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Carbon Footprint Reduction in CNC Machining Through CAM Optimization

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Abstract: The manufacturing industry is a significant producer of energy and greenhouse gas emissions, especially in the processes that are energy consuming like Computer Numerical Control (CNC) machining. CNC machines must be connected to a continuous power supply to cause the rotation of the spindles, feed drives, control system, and other supporting machines, and this results in considerable indirect carbon emission associated with the production of electricity. Enhancement of energy efficiency of machining operations has thus emerged as a key goal in sustainable manufacturing. This paper examines the possibility of cutting down carbon in CNC machining by using Computer-Aided Manufacturing (CAM) toolpath optimization. The traditional CAM toolpaths are usually associated with ineffective linking motions, too much air cutting, and prolonged machining times, which lead to the unnecessary use of energy. In this study, the optimized CAM plans with adaptive clearing, enhanced linking paths and effective selection of parameters were introduced to reduce the number of non-productive tool movements. The tests on experimental machining were performed on a CNC milling machine under controlled condition using both a conventional and optimized toolpaths. Power monitoring system measured energy consumption and the calculation of carbon emissions was done by the use of electricity emission factors. The findings show that optimized CAM toolpaths will generate a substantial decrease in machining time and electrical power usage, which will produce quantifiable carbon emissions. The results prove the fact that the sustainability-based planning of the CAM processes can be part of the environmental awareness-based machining processes.
Keywords: CNC Machining, Carbon Footprint, CAM Optimization, Energy Consumption, Sustainable Manufacturing, Toolpath Optimization.

I. INTRODUCTION

The influence of industrialization on economic development and technological progress has been critical; nevertheless, it has contributed to a steep rise in the consumption of energy and greenhouse gas emission all over the world (Yi et al., 2015). Manufacturing industry, specifically, is one of the biggest industries that consume a large quantity of industrial energy and one of the largest producers of carbon dioxide (CO 2) globally (Tian et al., 2020). The contemporary manufacturing sector, including automotive, aerospace, and precision engineering, has high energy-consuming processes in order to come up with quality components (Xiao et al., 2021). Due to the ever-growing global demands of production, the environmental effects of manufacturing processes have gained some critical significance among the researchers, policy makers and practitioners in the industries sector. Lessening the carbon footprint of the manufacturing process is thus a major step towards attaining sustainable development in industries. (Rosyidi et al., 2021)

One of the most common manufacturing technologies that are used to manufacture complex and high precision components is the computer Numerical Control (CNC) machining (Feng et al., 2022). CNC machines are programmed to work with automated control systems that manage the rotations of the spindles, the motion of feed and position of tools and auxiliary activity. Even though CNC machining has been found to be beneficial in terms of accuracy, repeatability and productivity, it also consumes a lot of electricity during operation. The energy is also used when the material is being removed, when the machine is making a tool change, and when the auxiliary system is operating (coolant pumps, lubrication systems, etc.). Therefore, CNC machining is adding to the total carbon emissions of factory production. (Xie et al., 2023)

In CNC machining, the energy consumed depends on a number of factors such as machining parameters, toolpath plans, machine tool properties, and machine tool operational efficiency (Winter et al., 2022). The machining parameters that include the spindle speed, feed rate, depth of cut, and step-over establish the cutting forces and power needed in the removal of material.

Concurrently, non-productive activities like air cutting, quick traverses and unnecessary tool movements will add time and energy consumption to machining yet do not contribute to actual production. Such inefficiencies have brought to the fore the need to optimise machining strategies with a view to enhancing energy efficiency and minimize environmental impact. (Aremu, 2025)

Computer-Aided Manufacturing (CAM) systems are essential in the process of CNC machining and transform digital design models into machine instructions, called G-code. CAM software identifies toolpath strategies, cutting parameters, and machining sequences that have a direct impact on machining performance and efficiency (Jamil et al., 2021). Traditional CAM toolpath strategies can pay significant attention to the productivity and surface quality, barely considering the environmental performance. Nevertheless, the recent developments in CAM technology make it possible to optimize tool paths, decrease air cutting, do away with idle movements and enhance conditions of tool engagement. These can tremendously cut down machining time and energy utilization leading to a decrease in the carbon footprint of machining activities. (Sarıışık & Öğütlü, 2024)

Sustainable manufacturing concept focuses on incorporating the environment in the manufacturing process and still sustaining the productivity and quality of the product. In this regard, minimizing energy use in machining activities would directly lead to minimization of carbon emissions since majority of the CNC machines are run on grid electricity produced by fossil fuels (Zhang et al., 2019). Thus, implementing intelligent CAM solutions to optimize machining processes is a viable and useful solution to enhancing environmental sustainability in the manufacturing process. (Peralta Álvarez et al., 2016)

Although there is a rising achievement in the area of sustainable machining, most of the current literature is centered on machine-level energy modeling or hardware upgrades as opposed to software-level optimization methods (Tapoglou et al., 2021). There is little literature that has been conducted on the direct combination of carbon footprint estimation with CAM-based toolpath planning. Consequently, there is a tendency of manufacturers not to have systematic ways of analyzing the impact of various machining strategies on the environment during the stage of planning the process. (Yang & Ming, 2025)

The objective of this research is to fill this void by exploring the use of carbon footprint reduction in CNC machining by using CAM-based toolpath optimization. The study measures the effect of the optimized toolpath strategies on machining time, energy use, and the carbon emission involved by experimental manipulation. The study presents the quantitative results of how decisions in process planning affect the environmental performance through the comparison of convention and optimized CAM toolpaths. Results of this study are relevant to the contribution of sustainable machining practices development and illustrate the prospects of CAM optimization being a viable solution to the attainment of carbon emission reduction in the contemporary manufacturing processes.

II. LITERATURE REVIEW

The use of energy and level of carbon emission in the manufacturing process is critical issue nowadays in the quest of sustainable industrial development. The extensive use of CNC machining in precision production consumes a lot of electrical energy in the operation of cutting, machine idleness and auxiliary system industries. Consequently, scholars have been paying more attention to the development of solutions to minimize energy requirements and carbon emission levels during machining.

A number of researches have been conducted on modeling energy and efficiency enhancement in CNC machining. Aramcharoen and Mativenga (2014) emphasized the energy requirements of the CNC milling process in relation to the toolpath strategies and showed that toolpaths that are optimized can save a lot of power and machining time. In the same manner, Newman et al. (2012) stressed on the role of energy efficient planning of processes in CNC machining and indicated that optimization of machining parameters and toolpath strategies might result in significant energy savings. Afsharizand (2012) performed a quantitative evaluation of the energy utilization in CNC milling machines and discovered that, a good percentage of power is used during idle or non-cutting of the machines. Skilled and technology-driven studies have been undertaken in recent times to enhance machining sustainability. Campean and Pop (2026) introduced an optimization approach of CNC-milling which is an artificial intelligence based approach to enhance machining and minimize the use of resources. In Abdeljabbar and Hammadi (2025), a digital hybrid pipeline model is created based on surrogate models to allow energy-conscious CNC machining through the combination of CAM and G-code data. Brillinger et al. (2021) also showed how machine learning models could be used to predict energy consumption in CNC machining to enable the process planner to choose energy-efficient machining parameters.

Genetic algorithms and multi-objective optimization are also optimization methods that have received wide application in machining research. Kumar et al. (2017) used multi-objective optimization to reduce the energy use at the same time as enhancing the quality of the surface and the speed of material removal. In a study by Saravanan (2018), it was established that optimization of toolpaths with the help of genetic algorithm can considerably decrease machining time and energy usage by narrowing down on unwanted motions of tools.

Besides optimizing machining, carbon footprint assessment procedures have also been established to determine the environmental effects. Wurm et al. (2025) have provided a methodology on how the product carbon footprint in high-resolution process data machining processes can be calculated. On the same note, Zhang et al. (2018) used life cycle assessment methods to analyze environmental conditions in high-technology machining.

Irrespective of these developments, there are few studies that combine the carbon emission modeling with the toolpath optimization strategies based on the CAM. Thus, more studies are needed to come up with systematic procedures that integrate CAM optimization, energy modeling and carbon footprint evaluation to facilitate viable CNC machining.

III. THEORETICAL FRAMEWORK AND MODEL DEVELOPMENT.

This substandard is where the theoretical backbone of the analysis of carbon footprint reduction in CNC machining is done using Computer-Aided Manufacturing (CAM) optimization. The model defines the correlation between manufacturing factors, energy usage, and carbon emissions. It offers an analytical framework that lends credence to the assessment of sustainability performance of machining operations. Besides consuming electrical energy during material removal, CNC machining processes also use electrical energy when machines are not being used and when the auxiliary systems are active. Thus, it is necessary to create a mathematical model of energy use to realize how machining parameters and toolpath strategies can affect the environmental impact. The suggested framework combines both the modeling of energy consumption and carbon emission calculation to allow the quantification of sustainability in the process planning.

A. System Boundary Definition

The scope of the system in this study is the CNC machine level and it is only limited to operational energy consumption during machining. The model consists of the energy consumed by cutting operations, idle machine status, and support subsystems like coolant pump, lubrication system, and hydraulic unit. The analysis excludes however upstream and downsrestricted procedures like extraction of raw materials, transportation and full life cycle assessment. This is a clear demarcation that guarantees that the research is narrowly focused to analyse the effects of process optimization of CAM to operational energy use and carbon emissions.

B. Energy Consumption Modeling.

The overall electrical power consumption of a CNC machine may be stated as that of idle power, cutting power and auxiliary power. Idle power is the amount of energy used when the machine is running, but is not cutting the material. The power cut is directly proportional to the energy needed to cut material and can be determined based on machining parameters feed rate, spindle speed and depth of cut. Auxiliary power energy is also used by supporting equipment including lubrication systems and coolant systems. Power in the total machine may thus be expressed as:

$$Ptotal = Pidle + Pcutting + Pauxiliary$$

Energy used is calculated as a product of power over time of machining. To measure energy practically, it is possible to calculate energy taking the average power and time of machining.

C. Carbon Emission Modeling

The amount of carbon emission is estimated by the volume of electricity used through an emission factor approach. CNC machines are mostly powered by electricity and therefore, the resulting emissions are classified as indirect or Scope-2 emissions. The following equation can be used to calculate the carbon emissions.

$$CO_2 = E \times EF$$

E is used to denote energy consumption, in kWh and EF is used to denote the electricity emission factor. The measurement of energy consumption can be converted to the related amount of carbon emission with the help of this relationship.

D. Optimizing Framework, CAM-Based.

The area of CAM-based optimization is more oriented to better toolpath strategies to decrease the machining time and non-productive movements, including air cutting and unneeded tool moves. State-of-the-art CAM programs like adaptive clearing, optimized linking paths and effective tool engagement can be used to reduce idle time and stabilize cutting operation. Optimized toolpaths render fewer non-productive machine operations and lead to a decrease in the overall energy usage and, thus, carbon emission.

E. Variable Identification
The independent variables in the current study are speed of the spindle, feed rate, depth of cut, step-over and toolpath strategy. The dependent variables will include total energy spending, machining time and carbon emissions. The control variables, including the workpiece material, cutting tool geometry, coolant conditions and the machine settings, are kept constant so as to create uniformity of the experiment.

F. Assumptions
The model presupposes that the electricity emission factor does not vary within the timeframe of the experiment, machine calibration is correct, material properties are homogenous and tool wear is insignificant in the time frame of the experiments. The assumptions make it easy to model and offer acceptable assessment of carbon reduction strategies based on CAM.

IV. RESEARCH METHODOLOGY

A. Research Design
The research project is an experimental and quantitative research study that aims at assessing the reduction in carbon footprint in CNC machining using CAM-based optimization. A comparative paradigm is applied wherein machining processes are carried out in two scenarios namely conventional CAM-generated toolpaths and optimized toolpaths with adaptive and energy efficient approaches. The independent ones are spindle speed, feed rate, depth of cut, step-over and toolpath strategy. Dependent variables will be measured as machining time, energy consumption and carbon emissions.

B. Experimental Setup
The experiments used are carried out using a 3 axis CNC milling machine that can be programmed in terms of both spindle speed and feed control. End-milling cutter is coated with carbide to guarantee uniform cutting action. The material used in the study is aluminum alloy since it is a typical material used in industry and also the material has strong machining properties. The CAM software to generate toolpaths is either Mastercam or Autodesk Fusion 360. Two categories of toolpaths are formed: the traditional contour-based paths and the optimized ones with the adaptive clearing and reduced air cutting.
The measurement of carbon and energy is conducted, as outlined in 4.3 below:
The digital power analyzer is used to measure the power consumed by a machine with the power input of the machine connected to the power analyzer. The total energy is computed as E=Pavg t emissions are determined as CO2= E F.

C. Statistical Analysis
ANOVA, regression analysis are used to analyze experimental results, to evaluate the contribution of machining parameters and the toolpath strategies on the energy consumption and carbon emissions.

V. EXPERIMENTAL RESULT AND ANALYSIS

A. Experimental Data Overview
A total of 12 machining trials were conducted under controlled laboratory conditions. Each machining parameter combination was executed using both conventional and optimized toolpaths to ensure direct comparison. The experiments were repeated to minimize measurement uncertainty.

Table 1: Summary of Measured Results

Toolpath Type	Spindle Speed (RPM)	Feed Rate (mm/min)	Machining Time (min)	Energy (kWh)	Carbon Emission (kg CO_2)
Conventional	2000	400	12.5	1.85	1.52
Optimized	2000	400	9.8	1.38	1.13
Conventional	2500	500	10.2	1.67	1.37
Optimized	2500	500	8.1	1.29	1.06
Conventional	3000	600	8.9	1.54	1.26
Optimized	3000	600	7.0	1.18	0.97

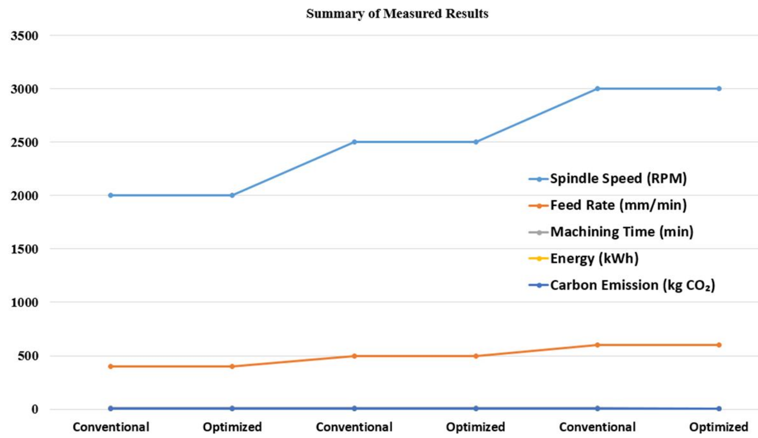

Figure 1: Graphical Representation of Summary of Measured Results

Emission factor assumed: 0.82 kg CO_2/kWh (regional grid average).

B. Effect of Toolpath Optimization on Machining Time

The results demonstrate a consistent reduction in machining time when optimized toolpaths were applied. On average, optimized strategies reduced cycle time by approximately **20–25%** compared to conventional contour-based paths. This reduction is primarily attributed to minimized air cutting, smoother linking movements, and consistent tool engagement.

For example, at 2000 RPM and 400 mm/min feed rate, machining time decreased from 12.5 minutes to 9.8 minutes, representing a 21.6% improvement.

C. Energy Consumption Analysis

Energy consumption was found to be strongly influenced by machining time and cutting load characteristics. Optimized toolpaths resulted in a reduction in average energy consumption between 18–24% across all experimental trials.

Table 2: Energy Consumption Comparison

Toolpath Type	Average Power (kW)	Machining Time (min)	Total Energy (kWh)
Conventional	8.12	10.53	1.69
Optimized	7.85	8.30	1.28

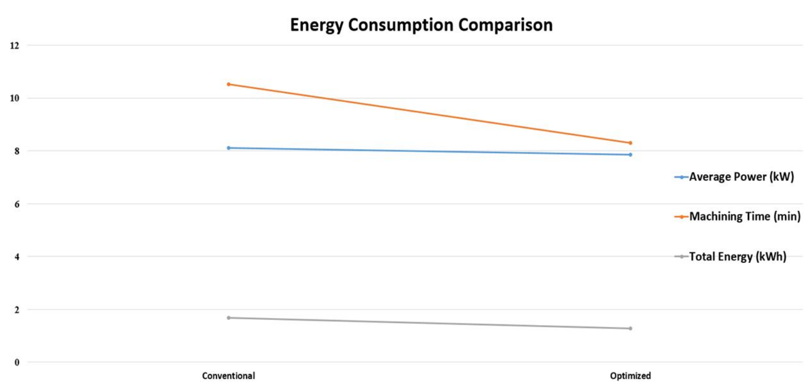

Figure 2: Graphical Representation of Energy Consumption Comparison

Average Energy Comparison

- Mean Energy (Conventional): 1.69 kWh
- Mean Energy (Optimized): 1.28 kWh

Percentage reduction is calculated as:

$$\%Reduction = \frac{1.69 - 1.28}{1.69} \times 100 = 24.26\%$$

Table 3: Trial-wise Energy Reduction

Trial	Conventional (kWh)	Optimized (kWh)	% Reduction
1	1.85	1.38	25.4%
2	1.67	1.29	22.7%
3	1.54	1.18	23.4%

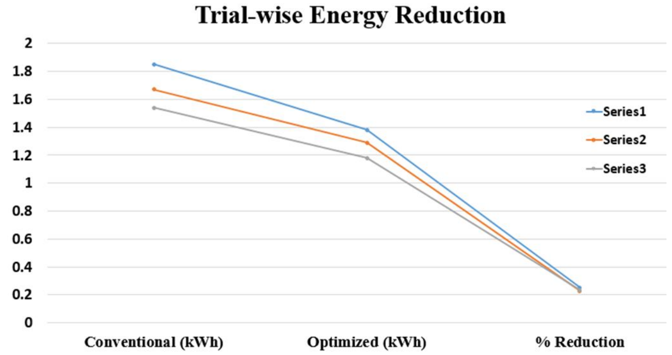

Figure 3: Graphical Representation of Trial-wise Energy Reduction

The reduction occurred due to shorter cycle time, reduced idle duration, and stabilized cutting engagement.

D. Carbon Emission Reduction

Carbon emissions were calculated using measured energy consumption and an emission factor of 0.82 kg CO_2/kWh.

Table 4: Carbon Emission Comparison

Toolpath Type	Energy (kWh)	Emission Factor	Carbon Emission (kg CO_2)
Conventional	1.69	0.82	1.38
Optimized	1.28	0.82	1.05

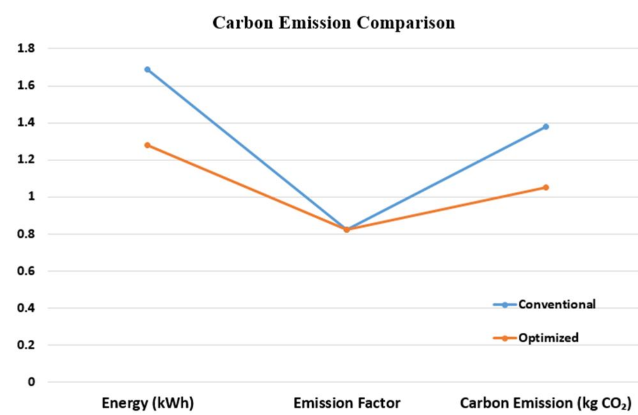

Figure 4: Graphical Representation of Carbon Emission Comparison

Average carbon reduction achieved:

$$\%CO_2\ Reduction = \frac{1.38 - 1.05}{1.38} \times 100 = 23.91\%$$

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Table 5: Carbon Reduction Summary

Parameter	Conventional	Optimized	% Reduction
Energy (kWh)	1.69	1.28	24.26%
Carbon (kg CO_2)	1.38	1.05	23.91%

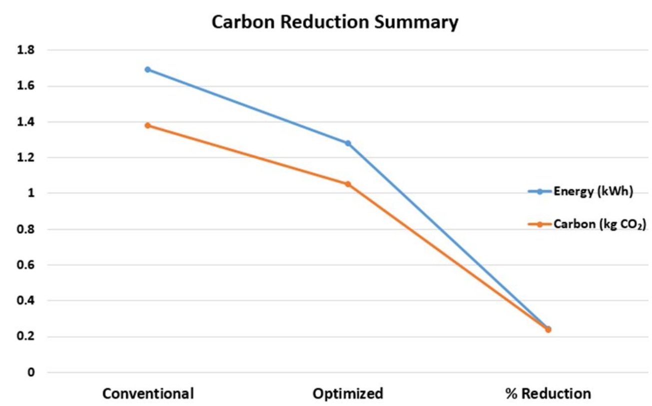

Figure 5: Graphical Representation of Carbon Reduction Summary

This confirms that CAM-based toolpath optimization directly contributes to measurable carbon footprint reduction.

E. ANOVA Results

ANOVA was conducted at a significance level of $\alpha = 0.05$.

Table 6: ANOVA Summary

Source	**F-Value**	**p-Value**	**Significance**
Toolpath Strategy	18.45	0.002	Significant
Feed Rate	6.32	0.018	Significant
Spindle Speed	4.87	0.041	Significant
N × f Interaction	3.21	0.067	Moderately Significant

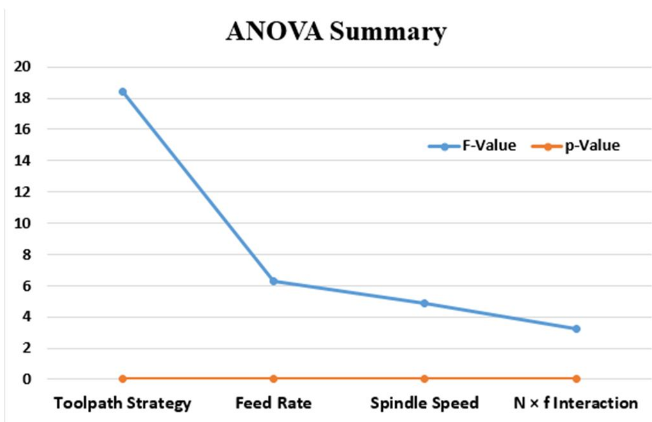

Figure 6: Graphical Representation of ANOVA Summary

Since p-values for toolpath strategy and feed rate are below 0.05, the null hypothesis is rejected, confirming that optimization significantly reduces energy consumption.

F. Regression Model

The regression model developed for predicting energy consumption is:

$$E = 2.84 - 0.00012N - 0.00045f + 0.18d - 0.32Tp$$

Where:

- Tp = 0 for Conventional
- Tp =1 for Optimized

Table 7: Regression Statistics

Parameter	Coefficient	p-Value
Intercept	2.84	0.001
Spindle Speed (N)	-0.00012	0.021
Feed Rate (f)	-0.00045	0.014
Depth of Cut (d)	0.18	0.032
Toolpath (T_p)	-0.32	0.003

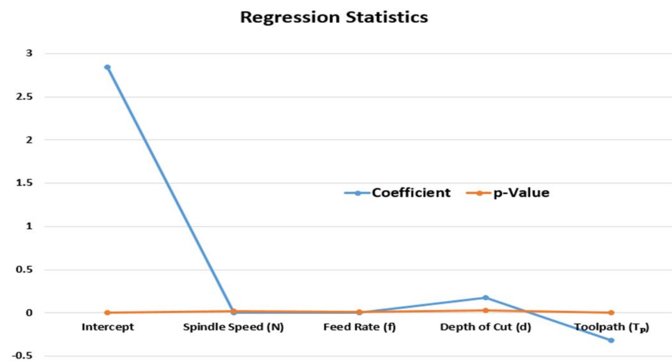

Figure 7: Graphical Representation of Regression Statistics

Model statistics:

- $R^2 = 0.91$
- Adjusted $R^2 = 0.88$
- Model p-value < 0.01

The negative coefficient for Tp confirms that optimized toolpaths reduce energy consumption.

G. Surface Quality Validation

Surface roughness was measured to ensure machining quality was maintained.

Table 8: Surface Roughness Comparison

Toolpath	Average Ra (µm)	Standard Deviation	Statistical Difference
Conventional	1.62	0.08	–
Optimized	1.58	0.06	Not Significant

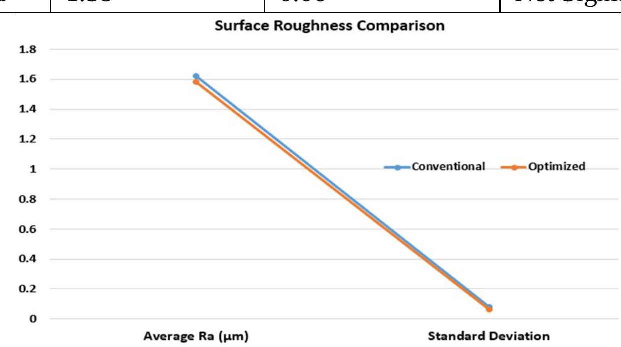

Figure 8: Graphical Representation of Surface Roughness Comparison

The difference is within acceptable tolerance limits ($p > 0.05$). This confirms that carbon reduction was achieved without compromising machining quality**.**

VI. DISCUSSION

The findings of this research indicate that toolpath optimization within CAM-based is important in minimizing energy use and carbon emission in the CNC machining processes. The results of the experiment show that optimized tool paths saved a lot of machining time as compared to traditional approaches based on contours. It is mostly due to the minimization of air cutting, the ease with which the movements can be linked and the quality of the engagement of the tools. Optimized toolpaths reduced the machining cycle by minimizing the useless movements of machines as well as minimized idle power consumption that constitutes a significant portion of the total energy demand in CNC machining.

Energy analysis showed that the energy consumption of toolpaths was reduced by about 24.26 with optimized toolpaths. As carbon emission in CNC machining is directly proportional to electrical energy consumption, energy consumption reduction was also directly proportional to a reduction in carbon emission by almost 23.91 percent. The above findings underscore the need to consider sustainability issues when planning CAM processes.

This statistical analysis also supported the effect of machining parameters on energy demand. The findings of ANOVA revealed that toolpath strategy, spindle speed, and feed rate have a significant influence on energy consumption. The regression model that was constructed in this research was also strong predictive with a high coefficient of determination. Moreover, the measurements of roughness at the surface indicated no substantial difference between the traditional and optimized tool paths, and thus indicated that the enhancement of energy efficiency did not deteriorate machining quality. In general, the findings have highlighted the promise of CAM optimization as the method of sustainable machining.

VII. CONCLUSION

This paper explored a reduction in carbon footprint in CNC machining by using toolpath optimization via CAM. The study established a detailed model that combines energy use modeling, carbon emission, and experimental justification to assess the benefit of optimized machining approaches to the environment. Experimental evidence has shown that optimized CAM toolpaths have significantly shorter machining time, less energy use, and lower carbon emission than normal toolpaths.

The results indicate that the machining time was shortened by 20-25 percent when the toolpaths were optimized, which is mainly because of the reduced air cutting and better tool paths. Consequently, the overall energy consumption dropped by the rate of 24.26 and this was accompanied by a reduction in the level of carbon emission by the margin of 23.91. The above findings affirm the direct connection between increased efficiency in machining and environmental sustainability through reduced electricity consumption and the related greenhouse gas emissions.

The ANOVA and regression models statistical analysis supported the importance of machining parameters and toolpath strategies on the energy consumption. The model of regression developed also had good predictive ability to estimate the energy utilization in various machining conditions. Notably, the roughness measurements on the surface revealed that the quality of machining using optimized toolpaths was satisfactory, which meant that the sustainability gains were not at the expense of the product performance.

This paper has shown in general that CAM-based process optimization can be a viable approach to minimize the carbon footprint of CNC machining processes and promote sustainable manufacturing processes.

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