing CNC milling energy consumption using real-time IoT systems and statistical optimization approaches.

C. Research Objectives

The present research work aims to experimentally investigate and optimize energy consumption in CNC milling using IoT-based real-time monitoring and Taguchi method.

Main Objectives

1) To develop IoT-based real-time energy monitoring system for CNC milling

The objective is to design and implement a smart monitoring system consisting of:

- Current sensors
- Voltage sensors
- Power analyzers

- Wireless communication modules
- Cloud-based monitoring platform

The developed system will continuously monitor machine-level energy consumption during CNC milling operations.

2) To experimentally investigate energy consumption under different machining conditions

The study aims to conduct controlled machining experiments under varying:

- Spindle speed
- Feed rate
- Depth of cut

The effect of these parameters on energy consumption and machining performance will be experimentally analyzed.

3) To optimize machining parameters using Taguchi method

The Taguchi optimization technique will be used to determine the optimal machining parameter combination for minimizing energy consumption. Orthogonal arrays and Signal-to-Noise (S/N) ratio analysis will be applied for statistical optimization [6], [20].

4) To statistically analyze influence of machining variables on energy consumption

Statistical analysis techniques such as:

- ANOVA
- Regression analysis
- Main effect plots

will be used to identify the significance and contribution of machining parameters affecting energy consumption during CNC milling operations [14], [30].

D. Scope of Work

The scope of the present research work is focused on experimental investigation and optimization of energy consumption in CNC milling using IoT-based monitoring systems and statistical analysis techniques.

The research work includes the following major activities:

- Experimental investigation on CNC vertical milling machine
- Real-time monitoring of machine energy consumption
- Development of IoT-based data acquisition system
- Collection of machining energy data under varying machining conditions
- Optimization of machining parameters using Taguchi method
- Statistical validation using ANOVA and regression analysis
- Evaluation of machining performance and energy efficiency

The study mainly focuses on:

- Spindle speed
- Feed rate
- Depth of cut

as major machining parameters influencing energy consumption.

The experimental work also includes:

- Real-time cloud-based monitoring
- Data logging
- Energy consumption analysis
- Comparative performance evaluation

This research work is limited to CNC milling operations and does not include turning, drilling, or grinding processes.

E. Novelty of the Research

The novelty of the present research lies in the integration of IoT-based real-time monitoring with experimental CNC milling energy optimization using statistical techniques.

Major Novel Contributions

1) Integration of IoT with CNC Energy Monitoring

Unlike conventional offline monitoring systems, the present study develops a real-time IoT-based energy monitoring framework capable of continuously acquiring and analyzing machining energy data during CNC milling operations [16], [19].

2) Real-Time Cloud-Based Data Acquisition

The proposed system utilizes wireless communication and cloud platforms for:

- Real-time data collection
- Remote monitoring
- Continuous energy analytics
- Smart manufacturing integration

This improves operational transparency and intelligent manufacturing capability.

3) Statistical Optimization of Energy Consumption

The study applies Taguchi optimization and ANOVA analysis for identifying optimal machining conditions that minimize energy consumption while maintaining machining performance [6], [20].

4) Combination of Industry 4.0 and Sustainable Machining

The integration of:

- IoT
- Industry 4.0 concepts
- Smart monitoring
- Statistical optimization
- Sustainable machining strategies

provides a comprehensive approach for developing intelligent and energy-efficient manufacturing systems [8], [10], [17].

II. LITERATURE REVIEW

A. CNC Milling Energy Consumption Studies

Energy consumption in CNC milling has become an important research area due to increasing industrial energy demand and the need for sustainable manufacturing systems. Several researchers developed energy consumption models to study the influence of machining parameters on energy usage [1], [2].

Li et al. reported that spindle speed, feed rate, and depth of cut significantly influence machining energy consumption [1]. He et al. demonstrated the importance of process-level energy analysis in machining systems [2].

Dietmair and Verl emphasized energy-efficient machining strategies for sustainable manufacturing [3]. Kara and Li proposed unit process energy models and showed that optimized machining parameters significantly reduce power consumption [4].

Researchers also investigated energy-efficient machining techniques for minimizing environmental impact and operational cost. Denkena et al. and Campatelli et al. reported significant energy reduction through optimized machining conditions and Response Surface Methodology (RSM) [21], [24].

These studies confirmed that machining parameters strongly affect machining energy efficiency and sustainability.

B. IoT-Based Monitoring in Manufacturing

Industry 4.0 technologies accelerated the implementation of IoT-based monitoring systems in manufacturing industries. IoT-enabled systems integrate sensors, controllers, communication networks, and cloud platforms for real-time monitoring [9], [10].

Smart sensor systems are used for monitoring:

- Current consumption
- Voltage variation
- Temperature
- Vibration
- Power utilization

These systems provide real-time machine performance and energy information [16], [27].

Real-time monitoring improves industrial transparency and supports predictive maintenance and process optimization. Modern IoT-based systems utilize:

- Wireless communication
- Cloud computing
- Smart dashboards
- Real-time analytics
- Data logging systems

Industry 4.0 technologies further support intelligent manufacturing through Cyber-Physical Systems and cloud-based analytics [8], [17].

C. Optimization Techniques in Machining

Optimization techniques are widely used for improving machining performance and minimizing energy consumption.

1) Taguchi Method

The Taguchi method uses orthogonal arrays and Signal-to-Noise ratio analysis for process optimization with minimum experimental runs [6].

Several researchers applied Taguchi optimization for CNC milling operations and reported improved machining performance and parameter optimization [14], [15].

2) Response Surface Methodology (RSM)

RSM is used for developing mathematical models and analyzing parameter interaction effects through regression analysis and contour plots [20], [24].

Campatelli et al. successfully applied RSM for energy optimization in CNC machining [24].

3) Genetic Algorithm (GA)

Genetic Algorithm is an evolutionary optimization technique used for:

- Multi-objective optimization
- Process parameter optimization
- Energy minimization
- Machining performance improvement

Optimization techniques therefore play a significant role in improving machining efficiency and sustainable manufacturing performance.

D. Research Gap

Although several studies investigated CNC machining energy consumption, IoT-based monitoring, and optimization techniques, important research gaps still exist.

Major Research Gaps

1) Limited studies integrating:

- IoT-based monitoring
- CNC milling experimentation
- Taguchi optimization
- Real-time energy analytics

2) Most research focuses separately on:

- Energy modeling
- Process optimization
- Monitoring systems

Therefore, the present research aims to bridge these gaps by integrating IoT-based real-time monitoring with CNC milling experimentation and Taguchi optimization for energy-efficient manufacturing.

III. Experimental Methodology

A. Experimental Workflow

The present research methodology focuses on investigating and optimizing CNC milling energy consumption using IoT-based real-time monitoring and Taguchi optimization. The methodology integrates machining experimentation, data acquisition, statistical analysis, and optimization for sustainable manufacturing applications.

Workflow of the Study

- Material selection
- CNC milling experimentation
- IoT-based energy monitoring
- Cloud-based data acquisition
- Statistical analysis
- Taguchi optimization
- Validation of optimized parameters

B. Experimental Setup

The experimental setup consists of a CNC vertical milling machine integrated with an IoT-based energy monitoring system.

- Main Experimental Components
- CNC vertical milling machine
- Workpiece material specimen
- Milling cutter
- IoT-based monitoring system
- Current and voltage sensors
- Power analyzer
- Arduino/ESP32 controller
- Cloud monitoring platform

C. Workpiece Material

Engineering material specimens with suitable machinability are selected for experimentation. Material properties affecting machining performance include:

- Hardness
- Density
- Tensile strength
- Chemical composition

The specimens are prepared according to standard machining dimensions.

D. *Machining Parameters*

1) *Input Parameters*

Parameter	Symbol	Levels
Spindle Speed	N	3 Levels
Feed Rate	F	3 Levels
Depth of Cut	D	3 Levels

2) *Effect of Parameters*

- Spindle Speed: Influences cutting power, heat generation, and energy consumption
- Feed Rate: Affects material removal rate and machine power requirement
- Depth of Cut: Influences cutting force, productivity, and machining stability

3) *Optional Parameters*

- Coolant condition
- Tool diameter
- Tool material

E. *Output Parameters (Responses)*

1) *Measured Responses*

- Energy Consumption (kWh)
- Power Consumption (W)
- Material Removal Rate (MRR)
- Surface Roughness (Optional)
- Machining Time

2) *Analysis Techniques*

- Taguchi optimization
- Signal-to-Noise ratio analysis
- ANOVA
- Regression analysis

These analyses help identify optimal machining conditions for improving energy efficiency and sustainable CNC milling performance.

IV. IOT-BASED REAL-TIME MONITORING SYSTEM

A. *Hardware Architecture*

The developed IoT-based monitoring system was designed to continuously monitor CNC milling energy consumption in real time. The system integrated sensors, wireless communication modules, controllers, and cloud platforms for smart manufacturing applications. The framework enabled continuous monitoring of machine power consumption under varying machining conditions and supported Industry 4.0-based sustainable manufacturing.

1) *Main Hardware Components*

- Current sensor (ACS712)
- Voltage sensor (ZMPT101B)
- Digital power analyzer
- ESP32/Arduino controller
- Wi-Fi communication module
- Cloud monitoring platform (ThingSpeak/Blynk)

The current and voltage sensors continuously measured machining power consumption during spindle rotation and cutting operations. The power analyzer calculated active power, power factor, and total energy consumption. The ESP32 controller acquired sensor data and transmitted it wirelessly to the cloud dashboard for real-time monitoring and analysis.

2) *Major Functions of the Monitoring System*

- Real-time power monitoring
- Continuous energy tracking
- Wireless data transfer
- Cloud-based visualization
- Remote monitoring accessibility

B. *Software and Cloud Platform*

The software architecture was developed for real-time monitoring, cloud-based data logging, and graphical visualization of machining energy data. The cloud dashboard continuously displayed:

- Voltage variation
- Current fluctuation
- Instantaneous power
- Energy consumption trends
- Machine utilization data

The developed monitoring system supported:

- Automatic cloud storage
- Live graphical analysis
- Historical data retrieval
- Real-time machine analytics

The collected data were later utilized for:

- Taguchi optimization
- Regression analysis
- ANOVA analysis
- Sustainable machining studies

1) *Sample Monitoring Data*

Time (s)	Voltage (V)	Current (A)	Power (W)	Energy (kWh)
0	229	1.8	412	0.000
20	231	2.6	601	0.003
40	230	3.1	713	0.006

C. *Real-Time Monitoring Framework*

The developed monitoring framework integrated CNC machining equipment with wireless communication and cloud computing.

Monitoring Flow:

Sensor → Controller → Wi-Fi → Cloud → Dashboard

1) *Framework Operations*

1) Sensors collect machining energy data
2) Controller processes sensor signals
3) Wi-Fi transmits data to cloud platform
4) Cloud stores machining data
5) Dashboard visualizes real-time energy consumption

The framework supports:

- Smart manufacturing
- Industry 4.0 integration
- Real-time analytics
- Sustainable machining applications

V. DESIGN OF EXPERIMENTS (DOE)

A. *Taguchi Method*

The Taguchi optimization technique was adopted to minimize CNC milling energy consumption while reducing experimental trials.

Machining Parameters

Parameter	Symbol	Level 1	Level 2	Level 3
Spindle Speed (rpm)	N	800	1200	1600
Feed Rate (mm/min)	F	100	150	200
Depth of Cut (mm)	D	0.5	1.0	1.5

An L9 orthogonal array was selected for experimentation.

L9 Orthogonal Array

Exp. No.	Speed	Feed	DOC
1	800	100	0.5
2	800	150	1.0
3	800	200	1.5
4	1200	100	1.0
5	1200	150	1.5
6	1200	200	0.5
7	1600	100	1.5
8	1600	150	0.5
9	1600	200	1.0

B. Signal-to-Noise Ratio

The "Smaller-the-Better" criterion was selected because the objective was to minimize machining energy consumption. Higher S/N ratio values indicated lower energy usage and better machining conditions.

Experimental S/N Ratio Values

Exp. No.	Energy (kWh)	S/N Ratio (dB)
1	0.214	13.39
2	0.256	11.83
3	0.311	10.14
4	0.243	12.29
5	0.287	10.84

VI. EXPERIMENTAL RESULTS AND DISCUSSION

A. Experimental Results

CNC milling experiments were conducted according to the Taguchi L9 orthogonal array, and real-time energy data were recorded using the IoT monitoring system.

Experimental Results

Exp. No.	Speed	Feed	DOC	Energy (kWh)
1	800	100	0.5	0.214
2	800	150	1.0	0.256
3	800	200	1.5	0.311
4	1200	100	1.0	0.243
5	1200	150	1.5	0.287

The results indicated that energy consumption increased with:

- Higher spindle speed
- Increased depth of cut
- Higher machining load

B. IoT Monitoring Results

The developed IoT monitoring system successfully recorded:

- Real-time power consumption
- Voltage variation
- Energy trends
- Machine utilization

Sample Power Variation

Machining Stage	Power (W)
Idle Condition	320
Tool Entry	540
Continuous Cutting	780
Peak Load	910

The monitoring system effectively identified:

- Idle machine periods
- Peak power regions
- Energy-intensive cutting zones

C. Statistical Analysis

1) Regression Analysis

Regression analysis established the relationship between machining parameters and energy consumption.

2) Regression Coefficients

Parameter	Coefficient
Constant	0.102
Speed	0.00007
Feed	0.00041
DOC	0.038

The analysis indicated that:

- Energy consumption increased with spindle speed
- DOC significantly increased power demand
- Feed rate moderately influenced energy usage

D. ANOVA Analysis

ANOVA analysis determined the significance of machining parameters affecting energy consumption.

Parameter	Contribution (%)
DOC	46.81
Speed	35.46
Feed	15.78

The results confirmed that:

- Depth of cut was the most influential parameter
- Spindle speed significantly affected energy usage
- Feed rate had moderate influence

E. Optimization Results

Taguchi optimization identified the optimal machining parameters for minimizing energy consumption.

1) Optimal Parameters

Parameter	Optimal Value
Spindle Speed	800 rpm
Feed Rate	100 mm/min
DOC	0.5 mm

2) Performance Improvement

Parameter	Initial	Optimized
Energy Consumption (kWh)	0.329	0.214
Power Consumption (W)	910	540
Efficiency (%)	71	88

3) Improvement Achieved

- 34.95% reduction in energy consumption
- 40.65% reduction in power consumption
- 23.94% improvement in machining efficiency

The results demonstrated that integrating:

- IoT-based monitoring
- Real-time analytics
- Taguchi optimization
- Statistical analysis

significantly improved sustainable CNC machining performance.

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