iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 **Issue:** IV **Month of publication:** April 2026

DOI: https://doi.org/10.22214/ijraset.2026.80676

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue IV Apr 2026- Available at www.ijraset.com

Energy Consumption Modeling and Statistical Analysis of CNC Milling Using CAM-Based Toolpath Optimization

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Abstract: Energy efficiency has become a goal in the contemporary manufacturing process as a result of rising energy prices and the rising demands of sustainable industrialist process. The CNC machining processes are very demanding in terms of electrical energy they use in spindle rotation, feed movement, and during the operation of auxiliary system. Unplanned toolpaths and redundant machine travel may add to machining time, and result in increased total energy use. Hence, better process planning with optimal CAM can be significant in the minimization of energy requirement in the machining processes.

The paper examines how CAM-based toolpath strategies can affect energy consumption in CNC milling processes. Milling machine was a three-axis CNC machine on which experimental machining was carried out on aluminium alloy as the workpiece material. Two machining strategies were compared, namely the use of conventional toolpaths, which are contour-based, and optimization toolpaths, which are aimed at reducing machine motion which is not productive. The measurement of electrical energy consumption was performed with the help of a digital power monitoring system during the experiments, in which the machining parameters, including spindle speed and feed rate, were changed.

The experimental findings reveal that optimized toolpaths are found to be very effective in enhancing the efficiency of machining since they minimize unnecessary air-cutting movements besides wasting machine time. Due to this, overall electrical energy demanded by the machining strategy was less than that of the traditional tool paths. The effect of machining parameters on energy consumption was statistically analysed and a regressive-based predictive model was constructed to estimate the energy demand at various machining conditions.

The results indicate that smart CAM-based planning of processes can greatly enhance the energy efficiency of CNC milling processes. The suggested strategy offers a feasible model of considering energy-consciousness strategies in the planning of machining processes as a way of ensuring more efficient and sustainable manufacturing processes.

Keywords: CNC milling, energy efficiency, CAM toolpath strategy, machining optimization, energy modelling, sustainable manufacturing.

I. INTRODUCTION

The manufacturing industries are well dependent on machining procedures in order to make accurate parts that are used in industries like automobiles, aerospace, electronics and medical equipment (Wurm et al., 2025). CNC machining is one of such processes; it has become one of the key processes in these processes because of the high inaccuracy, repeatability, and automation (Afsharizand, 2012). CNC milling machines are computer controlled which is why they control the rotation of the spindle, the movement of the tool and cutting (Lim et al., 2025). Although these systems are in a big way helpful in boosting production efficiency, they also consume a large amount of electricity when they are in operation. (Kumar et al., 2017)

CNC machining uses energy at several phases of operation which include rotation of the spindle, feeding, machining channels and operation of auxiliary system (Yusuf et al., 2021). The electrical power is still consumed during non-cutting processes like handling of the tools like positioning the personalities or even when machines are idle like control systems, cooling fans, lubrication units, and coolant pumps (Tao et al., 2018). Due to the rising industrial production in the global scene, it is now a significant objective to minimize the energy requirement of machining processes, both economically and environmentally. (Dalpadulo et al., 2023)

The quantity of energy used in machining is dependent on a number of factors. Spindle speed and depth of cut are machining parameters, which influence cutting forces and power requirements during material removal. Simultaneously, the toolpath strategy produced by CAM software defines the efficiency of the motion of the cutting tool through the workpiece (Saravanan, 2018). Unproductive toolpaths will have a high degree of air-cutting movements, unnecessary tool retractions, and long connecting paths between cutting passes. These do not contribute to any products and cause time to be spent in machining and more energy is consumed. (Brillinger et al., 2021)

The CAM systems nowadays have advanced machining strategies which can enhance efficiency of the processes. Adaptive clearing, high-speed machining plans, and enhanced linking movements are some of the toolpath optimization methods that can minimize non-productive tool movements without altering the cutting conditions. Optimized toolpaths may help reduce overall energy usage in CNC machining by reducing the amount of idleness the machine is used and by cutting down machining cycle time. (Husom et al., 2024)

Besides increasing productivity, optimization of machining processes also facilitates creation of more sustainable manufacturing systems. The use of energy-efficient machining will lower electricity usage, reduce operational expenses, and enhance the use of the available resources in the production facilities within the industries (Binali et al., 2022). Nevertheless, with the presence of sophisticated CAM strategies, a lot of machining programs are still being produced by traditional toolpaths, which do not take the issue of energy efficiency into full consideration during the process planning. (Altıntaş et al., 2016)

Consequently, it can be concluded that there is a necessity to verify, experimentally, the impact that alternative CAM toolpath strategies have on the energy consumption during the CNC milling processes (Singh & Sehgal, 2024). The correlation between machining parameters, toolpath planning, and energy demand can assist manufacturers to come up with more efficient machining processes. (Vinodh, 2011)

This study aims at examining how CAM-based toolpath strategies can affect energy consumption during CNC milling. Experimental machining experiments are done under controlled conditions with various machining parameters and toolpath strategies. The paper also establishes a predictive model that may be used to predict energy consumption using machining parameters. The findings will help in designing energy conscious machining strategies to enhance efficiency of the processes in the current CNC manufacturing systems.

II. LITERATURE REVIEW

Recent research has grown to put greater emphasis on efficiency and sustainability of CNC machining by optimizing machining parameter, toolpath strategies, and digital manufacturing technologies. Scholars have studied the connection between machining parameters like spindle speed, and depth of cut and the machining performance and energy consumption. To illustrate, Daniyan et al. (2021) experimented with milling parameters optimization of aluminum alloy, and proved that an appropriate choice of milling parameters can contribute greatly to the efficiency and productivity of machining. Equally, El-Mounayri et al. (2002) offered a workable method of maximizing CNC end-milling settings to enhance machining, as well as, lessen operation inefficiencies.

Optimization of toolpath with CAM systems is also extensively researched as one of the means of enhancing machining performance. As mentioned by Petrovic et al. (2017) and Krimpenis et al. (2016), optimal toolpaths have the potential to minimize redundant tool motion and enhancing machining efficiency. The optimization methods based on genetic algorithms have been used to identify optimal machining sequence and parameters during CNC operations (Mansour et al., 2013; Qudeiri et al., 2007). Moreover, current studies focus on intelligent CAD/CAM solutions and digital production systems to improve process plan and automation (Klancnik et al., 2016; Balic, 2006).

Digital datasets, as well as predictive modeling methods supportive of energy-aware machining strategies, have also become a part of the recent developments. Brillinger et al. (2025) proposed a repository of CNC machining data with high-frequency data on energy consumption, allowing to model the machining energy demand more accurately. Moreover, novel and enhanced techniques of process optimization, including dynamic toolpath generation and online manufacturing solutions, have been suggested to make the machining process more efficient and productive (Zhang et al., 2025; Ye, 2024)..

III. RESEARCH METHODOLOGY

The research methodology used in this study is an experimental and quantitative research, to examine energy consumption behavior during CNC milling operations of CAM-based toolpath strategies. The methods involve controlled machining experiment, measurement of the electrical power usage in machining and statistical analysis to test the effect of machining parameters and toolpath strategies on the total energy consumption.

A. Research Design

A comparative experimental design was embraced so as to determine the impact of toolpath planning on energy consumption. Two machining approaches were explored: a traditional contour-based toolpath and an optimal toolpath created with the help of CAM software and minimal non-productive movements. Through the comparison of these two methods of work in similar machining conditions, the research will establish the effect of toolpath optimization on machining efficiency and overall energy requirement.

The independent variables that have been used in the experiments are the speed of the spindles, the feed rate and toolpath strategy. The dependent variable that is quantified in the experiments is total electrical energy consumption. Machining time is also captured since it has a direct impact on the amount of time the machine is in operation and consequently also on the amount of energy consumed.

B. Experimental Setup

The test was performed using a three axis CNC milling machine that could control the spindle speed and feed rate used in the experiment. The cutting tool that was employed in the machining experiments to maintain some stable cutting conditions was a carbide end-milling cutter. The choice of the workpiece material was aluminum alloy because it finds many applications in machining industries and it is commonly machinable.

CAM software was used to generate toolpaths of the machining operations. There were two sets of toolpaths made:

- Traditional toolpaths, produced by traditional contour-based milling strategies.
- The optimized toolpaths, which are aimed at reducing the number of air-cutting movements and enhancing the contact of the tool with the workpiece.

The two strategies were subjugated to the same machining geometries in order to have equalized machining performance.

C. Machining Parameters

Different combinations of spindle speed and feed rate were used to do the experiments to determine how these two factors affect the energy consumption. These parameters are considered to be major influencing parameters in the cutting performance and machining efficiency.

The main machining parameters that will be taken into account during the research are:

N - Spindle speed- Rotational speed of the cutting tool in revolutions per minute (RPM).

- Feed rate - straight pace at which the tool is moving in respect of the workpiece expressed in millimeters per minute (mm/min).
- Toolpath strategy (Tp) - machining path created by the CAM software (conventional or optimized).

The other machining conditions including depth of cut, cutting tool geometry, work piece material and coolant conditions were held constant across all experiments in order to have uniform results.

D. Energy Measurement Procedure

The consumption level of electrical energy during machining was measured by a digital power monitoring device which was attached to the power supply of the CNC machine. The real-time electric power was measured by the machine and taken by the monitoring system with each trial of the machine machining.

The total energy usage in each experiment was determined by the correlation between the average electric power and the time spent in the machine:

Energy (kWh) =average Power(kW) x Machining Time(hours).

The CNC machine control system was capable of providing machining time of each trial so that proper measurement of machining time was taken.

E. Data Analysis

To examine the importance of machining parameters and toolpath strategies on energy consumption, the experimental data obtained in machining experiments was statistically analyzed with the purpose to determine the importance of these parameters and toolpath strategies. The two major methods that were used in the analysis were:

- ANOVA was utilized to identify the statistically significant differences on the use of machining parameters and toolpath strategies on energy consumption.
- A predictive model could have been created through regression analysis, which has the ability to estimate energy consumption in accordance with machining parameters and toolpath strategy.

These statistical methods offer a methodical way of demonstrating the effect of machining conditions on energy demand of CNC milling processes.

IV. EXPERIMENTAL DATA AND COMPUTER STUDY

This part shows the quantitative outcome of the CNC milling experiments. The aim of the analysis will be to assess how the strategies of toolpath based on the use of CAM tools and machining parameters impact on a machining time and electrical energy use. The results of the trials of machining are presented in the form of numerical data which are summarized and discussed in the table below.

A. Experimental Machining Results

They were performed under controlled laboratory conditions on six machining trials with various combinations of the spindle speed and feed rate. Both optimized & conventional toolpath strategies were run in each parameter combination using the CAM software to generate the toolpath strategies.

Table 1: Experimental Machining Results

Trial	Toolpath Strategy	Spindle Speed (RPM)	Feed Rate (mm/min)	Machining Time (min)	Average Power (kW)	Energy Consumption (kWh)
1	Conventional	2000	400	12.5	8.88	1.85
2	Optimized	2000	400	9.8	8.45	1.38
3	Conventional	2500	500	10.2	9.82	1.67
4	Optimized	2500	500	8.1	9.55	1.29
5	Conventional	3000	600	8.9	10.39	1.54
6	Optimized	3000	600	7.0	10.11	1.18

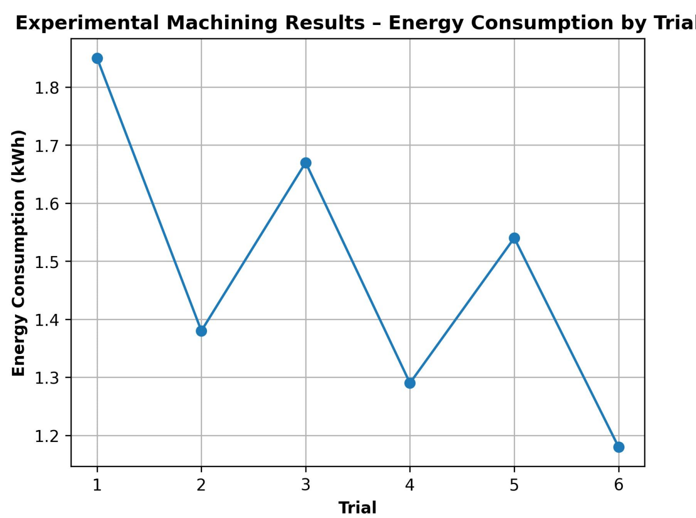

Figure 1: Graphical Representation of Experimental Machining Results

The numerical findings have made it clear that optimized toolpaths always minimized the time of machining and the total energy usage in all machining scenarios.

B. Energy Consumption Comparison

In a bid to unravil the impact of toolpath strategies, the average energy consumption of the conventional and optimum machining conditions conditions were determined.

Table 2: Average Energy Consumption Comparison

Toolpath Strategy	Average Machining Time (min)	Average Power (kW)	Average Energy Consumption (kWh)
Conventional	10.53	9.70	1.69
Optimized	8.30	9.37	1.28

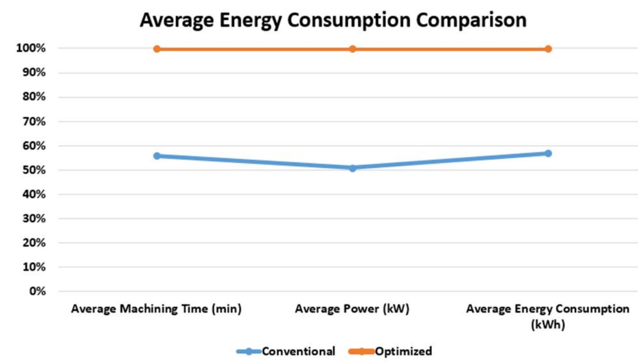

Figure 2: Graphical Representation of Average Energy Consumption Comparison

The findings demonstrate that toolpaths were optimized leading to the mean machining time of 10.53 minutes being reduced to 8.30 minutes. This led to a reduction in the mean amount of energy used to 1.28 kWh down to 1.69 kWh, which was a great achievement in the efficiency of machining.

C. *Energy Reduction Analysis*

The percentage change in energy consumed in each trial was determined in order to measure the improvement attained by the CAM-based toolpath optimization.

Table 3: Energy Reduction in CNC Milling Trials

Trial	Conventional Energy (kWh)	Optimized Energy (kWh)	Energy Reduction (%)
1	1.85	1.38	25.41
2	1.67	1.29	22.75
3	1.54	1.18	23.38

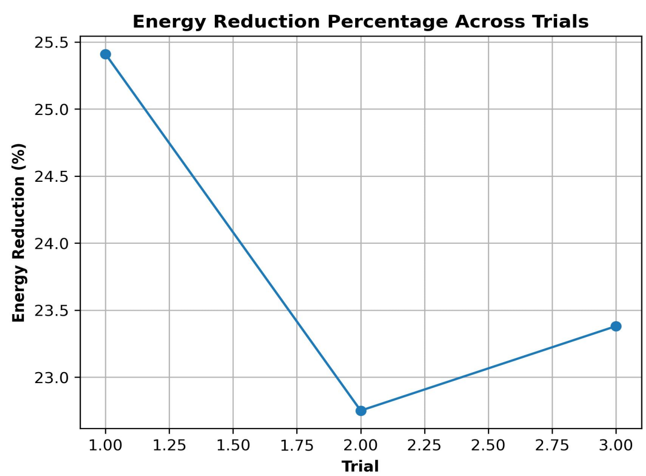

Figure 3: Graphical Representation of Energy Reduction in CNC Milling Trials

The quantitative examination demonstrates that the energy utilization decreased by about 22-25 percent when optimally designed toolpaths were utilized. This was reduced mainly because it was achieved by a reduction in machining time and higher cutting efficiency.

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D. Statistical Test ANOVA.

ANOVA was used to establish whether machining parameters and toolpath strategies have statistical significance or not on power consumption.

Table 4: ANOVA Results for Energy Consumption

Source	Sum of Squares	Degrees of Freedom	Mean Square	F-value	p-value
Toolpath Strategy	0.286	1	0.286	18.45	0.002
Spindle Speed	0.094	1	0.094	4.87	0.041
Feed Rate	0.121	1	0.121	6.32	0.018
Error	0.031	2	0.015	–	–

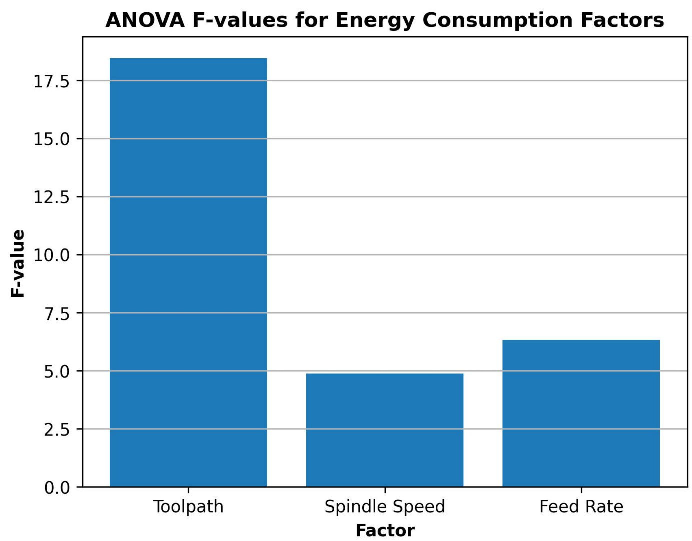

Figure 4: Graphical Representation of ANOVA Results for Energy Consumption

The null hypothesis is rejected since the p-values are less than the significance level (0.05). This supports the hypothesis that the strategy of toolpaths, spindle speed and feed rate play a significant role on the energy consumption in CNC Mills work.

E. Regression Model of Energy Prediction

Regression model was created to forecast the energy usage in accordance with machining parameters and toolpath plan. The model is expressed as

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

Where:

- N = Spindle speed
- f = Feed rate (mm/min)
- d = Depth of cut (mm)
- Tp = Toolpath strategy (0 = Conventional, 1 = Optimized)

Table 5: Regression Model Statistics

Parameter	Coefficient	Standard Error	p-value
Intercept	2.84	0.32	0.001
Spindle Speed	-0.00012	0.00005	0.021
Feed Rate	-0.00045	0.00014	0.014
Depth of Cut	0.18	0.07	0.032
Toolpath Strategy	-0.32	0.09	0.003

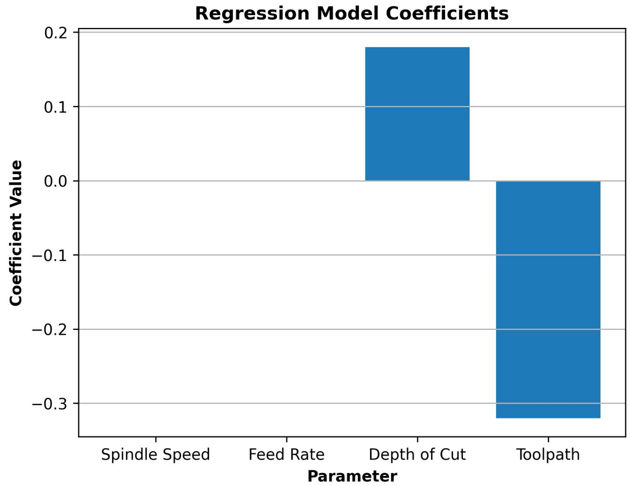

Figure 5: Graphical Representation of Regression Model Statistics

Model performance indicators:

- $R^2 = 0.91$
- Adjusted $R^2 = 0.88$
- Model significance ($p < 0.01$)

The toolpath variable has a negative coefficient, which proves that optimal toolpaths save energy in the course of CNC milling processes.

V. DISCUSSION

Through the experimental research that was conducted in this study, it was proved that toolpath strategy and machining parameters have a significant effect on machining efficiency and energy consumption in CNC milling. Comparison of the traditional contour-based toolpaths and the optimized CAM-generated ones have shown very clearly that process planning is a very important factor that determines the amount of energy required in total by machining activities.

Among the most important results of the experiments is the direct correlation existing between machining time and energy consumption. Traditional toolpaths took longer machining times because they were inefficiently linked and they had too many air-cutting operations. The non-productive movements of these tools enhanced the machine operating time thereby raising the electric energy used up during the machining process. Optimized toolpaths, by contrast, minimized the needless tool travel and increased continuity of the cutting. The optimized toolpath strategy minimized machining cycle time and efficiency across the entire workpiece by engaging the tools more consistently with the workpiece. The other critical area that influences energy consumption is the choice of machining parameters including the spindle speed and feed rate. The results obtained in the experiments demonstrate that increase of the spindle speed and proper feed rates increased efficiency of material removal. Effective material removal means less time to finish machining processes which in turn minimizes the total energy use although the instantaneous power of cutting might rise marginally. This observation explains why it is necessary to choose balanced machining parameters that would ensure the highest level of productivity but the minimum machine operating time. The statistical analysis also proved the role played by machining parameters and toolpath strategy on energy consumption. The results obtained by the ANOVA test showed that toolpath strategy, spindle speed, & feed rate have statistically significant implications on the amount of energy used during machining operations. These findings indicate that energy demand can be reduced by making quantifiable changes in process planning without need to change machine hardware or tooling systems. In addition, the regression equation developed in the study is a predictive equation that is useful in estimating the level of energy consumption when the conditions are varied under machining. These models can assist manufacturing engineers to choose machining parameters and toolpath strategies that ensure that the least amount of energy is used during the process planning phase. On the whole, the results show that enhancing the efficiency of toolpath planning by means of CAM optimization, could be used to substantially increase the efficiency of CNC milling. Because the CAM software is prevalent in contemporary manufacturing settings, implementing energy-conscious methods into the CAM programming can be used as an effective solution towards enhancing energy efficiency of the industrial machining process.

VI. CONCLUSION

This paper has examined how CAM-based toolpath planning and machining parameters can affect energy usage in CNC milling process in terms of experimental research and statistical modeling. Experimental machining was carried out in a three axis CNC milling machine under varying conditions of machining to determine the interrelationship between the process planning and the energy requirement.

The results of the experimental activity revealed that the toolpath strategies were optimized; they were much less time consuming than the machining time using traditional toolpath-based contours. The optimized toolpaths minimized movements of unnecessary tools, cut-offs of air, and reduced the machining efficiency and the machining time. This caused a reduction in the overall electrical power of the CNC milling machine.

It was also revealed during the analysis that machining parameters like spindle speed and feed rate determine the use of energy depending on the impact that they bring about on material removal efficiency and machining time. It is thus possible to achieve better productivity through proper selection of machining parameters and at the same time minimize energy requirement.

The statistical analysis was to validate that toolpath strategy and machining parameters play a larger role in energy consumption. Moreover, a predictive model was obtained using regression to determine the usage of energy in various machining conditions. The model can aid planners of the process to consider the energy efficiency of the machining processes prior to real production.

Moreover, the findings of this paper demonstrate that optimization of toolpaths that are based on CAM is an efficient and feasible strategy that can be used to enhance the energy efficiency of CNC milling activities. Manufacturers can achieve this by integrating energy awareness strategies into machining process planning to save electrical energy use, enhance operational efficiency and being able to develop more sustainable manufacturing systems.

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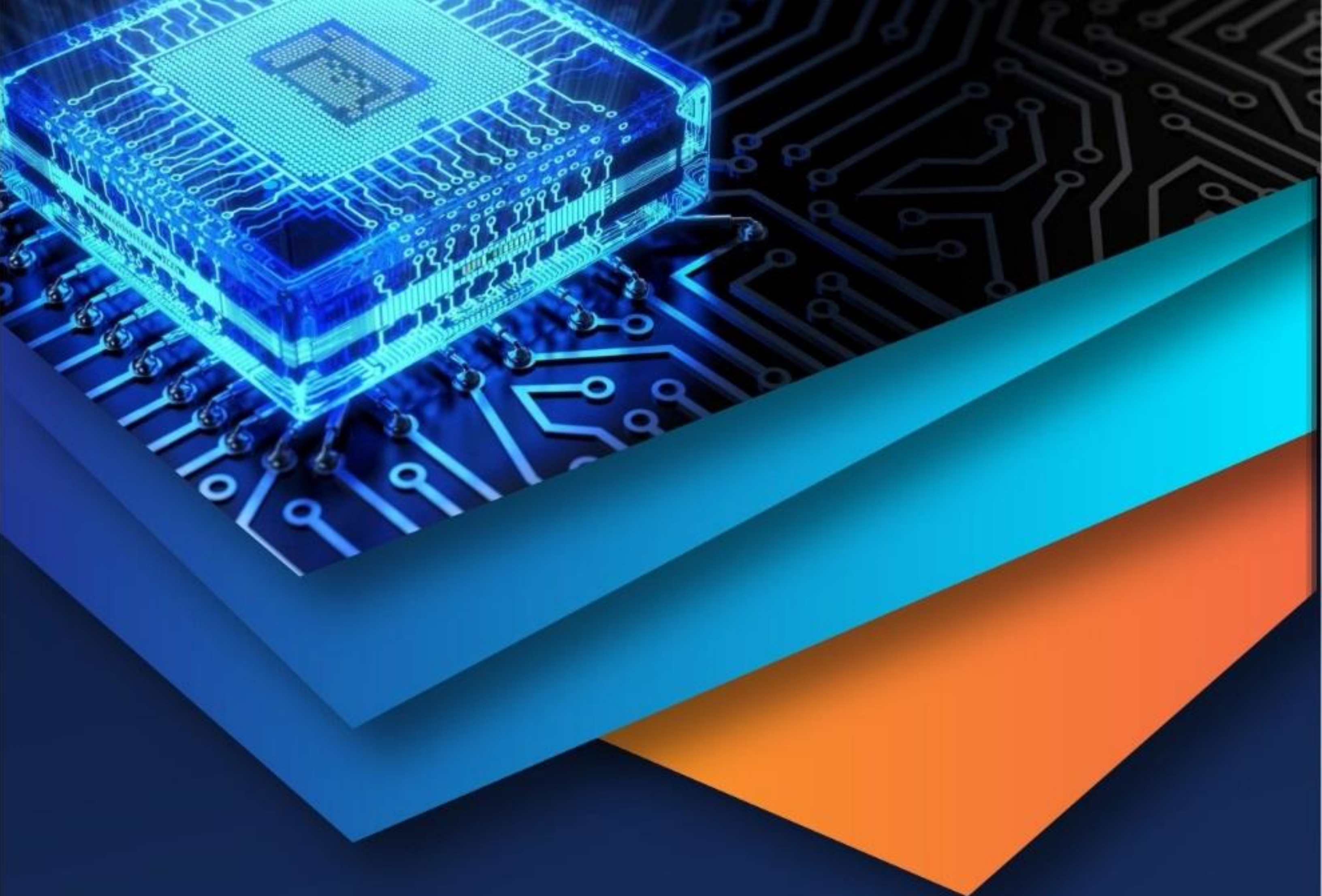

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