JOURNAL OF PRODUCTION ENGINEERING VOL. 29, NO. 1 (2026)
DOI: 10.24867/JPE-2026-01-038

Original research article

Journal of
Production Engineering

https://jpe.ftn.uns.ac.rs/index.php/jpe
ISSN: 1821-4932 (print), ISSN: 2956-2252 (online)

Experimental investigation and multi-objective optimization of energy consumption in high-efficiency milling

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ABSTRACT

The increasing demand for sustainable manufacturing and energy-efficient production systems has emphasized the importance of reducing energy consumption while maintaining high productivity in machining processes. This study investigates the relationship between cutting parameters, energy consumption and material removal rate during high-efficiency milling of aluminium. Experimental investigations were conducted on a three-axis CNC machining centre equipped with an electrical energy monitoring system. The influence of milling width and depth of cut on energy consumption was analysed using a full factorial experimental design, while spindle speed and feed rate were kept constant. The obtained results were statistically evaluated using analysis of variance (ANOVA), and an empirical regression model for predicting energy consumption was developed and validated. Furthermore, a multi-objective optimization procedure was performed to simultaneously maximize productivity and minimize energy consumption. The results revealed that increasing the cutting parameters leads to higher energy demand but also significantly improves the material removal rate. The optimal machining conditions were identified at a depth of cut of 30 mm and a milling width of 1.22 mm, resulting in a material removal rate of 22,027.92 mm³/min and an energy consumption of 0.002185 kWh. The proposed methodology provides practical guidelines for improving the energy efficiency and sustainability of high-efficiency milling processes and may support future implementation within smart manufacturing and Industry 4.0 environments.

ARTICLE INFO

Received: 15 March 2026
Revised: 21 May 2026
Accepted: 5 June 2026

KEYWORDS:
High-efficiency milling;
Energy consumption;
Sustainable manufacturing;
Optimization;
Aluminium machining.

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This paper is an extended version of the conference paper presented at DEMI 2025.

1. INTRODUCTION

In order to support industrial development in accordance with the concepts of Industry 4.0 and sustainable manufacturing, it is necessary to integrate a large number of elements and procedures from the fields of machining, manufacturing technologies, information systems, software technologies, ecology and production management. The production systems created through this integration are expected to satisfy the increasing demands of the modern global market, which requires improved product functionality and reliability, reduced production costs and environmentally responsible manufacturing practices. Consequently, these requirements impose significant challenges regarding machining process design and control, achievement of high surface quality and dimensional accuracy, increased productivity, reduced waste generation and improved energy efficiency.

In recent years, energy efficiency has become one of the most important performance indicators in modern manufacturing systems. Besides productivity and product quality, industrial companies are increasingly focused on reducing energy consumption and minimizing environmental impact. This trend is particularly important because manufacturing industries account for a significant portion of global energy demand and greenhouse gas emissions. Therefore, developing energy-efficient machining strategies has become one of the key objectives of sustainable manufacturing.

Published by the University of Novi Sad, Faculty of Technical Sciences, Novi Sad, Serbia.

These requirements have accelerated the development and implementation of advanced machining strategies, among which high-efficiency machining (HEM) has received considerable attention. High-efficiency machining is based on the application of larger axial depths of cut and smaller radial engagements while maintaining stable cutting conditions and high material removal rates. However, introducing this strategy into conventional machining environments remains a challenging task. High-efficiency machining does not have clearly defined theoretical frameworks and application limits, which requires detailed experimental investigations, material machinability evaluation and comprehensive analysis of process performance indicators.

The modern mechanical engineering industry is continuously faced with the need to increase productivity, economic efficiency and manufacturing flexibility. During rough machining operations, the primary objective is to remove the maximum amount of material in the shortest possible time while preserving cutting tool integrity. At the same time, manufacturers are under increasing pressure to reduce energy consumption in order to decrease operating costs and improve environmental sustainability.

From a technical point of view, machining energy efficiency is commonly defined as the relationship between the useful output energy and the total energy supplied to the manufacturing system. The machining process itself consists of several energy-consuming stages, including machine start-up, standby operation, spindle acceleration, activation of cooling and lubrication systems and the actual material removal process. Therefore, understanding the contribution of machining parameters to the overall energy demand is essential for improving process efficiency.

A significant amount of previous research has been devoted to the analysis of energy consumption, productivity and process efficiency. Daniyan et al. [2] investigated the influence of cutting parameters and energy requirements on improving the sustainability of aluminium machining using response surface methodology. Korkmaz et al. [3] analysed the relationship between machining parameters, cooling conditions, energy consumption, tool wear and surface roughness. Wang et al. [4] developed predictive models for specific cutting energy consumption during high-speed machining of aluminium alloys.

Several studies have also focused on optimization strategies. Zhang et al. [5] reported that increasing the material removal rate may improve energy efficiency under appropriate machining conditions. Zaidi et al. [6] investigated the influence of machining parameters on surface roughness, burr formation and specific energy consumption during aluminium milling. Öztürk and Kara [7] optimized machining parameters to simultaneously reduce surface roughness and energy consumption, while Zhang et al. [8] proposed a multi-objective optimization approach considering productivity, carbon emissions and surface quality.

Recent developments in sustainable manufacturing and Industry 4.0 have further emphasized the importance of energy-aware machining processes. Sustainable manufacturing aims to simultaneously satisfy economic, environmental and technological requirements [13]. In addition, digital manufacturing technologies enable continuous process monitoring and create opportunities for intelligent process optimization and energy management [14,15].

Although numerous studies have investigated machining energy consumption, there is still limited research dealing with energy modelling and optimization under high-efficiency milling conditions characterized by large depths of cut and small radial engagements. Furthermore, the simultaneous consideration of productivity and energy consumption remains insufficiently explored.

Therefore, the aim of this study is to experimentally investigate the influence of milling width and depth of cut on energy consumption during high-efficiency milling of aluminium. Statistical analysis and empirical modelling are employed to establish relationships between machining parameters and electrical energy consumption. Furthermore, a multi-objective optimization procedure is performed in order to simultaneously maximize material removal rate and minimize energy consumption. The obtained results may contribute to the development of sustainable and energy-efficient machining strategies suitable for future smart manufacturing environments.

2. EXPERIMENTAL SETUP

The experiment was conducted on a three-axis CNC milling centre EMCO Concept Mill 450 equipped with a Sinumerik 810D/840D control unit (Fig. 1). The machine tool has a maximum spindle speed of 12,000 rpm and an installed power of 11 kW, making it suitable for experimental investigations under high-efficiency machining conditions. The experimental setup was designed to enable reliable monitoring of electrical energy consumption during milling operations. Figure 1 shows the cutting tool and workpiece configuration used during the high-efficiency milling experiments.

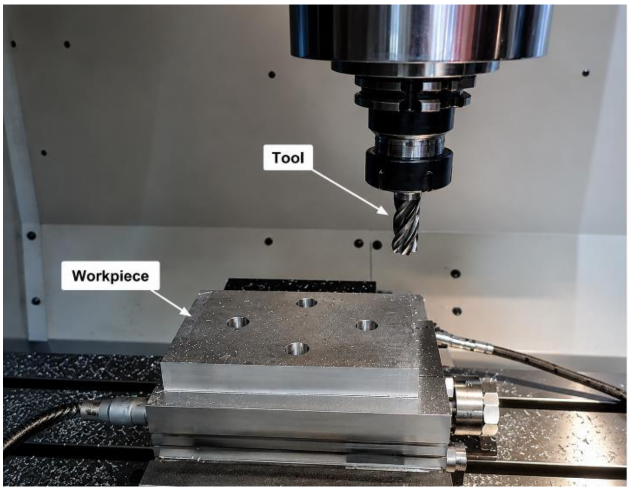

Fig. 1 Cutting tool and workpiece configuration used in the high-efficiency milling experiments.

The cutting tool used during the experiment was a solid carbide end mill S814HA manufactured by Dormer. The milling cutter diameter was D_c = 16 mm, the cutting edge length was l_2 = 32 mm, while the overall tool length was l_1 = 92 mm. The tool consisted of four cutting edges (Z_n = 4), allowing stable cutting conditions under increased material removal rates.

Aluminium was selected as the workpiece material due to its widespread industrial application, favourable machinability, low density and excellent strength-to-weight ratio. Owing to these properties, aluminium alloys are extensively used in aerospace, automotive and general engineering applications. In addition, aluminium is frequently selected for studies related to sustainable manufacturing because of its good recyclability and relatively low cutting forces compared to other engineering materials.

Cooling and lubrication were performed using an emulsion prepared by mixing demineralized water with synthetic oil Castrol Hysol T15 at a concentration of 5%. The cutting fluid was supplied externally using a flooding strategy in order to ensure adequate heat dissipation and chip evacuation during machining.

Electrical energy consumption was measured using a Mavowatt 30 power quality analyser. The device complies with EN50160, EN61000-4-7 and EN61000-4-15 standards and enables the measurement of electrical quantities, harmonic components and transient phenomena. The measuring equipment was connected directly to the electrical cabinet of the machine tool to continuously monitor the electrical energy consumed during the machining process.

The variable machining parameters used during the experiment were milling width a_e (mm) and depth of cut a_p (mm), each varied at three levels (Table 1). A full factorial experimental design was adopted, resulting in nine combinations of input parameters. Statistical analysis and mathematical modelling were performed using Design Expert 7 software.

The spindle speed and feed rate were kept constant at n = 4000 rpm and v_f = 600 mm/min, respectively, according to the selected high-efficiency machining strategy. During each experimental run, the workpiece was clamped in the machine fixture and electrical energy consumption was recorded throughout the cutting operation.

To obtain the net energy associated with material removal, the measured energy values were corrected by subtracting the machine energy consumption immediately before tool engagement. At that stage, the machine was operating under standby conditions, the cooling and lubrication system was activated, and the cutting tool was positioned at the tool approach point. Consequently, the reported values correspond exclusively to the energy required for the actual chip formation process.

3. RESULTS AND DISCUSSION

3.1 Energy consumption analysis

In addition to the analysis of electrical energy consumption E (kWh) during a single milling pass, the material removal rate (MRR) was also calculated as an important indicator of process productivity. The material removal rate MRR (mm³/min) was determined as the product of the depth of cut ap (mm), milling width ae (mm) and feed rate vf (mm/min). The calculated values of material removal rate and the measured values of electrical energy consumption are presented in Table 1.

Table 1 – *Experimental plan and results.*

Exp.	Depth of cut, a_p (mm)	Milling width, a_e (mm)	Material removal rate, MRR (mm³/min)	Energy consumption, E (kWh)
1.	10	1.0	6000	0.00167
2.	10	1.5	9000	0.00201
3.	10	2.0	12000	0.00252
4.	20	1.0	12000	0.00189
5.	20	1.5	18000	0.00226
6.	20	2.0	24000	0.00256
7.	30	1.0	18000	0.00199
8.	30	1.5	27000	0.00233
9.	30	2.0	36000	0.00291

The obtained results indicate a clear relationship between the selected machining parameters and energy consumption. The highest electrical energy consumption (E = 0.00291 kWh) was obtained for the combination of the highest cutting parameter values (a_p = 30 mm and a_e = 2 mm). Conversely, the lowest energy consumption (E = 0.00167 kWh) was recorded for the lowest parameter values (a_p = 10 mm and a_e = 1 mm).

The influence of machining parameters on energy consumption is illustrated in Fig. 2. It can be observed that increasing the milling width leads to an almost linear increase in energy consumption. A similar trend is observed for increasing values of depth of cut, although the relationship is slightly nonlinear. A more pronounced increase in energy demand can be observed at higher parameter combinations, which is expected due to the increased material engagement during the cutting process. Increasing both milling width and depth of cut enlarges the cross-sectional area of the undeformed chip.

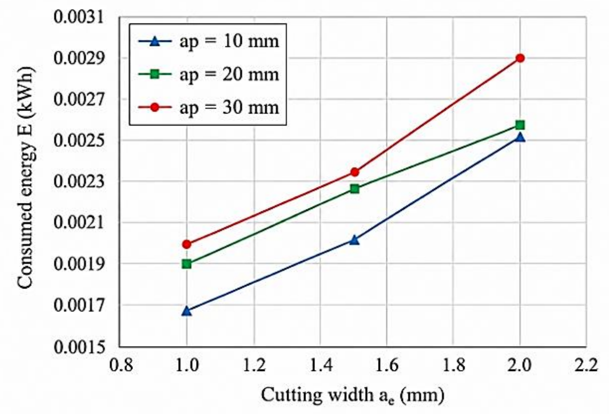

Fig. 2 Influence of cutting parameters on energy consumption.

Consequently, higher cutting forces are generated, leading to an increase in the required cutting power. Since the cutting speed and feed rate were maintained constant throughout the experiment, the observed changes in energy consumption can primarily be attributed to variations in the cutting force generated by different combinations of machining parameters.

Although larger cutting parameters increase energy consumption, they simultaneously increase process productivity by significantly increasing the material removal rate. This observation highlights the importance of balancing productivity and energy requirements when selecting machining parameters for high-efficiency milling applications.

From an industrial perspective, the obtained results indicate that energy consumption should not be considered independently from productivity indicators. Instead, both aspects should be simultaneously analysed in order to achieve sustainable and economically efficient machining processes. Such an approach is particularly relevant for modern manufacturing systems operating under Industry 4.0 principles, where energy efficiency and productivity are considered complementary rather than conflicting objectives.

3.2 Energy consumption modelling

Mathematical modelling was performed in order to establish a quantitative relationship between the selected machining parameters and electrical energy consumption during high-efficiency milling. Different model structures were evaluated in the Design Expert 7 software environment, and a linear model with two input parameters was selected due to its simplicity, adequacy and good agreement with the experimental data.

The developed regression model was obtained using the least squares method and can be expressed as:

$$E = 6{,}74 \cdot 10^{-4} + 1{,}72 \cdot 10^{-9} \cdot a_p + 8{,}13 \cdot 10^{-4} \cdot a_e \quad (1)$$

where (E) represents the electrical energy consumption (kWh), (a_p) is the depth of cut (mm), and (a_e) is the milling width (mm).

The obtained model indicates a positive relationship between both cutting parameters and energy consumption. An increase in either depth of cut or milling width results in a higher energy demand due to the increased material engagement during machining. Among the investigated factors, milling width exhibited a more pronounced influence on energy consumption within the selected parameter range.

In order to validate the developed regression model, an analysis of variance (ANOVA) was performed. The obtained statistical parameters are presented in Table 2. The obtained statistical indicators confirmed the significance of both the selected factors and the developed mathematical model. The low *p*-values and high *F*-values indicate that the selected parameters have a statistically significant effect on electrical energy consumption.

Furthermore, the coefficient of determination reached a value of ($R^2 = 0.974$), indicating a high level of agreement between the measured and predicted values. The obtained results demonstrate that the proposed model is capable of accurately describing the behaviour of the investigated process within the selected experimental domain.

Table 2 – *Analysis of variance (ANOVA) results for the developed energy consumption model.*

Source	SSD	DOF	MSD	F-value	p-value
Model	1.17×10^{-6}	2	5.86×10^{-7}	110.0	0.0001
Depth of cut, ap	2.38×10^{-7}	1	2.38×10^{-7}	33.9	0.0012
Milling width, ae	9.92×10^{-7}	1	9.92×10^{-7}	186.8	0.0001
Residual	3.19×10^{-8}	6	5.30×10^{-9}	–	–
Total	1.20×10^{-6}	8	–	–	–

3.3 Multi-objective optimization

Since the developed mathematical model demonstrated good agreement with the experimental results, it was subsequently used for process optimization. In rough milling operations, the primary objective is to remove the maximum amount of material within the shortest possible machining time while maintaining low energy consumption. Therefore, a multi-objective optimization approach was adopted to simultaneously maximize the material removal rate and minimize electrical energy consumption.

The optimization framework and the corresponding constraints are presented in Table 3. The investigated machining parameters, namely depth of cut and milling width, were kept within the experimentally defined domains. Material removal rate was selected as the parameter to be maximized, whereas electrical energy consumption was selected as the parameter to be minimized.

Table 3 – *Multi-objective optimization framework and constraints.*

Parameter	Objective	Lower limit	Upper limit	Lower importance	Upper importance
Depth of cut, a_p (mm)	In range	10	30	1	1
Milling width, a_e (mm)	In range	1.0	2.0	1	1
Material removal rate, MRR (mm^3/min)	Maximize	6000	36000	1	1
Energy consumption, E (kWh)	Minimize	0.00167	0.00291	1	1

Based on the defined objective functions and optimization criteria, several feasible solutions were obtained. The optimization procedure was performed using a desirability-based approach, where the optimal solution was determined by simultaneously satisfying both productivity and energy-related requirements.

Figure 3 presents the response surface generated from the developed empirical model. The response surface illustrates the combined influence of depth of cut and milling width on electrical energy consumption. As expected, increasing both machining parameters leads to higher energy consumption due to the increased material engagement during the milling process.

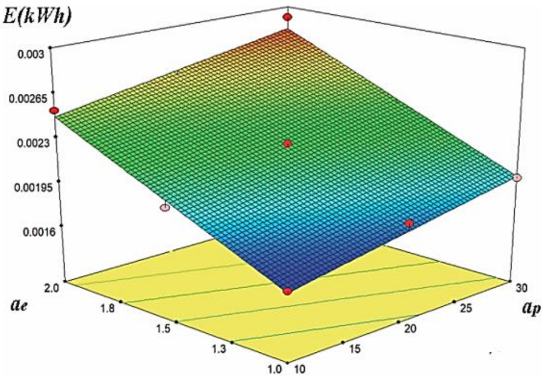

Fig. 3 *Response surface of the developed energy consumption model.*

The obtained solutions are presented in Table 4, while the desirability distribution is illustrated in Fig. 4. The results indicate that higher values of cutting parameters are generally favourable for increasing productivity, although they also lead to increased energy consumption. Therefore, the optimization procedure identifies a compromise solution that balances both objectives.

Table 4 – *Optimal solutions obtained for rough milling operations.*

Solution	a_p (mm)	a_e (mm)	MRR (mm³/min)	E (kWh)	Desirability
1	30.00	1.22	22027.92	0.002185	0.559
2	29.99	1.17	21065.54	0.002141	0.558
3	29.98	1.16	20999.23	0.002138	0.557

The optimal machining conditions were obtained for a depth of cut of (a_p = 30) mm and a milling width of (a_e = 1.22) mm. Under these conditions, a material removal rate of (22,027.92) mm³/min was achieved, while the corresponding electrical energy consumption was (0.002185) kWh.

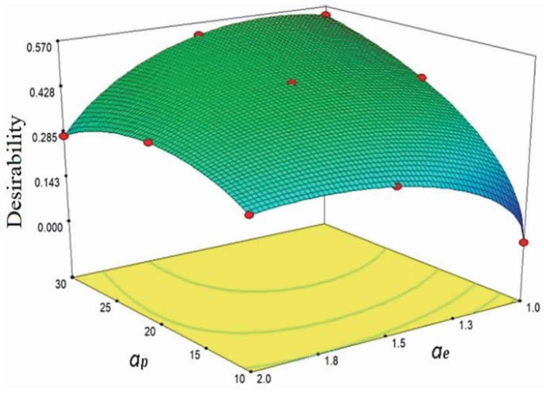

Fig. 4 *Desirability function for multi-objective optimization.*

The obtained results confirm that high-efficiency milling can simultaneously provide high productivity and acceptable energy consumption when appropriate cutting parameters are selected. This finding is particularly important for modern manufacturing systems, where energy efficiency and production performance are increasingly considered together during process planning.

From a practical perspective, the developed optimization methodology can support engineers in selecting machining parameters during rough milling operations. In addition, such approaches may serve as a basis for future implementation of intelligent decision-support systems within sustainable and Industry 4.0 manufacturing environments.

3.4 Practical implications for sustainable manufacturing

The obtained results demonstrate that the selection of machining parameters has a significant influence on both energy consumption and process productivity. Therefore, energy consumption should not be considered as an isolated performance indicator, but rather as an integral part of process planning and optimization.

From an industrial perspective, the proposed methodology can support the implementation of energy-efficient machining strategies, particularly during rough milling operations where large volumes of material must be removed within a limited production time. The developed empirical model enables engineers to estimate energy requirements in advance and select machining parameters according to production priorities.

The presented approach is also consistent with current trends in sustainable manufacturing, where the objective is to simultaneously improve productivity, reduce energy demand and minimize environmental impact. The optimization results indicate that an appropriate combination of cutting parameters can provide a satisfactory balance between these often conflicting objectives.

In addition, the developed modelling framework may serve as a basis for future integration with digital manufacturing systems and Industry 4.0 technologies. Real-time data acquisition, predictive analytics and intelligent process optimization may further improve the energy efficiency of machining operations and support data-driven decision making in modern manufacturing environments.

Although the present study was performed under specific machining conditions, the proposed methodology can be extended to other workpiece materials, cutting tools and machining strategies. Future research may include additional process variables, such as cutting speed, feed per tooth and cooling strategies, in order to develop more comprehensive energy prediction models.

4. CONCLUSION

In this study, an experimental investigation of energy consumption and productivity during high-efficiency milling was performed. The influence of depth of cut and milling width on electrical energy consumption was analysed under constant spindle speed and feed rate conditions.

The experimental results showed that increasing the cutting parameters increases the energy demand of the milling process. Lower values of depth of cut and milling width resulted in lower electrical energy consumption, whereas higher values increased the overall energy requirements. However, larger cutting parameters also contributed to a substantial increase in the material removal rate, indicating a direct relationship between productivity and energy consumption.

An empirical mathematical model describing electrical energy consumption was successfully developed and statistically validated. The high coefficient of determination ((R^2 = 0.974)) confirmed a strong agreement between the measured and predicted values, demonstrating the adequacy of the proposed model within the selected experimental domain.

Furthermore, a multi-objective optimization procedure was performed by simultaneously maximizing the material removal rate and minimizing energy consumption. The optimal machining conditions were obtained for a depth of cut of (a_p = 30) mm and a milling width of (a_e= 1.22) mm, resulting in a material removal rate of (22,027.92) mm³/min and an energy consumption of (0.002185) kWh.

The obtained results confirm that high-efficiency milling can provide a favourable balance between productivity and energy requirements when appropriate cutting parameters are selected. In addition, the proposed methodology may support process planning activities aimed at improving energy efficiency and reducing the environmental impact of machining operations.

The developed modelling and optimization framework may also serve as a basis for future implementation of sustainable manufacturing principles and Industry 4.0 technologies. Future research should include additional machining parameters, different workpiece materials and advanced monitoring systems in order to develop more comprehensive energy prediction models applicable to a wider range of industrial applications.

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