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Comparison of Automation-Supported and Conventional Methods for Measuring Energy Consumption in Computer Numerical Control Machining

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Abstract: Optimizing energy consumption in machining processes is critical for achieving sustainable manufacturing. This study introduces an Automation-Supported measurement approach that integrates a custom power analyzer with real-time data logging and visualization capabilities to accurately measure energy usage during CNC (computer numerical control) operations. Statistical comparisons were conducted using the independent samples *t*-test and Taguchi analysis to evaluate the effectiveness of the proposed method against traditional measurement techniques. The results revealed that there is a statistically significant difference ($p < 0.05$) in the current measurements across X, Z, and spindle motors between the proposed and conventional methods. The advanced method based on automation reduced the error rate in measuring spindle motor power consumption due to the selection of processing parameters from 34.17% to 2.7%. Additionally, Taguchi analysis demonstrated that the measurement method influenced the optimization of machining parameters, with S/N ratio improvements observed. These findings confirm that the proposed method enhances energy efficiency, reduces environmental impact, and supports sustainable manufacturing practices.

Keywords: energy consumption; measurement method; machining parameter optimization; automation; energy efficiency

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1. Introduction

Automation-Supported measurement integrates advanced automation technologies, real-time data collection, and advanced control systems into manufacturing processes. This approach enhances production efficiency by enabling precise data acquisition, adaptive optimization, and seamless machine-to-machine integration. The application of Automation-Supported systems in energy measurement improves accuracy, facilitates predictive maintenance, and enables proactive energy management, ultimately contributing to a sustainable and efficient manufacturing process [1–4]. The manufacturing industry consumes approximately 30% of global energy and contributes 36% of carbon dioxide emissions [5]. Figure 1 illustrates electricity consumption distribution by sector. Reducing energy use enhances machining efficiency [6], but achieving higher quality often demands more energy. Success lies in balancing power consumption with surface quality. Excess energy use increases costs

and emissions, prompting strategies to save energy in machining [7]. Key methods include optimizing cutting parameters: speed, feed rate, and depth of cut [8]. Careful analysis helps identify optimal settings to minimize energy while maintaining productivity and quality. In this context, this work emphasizes the critical importance of real-time measurement, utilizing advanced automation technologies to obtain accurate optimization data. This approach enables manufacturing businesses to efficiently balance energy consumption and production quality while promoting sustainability and reducing costs.

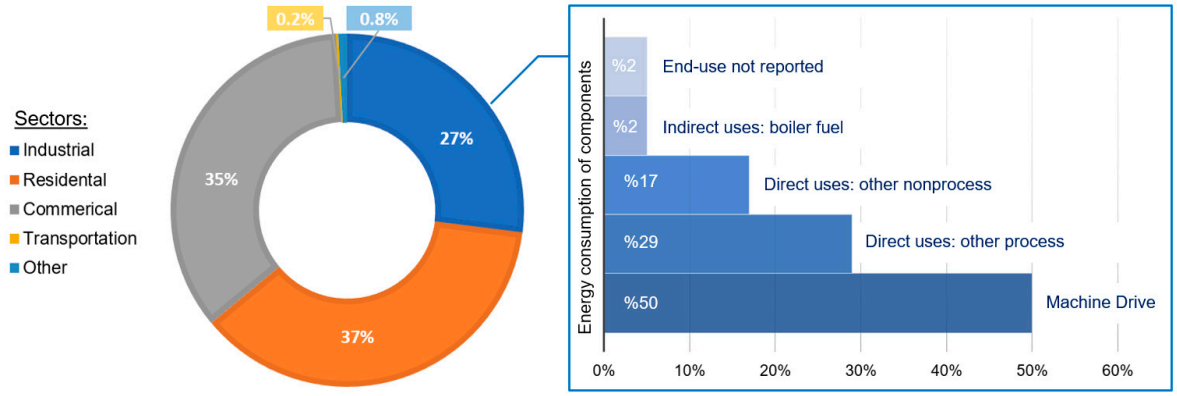


Figure 1. Electrical power consumption by sector [9].

Power measurements depend on various preconditions that affect the obtained data, and standardized test procedures are necessary [10]. Dahmus and Gutowski's energy analysis method separates the power demand of machine tools into three modes: standby, air-cutting, and cutting (Figure 2) [11]. The power demand for chip removal varies based on the machine's load. The electrical energy is consumed by various computer numerical control (CNC) components, including the controller, servo drive, control systems, fans, pumps, lighting elements, and coolant.

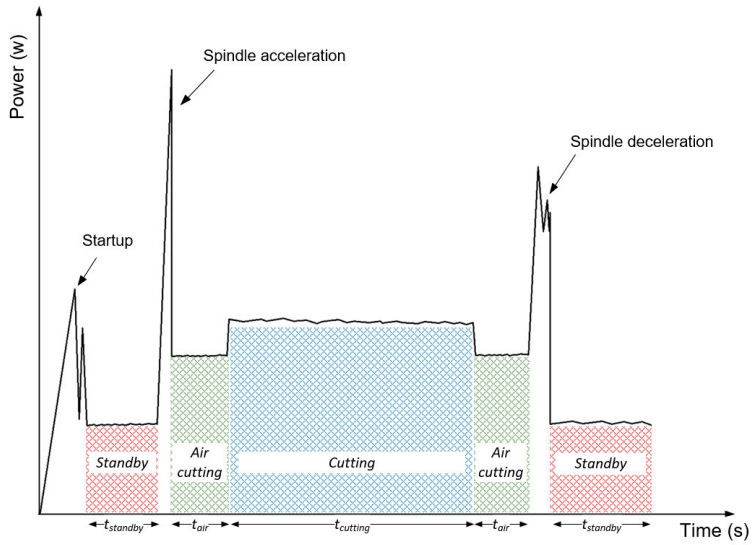


Figure 2. Power profile of a machine tool during machining [12].

Accurately measuring power consumption for machines and processes is crucial for optimization, as reliable data collection enables informed decision-making and effective analysis. For example, the servo drives responsible for chip removal account for 40% of the total power consumed from the main supply, while other CNC units utilize the remaining electricity in varying proportions (Figure 3) [13,14]. Axial and spindle motors

play a key role in achieving desired cutting parameters, such as cutting speed, feed rate, and depth of cut, by adjusting their speed and power accordingly. These motors operate at varying frequencies, adapting quickly to changes, which highlights the importance of precise power measurements.

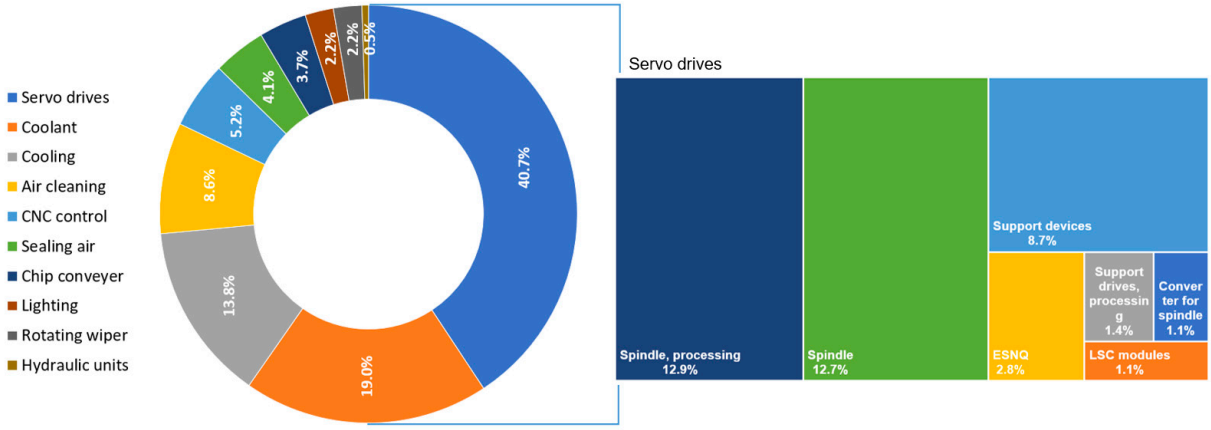


Figure 3. Electrical power consumption of main functions during machining [13].

2. State of the Art

Specific electrical energy consumption can vary significantly across machining processes. For instance, grinding requires higher specific cutting energy compared to turning or milling due to the cutting forces generated by the unique shapes of the tools involved [15]. This variability underscores the need for accurate measurement strategies that account for the energy consumed by axial and spindle motors, as these components are integral to improving cutting parameters and ensuring efficient operation.

Despite this, many studies measure power usage at the main phase (220 V), which may include contributions from non-cutting-related CNC components or omit the impact of variable frequencies, potentially leading to less precise characterizations. Akkuş and Yaka [16] investigated the effects of cutting parameters on energy consumption during the turning of Titanium 6Al-4V ELI alloy. They performed power measurements from the main input of the CNC machine using the Hioki Power Quality Analyzer PW3198 device and calculated it as the energy consumed per cycle. This method considers the energy consumed not only during cutting but also during the free movement of the cutting tool. Camposeco-Negrete [17] showed in his study that the success of wire electrical discharge machining (wire-EDM), an energy-intensive process, depends on selecting the correct processing parameters. The power measurements of the experimental study were carried out by connecting a power analyzer to the main switch of the wire-EDM device. Pan et al. [18] used power sensors to measure power consumption in their experimental studies, where they used different algorithms to estimate the energy consumption of a CNC machining process and improve the estimation performance. Pawanr et al. [19] developed an approach to model the energy consumption of machine tools during the machining of cylindrical parts and divided the energy consumption of the machine tool into different energy modules such as start-up, standby, spindle acceleration, cutting and auxiliary operations. In their study, they also examined the consumption of other energy modules, such as spindle acceleration and auxiliary operations, and measured the power using the Fluke 435 series II power analyzer directly from the main supply of the CNC machine tool. Cao et al. [20] obtained data from the mains via the WT1800 high-precision power analyzer. They developed an estimation method based on program decomposition and parallel neural networks to quickly and accurately estimate energy consumption in CNC milling operations. Feng et al. [21] developed an energy model covering cutting and

non-cutting energy consumption to optimize critical performance indicators such as energy consumption, processing time, and surface roughness in machining processes. The energy consumptions based on this model are carried out over the network using the WB-9128 three-phase power sensor.

Some studies have employed mathematical techniques to calculate net cutting energy, but these methods often assume ideal conditions and may fail to capture the consumption history of individual CNC components. Additionally, some studies have used nontrue-RMS (nontrue-root mean square) power meters or manual measurement methods, which, while valuable, may face challenges in achieving the resolution or realistic representation needed for accurately reflecting energy consumption. Edem and Balogun [22] investigated the effects of cutting-edge radius on specific cutting energy and surface quality in dry machining processes of aluminum AW6082-T6 alloy and AISI 1018 steel. The specific energy coefficient was calculated as an indicator of a sustainable milling process, and the surface quality of the machined parts was examined. Power measurements were made with a three-phase Fluke 434 power quality analyzer over the network, and specific energy coefficients were calculated from the power–material removal rate (MRR) graph. Nur et al. [23] proposed using measured cutting forces to calculate the electrical energy consumed in the machining of hardened stainless steel materials. They used a portable power monitor to determine the energy consumption per cutting operation and established the mathematical equation of the relationship between cutting force and energy consumption. In their study, where they aimed to optimize the cutting parameters for minimum surface roughness and energy consumption using a CNC milling machine, Öztürk and Kara [24] calculated the power consumption by utilizing the total Specific Energy Consumption (SEC) equation, which gives the relationship between the processing power and electric current in three-phase motors. Warsi et al. [25] developed a new specific cutting energy (SCE)-based process map for turning Al 6061 T6 alloy from the conventional to high-speed machining range by measuring the energy consumed by the CNC lathe from the mains using a standard power analyzer.

This study proposes an advanced Automation-Supported measurement methodology that provides real-time and high-precision power consumption measurement, making a significant contribution to the energy-efficient and sustainable machining process. Unlike traditional methods, this approach increases the measurement accuracy (92.1% reduction in error rate) and enables the optimization of processing parameters more efficiently. The statistical analyses show that the proposed methodology improves energy efficiency by determining the power consumption on the spindle and axis motors more accurately. In addition, the optimization techniques used contribute to the determination of cutting parameters at the most appropriate levels, supporting the production process to become more sustainable and economical. The findings support the approach in CNC energy measurement by providing higher precision, sustainability and process optimization compared to traditional techniques.

Energy Consumption Measurement Strategies

There are two basic methodologies for measuring energy consumption performed by CNCs, namely the Direct (a in Figure 4) and Indirect methods (b in Figure 4), which are widely preferred in the literature studies. In the Indirect measurement method, energy consumption measurements are measured from the main phase, while in the Direct measurement method, they are performed via the axis motors.

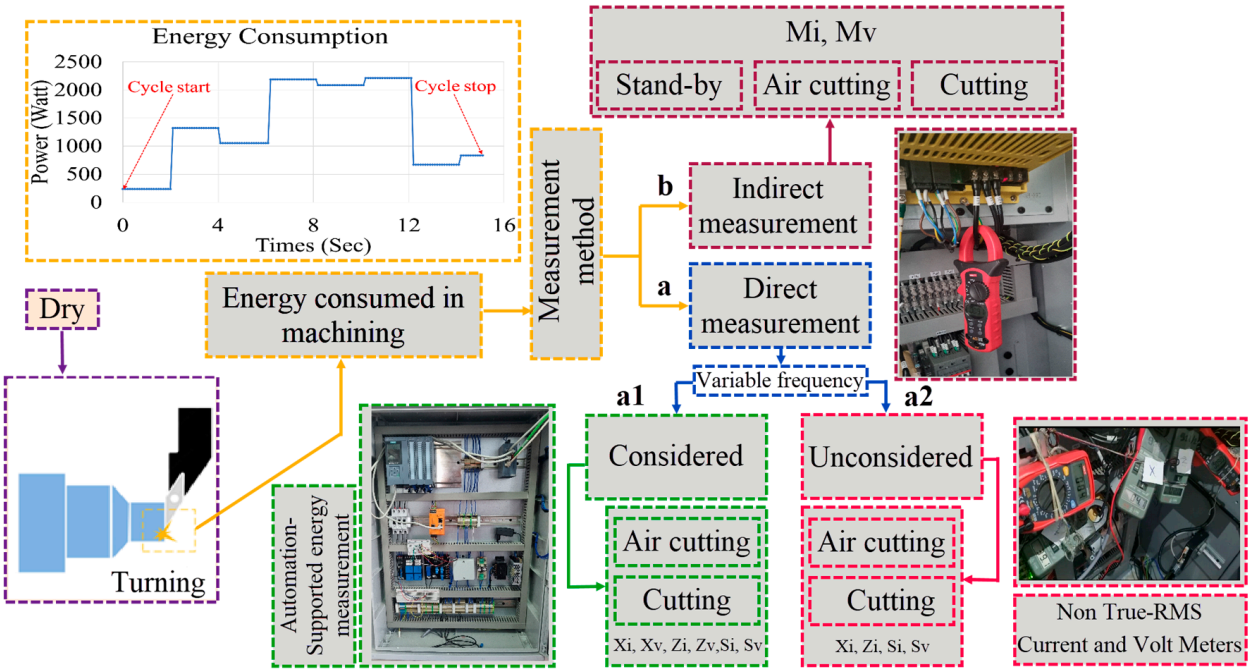


Figure 4. The framework of different energy measurement methods used in machining operation.

The Direct method is divided into two: the Considered method (a1 in Figure 4), which takes variable frequency into account, and the Unconsidered method (a2 in Figure 4), which does not consider it. Clamp-on ammeters and voltmeters are commonly used to measure the power consumed by CNC engines with the Unconsidered measurement method [22,26,27]. Measurements made with advanced power analyzers operating below 50 Hz are also included in this method. In the Unconsidered method, it may not be considered that servo motors have variable frequency, and the measuring instruments without True-RMS capability may be used.

The Considered method involves electrical measurements through the spindle and axis motors, similar to the Unconsidered method. However, in this method, the variable frequency control feature of the servo driver is considered, and True-RMS measurement devices are used to improve measurement accuracy. The terms 'Direct', 'Indirect', 'Considered', and 'Unconsidered' are widely used to classify measurement strategies in energy consumption studies related to machining but are not explicitly found in the literature; rather, they are utilized in this work to present measurement approaches in a structured and comprehensible manner.

Figure 4 outlines the energy measurement methodologies used during the standby, air-cutting, and cutting stages. The measured current and voltage are labeled according to their measurement locations. For instance, Mi and Mv indicate measurements taken from the main power supply, while Xi, Xv, Zi, Zv, Si, and Sv represent measurements obtained from the axis and spindle motors, respectively.

In the Indirect method (b in Figure 4), energy measurements are taken from the main phase of the CNC (Figure 4) [19,28]. The frequency of the main phase signals is constant at 50 Hz, so the devices used in the measurement do not need to be frequency-sensitive. However, all components of the CNC contribute to this energy consumption. It is necessary to remove the energy consumption not affected by chip removal from the total energy consumption to optimize the machining parameters for energy savings. Researchers use several Specific Energy Consumption (SEC) equations (Equation (1), general description) to calculate the amount of energy required to remove a unit volume of material in CNC machining [29]. SEC is affected by cutting parameters, tool material and geometry, and

the workpiece material. Optimizing these parameters can reduce energy consumption and increase machining efficiency.

$$\text{SEC} = \frac{\text{Total Energy Consumed}}{\text{Material Removed or Workpiece Surface Area}} \quad (1)$$

The measurement methodology is limited in assuming the CNC operates under ideal conditions. However, as is known, the energy consumption characteristics of CNCs may change due to unpredictable factors such as vibration and decreased operating performance of CNC components over time [30]. To optimize the cutting phase, researchers must measure spindle and axial motors, primarily related to the cutting parameters. The spindle and axial motors consume energy consumption, which is influenced by the pure cutting parameters.

The relationship between cutting parameters and motor energy consumption can be detailed as follows: The cutting speed is proportional to the spindle motor speed, and the cutting feed rate is proportional to the servo motor speed. To increase machining efficiency, increasing the cutting speed and feed rate is necessary to shorten the machining time. However, increasing the speed of the spindle and servo motors may cause more energy consumption. Elucidation of this complex relationship between cutting parameters and motor consumption energy is an essential energy-saving effort. As a result, determining motor energy consumption values is the primary factor in optimizing cutting parameters for energy efficiency [31].

The CNC servo drive supplies power to control the spindle and axial motors, ensuring efficient chip removal during cutting. It can rapidly adapt the electrical frequency to align with the material's characteristics and programmed specifications. It is important to note that the intensity of both current and voltage may fluctuate (Figure 2). Frequency changes in energy consumption measurements from axis motors can cause measurement errors. True-RMS meters provide accurate readings across various waveforms, including non-sinusoidal and distorted waveforms. This specification is crucial because many modern electronic devices generate non-sinusoidal waveforms, such as variable servo drives and switch-mode power supplies. Therefore, to capture and quantify dynamic electrical variations accurately, it is necessary to use measurement devices with True-RMS capability [32].

3. Materials and Methods

This study presents a statistical investigation based on experimental results to test the validity of an advanced Automation-Supported measurement method for energy efficiency in CNC machining. The framework of the experimental setup and statistical analysis used to evaluate different energy consumption measurement methods during processing is given in Figure 5. It outlines the machining parameters, experimental setup, measurement approaches, data collection process, and result visualization interface developed in the study.

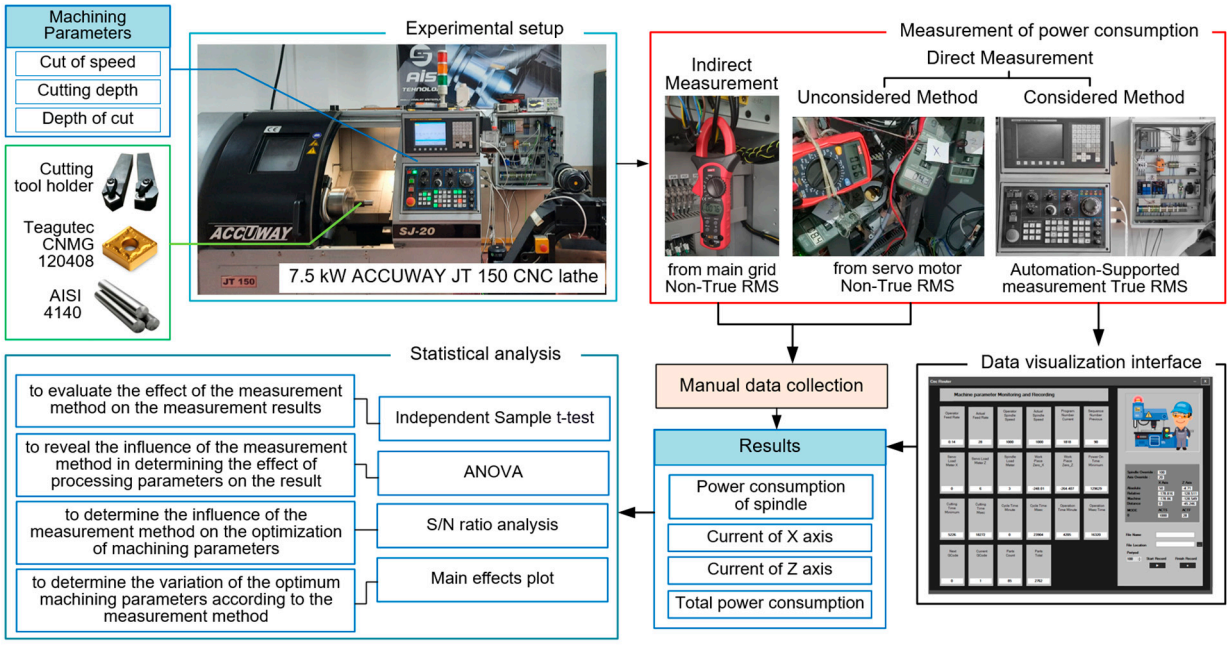


Figure 5. Research framework for the comparison of power consumption-measuring methods.

3.1. Materials and Machines

The experimental sample material for this investigation consisted of cylindrical specimens made of AISI 1045 steel, which was sourced from SH Technical Solution Engineering Industry and Trade Co., Ltd., located in Sakarya, Turkey. AISI 1045 is widely used in manufacturing due to its high strength, low ductility, and ready availability. The specimens had dimensions of Ø50 × 250 mm. The experimental procedures were executed with planning of the feed rate and depth of cut values to ensure a consistent chip volume throughout the experiments. Detailed information regarding the experiment design, parameters, measurement methodologies, measuring devices, and software programs used is presented in Table 1 of this study. Furthermore, Table 1 contains essential information, including the experiment parameters and their corresponding levels, the experiment design, and specifications for the cutting insert used in the study.

Table 1. Equipment and general information about the experimental study.

Machining Equipment and Conditions	Definitions
Material	AISI 4140
CNC lathe	ACCUWAY JT 150 7.5 kW
CNC controller model	FANUC^{TM} OI Mate-TD
Cutting tools	* Teagutec CNMG 120408-MT TT8125
Tool holder	* HSS Taegutec TCLNR 2525 M1204-F
Coolant	No coolant
Energy consumption-measuring device	Automation-Supported energy measurement tool
Cutting parameters	
(V) Cutting speed (m/min)	150, 180, 210, 240, 270, 300
(f) Feed rate f (mm/rev)	0.22
(a) Depth of cut a (mm)	1, 1.5

* sourced from SH Technical Solution Engineering Industry and Trade Co., Ltd., located in Sakarya, Turkey.

3.2. Experimental Setup

The system components that can perform real-time power measurements under variable frequencies and characterize the energy consumed during the cutting process according to the type of work performed are described in this section. System components

consist of two main parts: a custom power analyzer and a data visualization interface. The components of the designed system are shown in Figure 6.

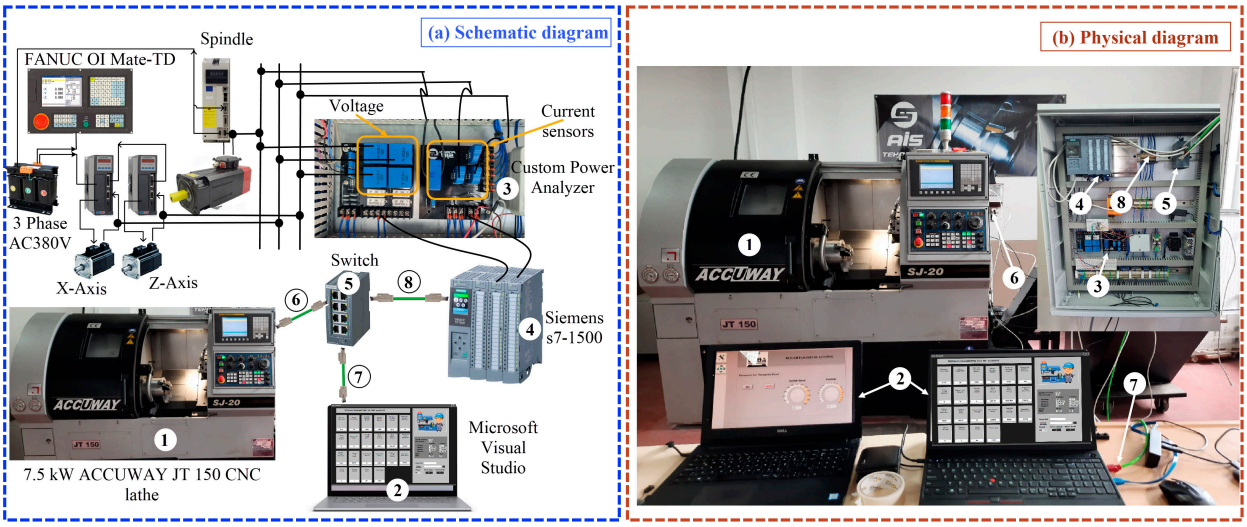


Figure 6. The components of the Automation-Supported energy consumption measurement system.

3.3. Development of the Custom Power Analyzer

The custom power analyzer (number 3 in Figure 6a,b) consisted of a current and voltage measurement board to calculate the power values over the axes (X and Z) and spindle motors during the cutting phase. Both boards can measure variable frequency current and voltage values for up to four axes (Figure 7). The main task of these cards is to reduce the high current (100 A) and voltage (500 V) values that occur in the motors during the cutting process to current and voltage levels that a microcontroller can measure. CNC milling and lathe machines have distinct motor powers for their spindle and axes. The spindle reaches the highest torque among the motors. Axis motors generally require lower torque compared to the spindle motor.

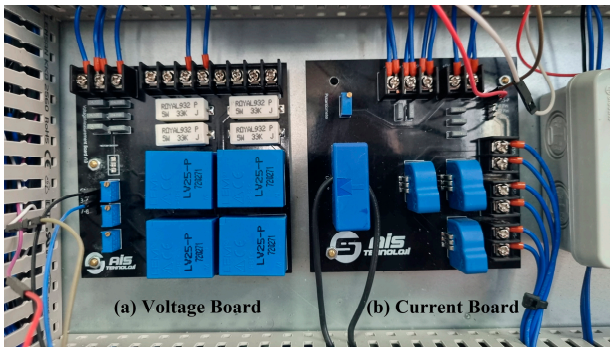


Figure 7. Components of the custom power analyzer: (**a**) voltage and (**b**) current measurement board.

The voltage measurement board also integrated four LEM voltage sensors, specifically the LV25-P model. During chip removal processes, these sensors accurately measured voltages reaching up to 500 V in each motor. The LV25-P sensor (sourced from Özdisan Electronics Inc., located in Istanbul, Turkey) effectively transformed these high voltage values into significantly lower current values. The output current from the LV25-P sensor was further converted to a 0–10 V voltage value by adding an appropriately adjusted resistor to facilitate effective voltage measurement. This conversion value provided seamless compatibility with the maximum input voltage value of the microcontroller.

Four LEM current sensors were utilized for the four-axis current measurement board. One sensor model was LA55-P, specifically employed to measure currents up to 55 amps in the spindle motor during chip removal processes. The other three sensors utilized were LTS15-NP, each capable of measuring up to 15 A for the axis motors, aligned with the technical specifications of the 7.5 kW CNC lathe. The LA55-P sensor's (sourced from Özdisan Electronics Inc., located in Istanbul, Turkey) distinguishing feature lies in its ability to handle higher amperage values encountered in the spindle motor, providing accurate measurements during demanding machining tasks. On the other hand, the LTS15-NP sensor (sourced from Özdisan Electronics Inc., located in Istanbul, Turkey), designed for axis motors, can directly convert its measured high amperage value to a 0–10 V output without requiring additional hardware. In contrast, the LA55-P sensor's output current value is converted to a 0–10 V output voltage level through an adjustable resistor, ensuring compatibility with the microcontrollers used in the system. In summary, the integration of the current measurement card equipped with these LEM current sensors facilitated the microcontrollers in efficiently measuring the spindle motor's 55A current and the three-axis motor's 15A currents, converting them into 0–10 V voltage levels for precise and comprehensive monitoring of the CNC lathe's power dynamics.

Siemens PLC (Programmable Logic Controller) s7-1500 microcontrollers (sourced from KNC Industrial Automation Technologies Trade Ltd. Co., located in Istanbul, Turkey) (number 4 in Figure 6) were utilized instead of standard microcontrollers like Arduino. This decision was based on the advantage that PLCs offer higher-resolution measurements capable of handling voltages at $\pm$10 V levels. The variable low-AC voltages obtained from the current and voltage board were efficiently converted into numerical data using the PLC with a high scanning speed of 1 KHz. The PLC software (Siemens Simatic TIA Portal V17) was strategically designed and implemented using the zero-crossing mode to precisely measure the variable AC voltage amplitudes. This approach allows for accurate detection of voltage changes at the points where the signal crosses zero, enabling reliable and real-time data acquisition.

The combination of the fast scanning speed and the zero-crossing mode implementation ensures the fidelity of the voltage measurements, enhancing the overall accuracy and reliability of the system. Moreover, the developed software incorporates PROFINET communication protocols, enabling seamless transfer of the converted current–voltage digital data to a computer. This integration facilitates efficient data exchange between the PLC system and the computer, allowing for real-time monitoring and analysis of the measured electrical parameters during the cutting phase.

3.4. The Implementation of the Data Visualization Interface

The developed interface (Figure 8) facilitates PLC-PC (personal computer) and CNC-PC communication, enabling real-time machining and measurement data visualization. This communication between the components ensures that energy consumption data are presented promptly and accurately, allowing operators to monitor and analyze the machining process effectively. The interface provides energy consumption, G code data, and essential machining data such as axis coordinates, machining times, and the number of parts (Figure 9).

An interface design was developed using Microsoft Visual Studio 2019 software to visualize and display electrical changes occurring during the machining process. The acquired data were transferred to the computer environment through OPC-Server, which was integrated seamlessly with the PLC and CNC controller. The successful implementation of FANUC^{TM} FOCAS (FANUC^{TM} Open CNC API Specification) Library dynamic link library (DLL) files within the OPC-Server facilitated the essential communication and data

exchange between CNC systems and external devices, such as computers or software applications. This enabled the interface to give users unproblematic access to an extensive range of CNC data and functions, streamlining vital tasks, including data collection, real-time monitoring, program management, and process optimization.

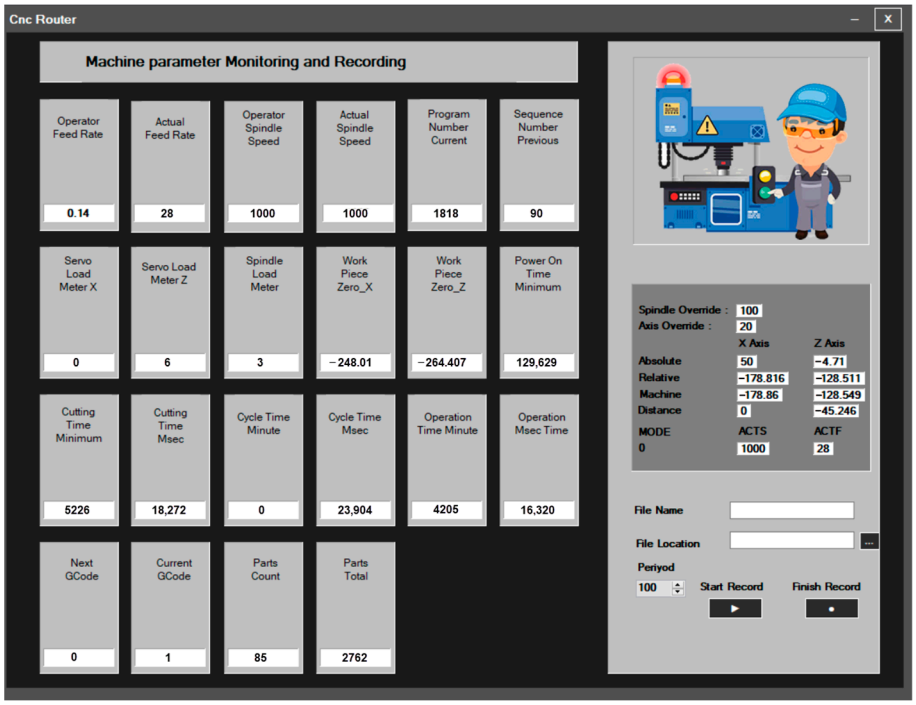


Figure 8. Data visualization interface designed for storing and visualizing data.

CYCLE START	ACTUAL FEED RATE	ACTUAL SPINDLE SPEED	CUTTING DEPTH	POZITION X	POZITION Z	G CODE CURRENT	SEQUENCE NUMBER CURRENT	PROGRAM NUMBER CURRENT	SPINDLE VOLTAGE	SPINDLE CURRENT	X AXIS CURRENT	Z AXIS CURRENT
TRUE	5000	1065	−10.781	−122.667	−10.781	0	50	1818	52.78759	4.488495	−0.8	0.84
TRUE	5000	1065	−10.781	−122.667	−10.781	0	50	1818	52.78759	4.488495	−0.8	0.84
TRUE	5000	1065	−10.781	−122.667	−10.781	0	50	1818	52.78759	4.488495	−0.8	0.84
TRUE	5000	2034	−80.113998	−180.440994	−80.113998	0	60	1818	93.886078	14.080505	0.16	1.66
TRUE	5000	2034	−80.113998	−180.440994	−80.113998	0	60	1818	93.886078	14.080505	0.16	1.66
TRUE	5000	2034	−80.113998	−180.440994	−80.113998	0	60	1818	93.886078	14.080505	0.16	1.66
TRUE	4643	2031	170.781006	−180.440994	−170.781006	0	60	1818	93.886078	14.080505	−0.31	1.66
TRUE	4643	2031	170.781006	−180.440994	−170.781006	0	60	1818	93.886078	14.080505	−0.31	1.66
TRUE	447	2033	195.419998	−182.440994	−195.419998	1	80	1818	115.7964	18.899399	−0.07	1.46
TRUE	447	2033	195.419998	−182.440994	−195.419998	1	80	1818	115.7964	18.899399	−0.07	1.46
TRUE	447	2033	195.419998	−182.440994	−195.419998	1	80	1818	115.7964	18.899399	−0.07	1.46
TRUE	447	2034	−212.237	−182.440994	−212.237	1	80	1818	111.33769	18.712418	−0.11	1.62
TRUE	447	2034	−212.237	−182.440994	−212.237	1	80	1818	111.33769	18.712418	−0.11	1.62
TRUE	447	2035	221.658005	−182.440994	−221.658005	1	80	1818	114.71144	19.287567	2.35	1.46
TRUE	447	2035	221.658005	−182.440994	−221.658005	1	80	1818	114.71144	19.287567	2.35	1.46
TRUE	447	2035	221.658005	−182.440994	−221.658005	1	80	1818	114.71144	19.287567	2.35	1.46
TRUE	7071	2034	−69.113998	0	−69.113998	0	100	1818	69.204285	9.681702	1.75	−1.47
TRUE	7071	2034	−69.113998	0	−69.113998	0	100	1818	69.204285	9.681702	1.75	−1.47
TRUE	7071	2034	−69.113998	0	−69.113998	0	100	1818	69.204285	9.681702	1.75	−1.47
TRUE	7071	2034	−69.113998	0	−69.113998	0	100	1818	69.204285	9.681702	1.75	−1.47
FALSE												

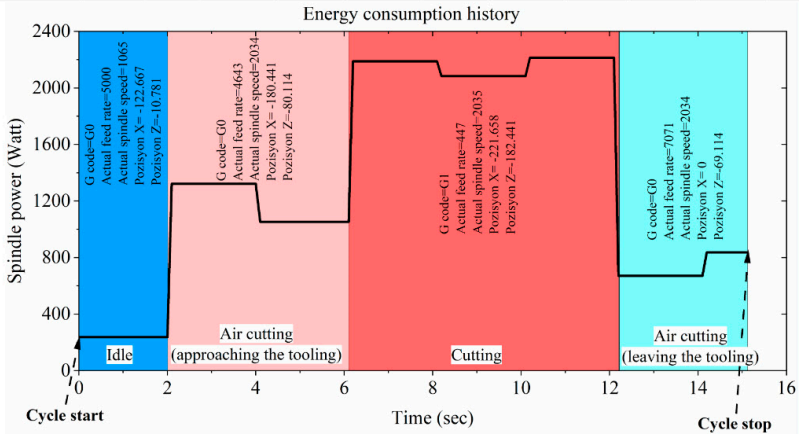


Figure 9. Real-time electrical and machining data obtained via data visualization interface.

In support of diverse connectivity requirements, the FANUC^{TM} FOCAS Library supports Ethernet and HSSB (High-Speed Serial Bus) communication protocols, imparting the desired flexibility for establishing connections with external devices to FANUC^{TM}-controlled CNC systems. While the developed system was explicitly tailored for CNC machines equipped with FANUC^{TM} OI Mate-TD controllers, its adaptability allows for seamless customization and implementation with other branded products, leveraging the corresponding products of the specific brand.

While real-time electrical and processing data obtained through the data visualization interface were collected, the process was automatically started according to the status data of the CNC and ended with the cycle start and stop information. Data were collected at 100 ms intervals, and some Excel lines were removed for simplicity. Energy consumption data were associated with CNC status data thanks to Automation-Supported measurement. Some of the data collected by the interface are presented in Figure 9 for clarity.

4. Results

4.1. Evaluation of Energy Consumption Characteristics of Measurement Methods

This study examines the performance of an Automation-Supported energy consumption measurement method that can perform operation-based measurements during CNC machining and compares it with other methods. For this purpose, three different energy consumption measurement methods, Indirect, Unconsidered, and Considered, were used in experimental studies. Our developed interface facilitated the automatic initiation of data recording at the commencement of the turning operation (cycle start) and automatic cessation at the operation's conclusion (cycle stop) for Automation-Supported measurements. In contrast, the two remaining methods involved manual processes: observation and data logging, as documented in existing literature.

The peak current in the spindle, X-axis, and Z-axis was found to be 22.98 A, 3.38 A, and 2.34, respectively, using Automation-Supported methodology (Figure 10). Similarly, when using the Unconsidered approach, the peak current was 21.7 A, 4 A, and 3.8 A for the spindle, X-axis, and Z-axis, respectively. Throughout the cutting phase, regardless of the measurement technique employed, the spindle motor consistently exhibited the highest current demand in all experiments, followed sequentially by the X- and Z-axes. However, there was a significant difference (predicted error) between the two measurement methodologies in the effect of experimental parameter variations on the current magnitude. For instance, the absolute percentage predicted error between spindle motor measurements reached 45.5% (illustrated by the blue line), while this discrepancy peaked at 110.5% for the X-axis and 167.6% for the Z-axis (Figure 10). The measurements were performed with Unconsidered and Automation-Supported methods, and the average current values in the cutting phase were used.

Figure 11 shows the average total power values consumed during the cutting phase using Automation-Supported and Indirect methods. The graph displays the total power consumption of the CNC main bus (represented by the red bars) and the axis and spindle motors (represented by the blue bar). The black line represents the percentage ratio of the total power drawn by the servo drive that supplies the required power to the motors to the total power drawn from the CNC main bus.

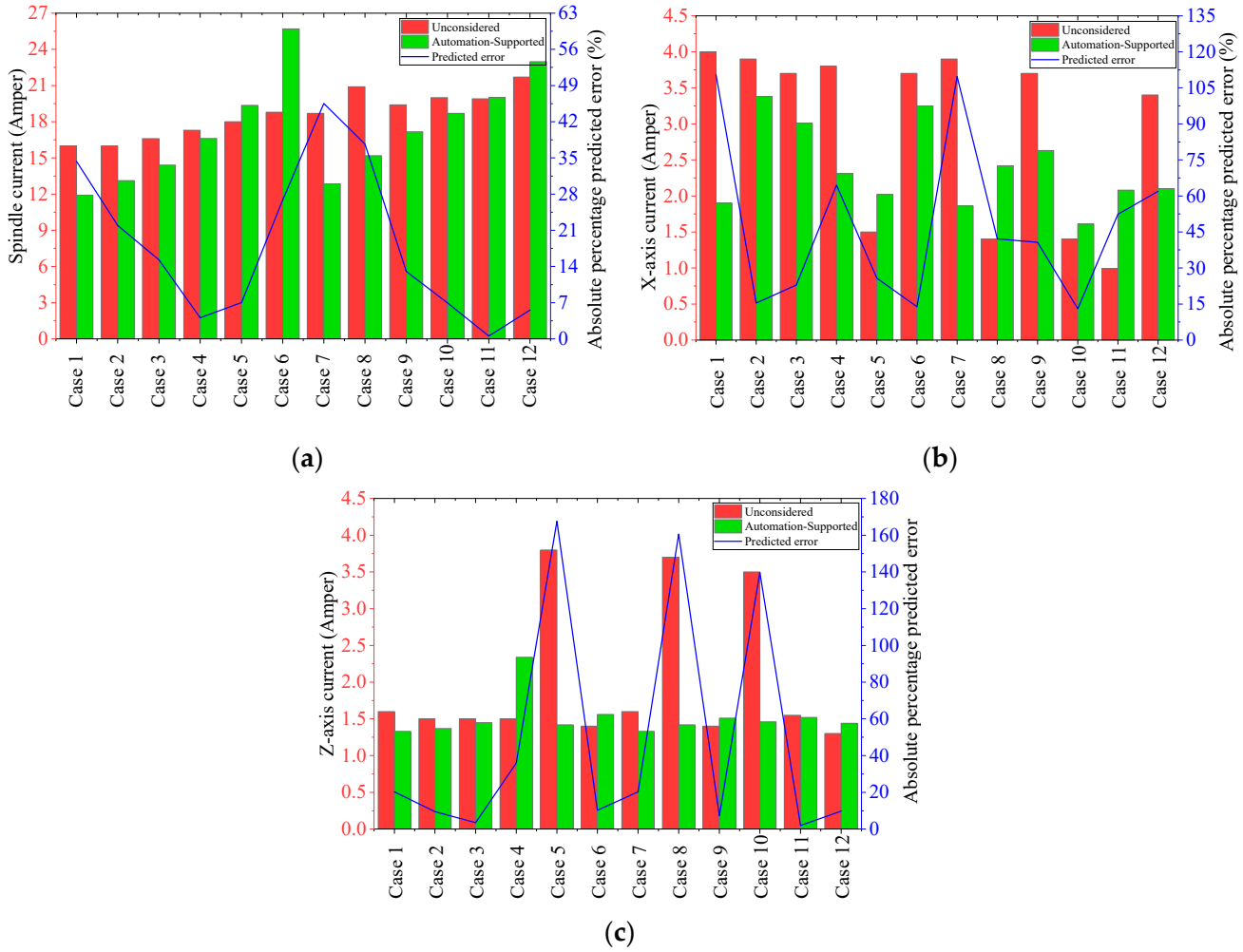


Figure 10. The average current values consumed by motors: (**a**) spindle, (**b**) X-axis, and (**c**) Z-axis motors. Prediction error was calculated using the formula "*absolute percentage predicted error (%) = |((Unconsidered − Automation-Supported)/Automation-Supported) × 100)|*".

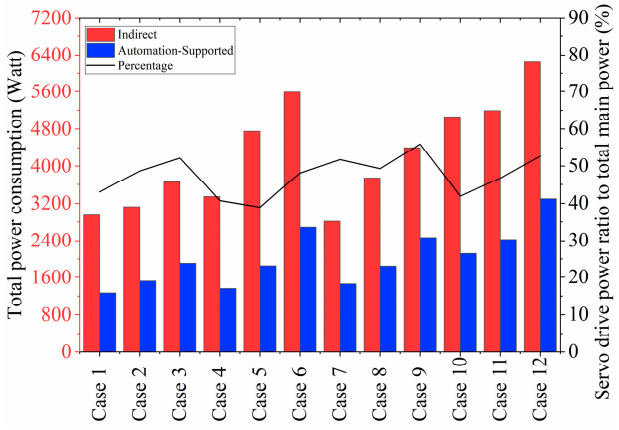


Figure 11. Average total power values were measured during the cutting phase.

The total power values measured from the main phase and the power consumed by the servo driver are shown in Figure 11. There was a linear relationship between Indirect and Automation-Supported, unlike the relationship between Unconsidered and Automation-Supported methods. This is due to the standard 50 Hz of the CNC main phase, which is not affected by variable frequency measurement. However, the total power calculated by the Indirect method also includes the power consumed by various CNC components, such

as the controller, fans, lighting elements, and coolant, which have no direct effect on the cutting parameter. In all experiments, the total energy consumed by the CNC components is higher than the total power consumed by the servo drive, confirming that the other components also consume energy. Moreover, the experiments showed that the power consumed by the servo driver ranged from 39% to 56% of the power consumed by the main phase, consistent with the rate of 40.7% in Figure 3 and reported in the literature [11]. It can be concluded that optimization of machining parameters based on CNC main phase power consumption evaluation may lead to inaccurate results.

The power consumption of the spindle motor during the cutting and air-cutting phases, as measured by the Automation-Supported and Unconsidered methods, is shown in Figure 12. Both measurements indicate that the spindle motor requires more power during cutting. The highest power requirement for the spindle motor in both methods was observed in Case 12. However, the highest power measured using the Automation-Supported method was 3274 W, while that measured using the Unconsidered method was 3711 W during the cutting phases. Additionally, the power values exhibited varying upward and downward trends and magnitudes depending on the measurement method used. For instance, according to Automation-Supported measurements, the spindle power during the cutting phase is 38.5% to 244.6% higher than during air-cutting. In contrast, Unconsidered measurements reported a range of 11.2% to 409.0%.

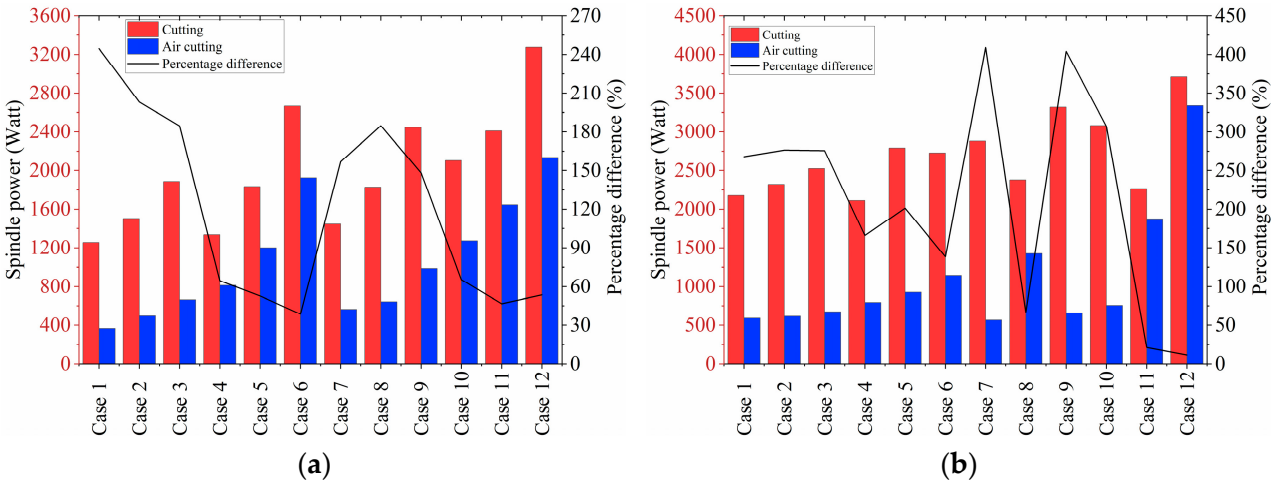


Figure 12. The power consumption in the spindle was measured using (**a**) Automation-Supported and (**b**) Unconsidered methods. The black line illustrates the percentage increase in spindle power consumption during the cutting phase compared to the air-cutting phase.

4.2. Statistical Evaluation of Measurement Methods

4.2.1. Independent Sample *t*-Test

The independent sample *t*-test is a parametric test used to determine whether a statistically significant difference exists between the group means of two related independent groups [33]. The independent sample *t*-test was conducted to test whether the effect of the measurement method (Unconsidered and Industry 4-based) on the results is statistically significant in measuring the amount of current consumed by the spindle motors with the X- and Z-axes.

The results of the independent sample *t*-test are given in Table 2. As a result of the test, it was determined that there was a statistically significant difference between the measurement methods in all of the current measurements taken by X, Z, and spindle motors at a 95% confidence level ($p < 0.05$). This result shows that the measurement method significantly affects the measurement results for all axis motors.

Table 2. Independent sample *t*-test results.

	Levene's Test for Equality of Variances		***t*-Test for Equality of Means**		
	***f*-Value**	***p*-Value**	***t*-Value**	**Dof**	***p* (2-Tailed)**
Current in X-axis	15.941	0.0006	1.464 1.464	22 15.658	0.157 0.163
Current in Z-axis	15.256	0.0007	2.265 2.265	22 13.324	0.034 0.041
Current in Spindle	6.058	0.022	0.956 0.956	22 15.190	0.349 0.354

4.2.2. Analysis of Variance

Analysis of variance (ANOVA) is a statistical approach used to examine the difference in means between one dependent variable and one or more independent variables. In ANOVA, the dependent variable is the response variable, and the independent variables are the factors [34,35]. Different values of the independent variables are determined as factor levels. ANOVA was performed to reveal the measurement method's effect in determining the machining parameters' impact on the result (Table 3). The contribution (%) value calculated for each machining parameter in the table indicates the impact of each factor on the total result [36]. In addition, as a result of the independent sample *t*-test for total power consumption, it was found that there was a statistically significant difference between these two measurements at a 95% confidence level ($t = 5.995$, $p < 0.05$).

Table 3. Analysis of variance of total power consumption.

	Factor	**DoF**	**SS**	**MS**	***f*-Value**	***p*-Value**	**Contribution (%)**
Indirect method	Cut of speed	5	11,789,836	2,357,967	13.10	0.007	83.87
	Cutting depth	1	1,368,225	1,368,225	7.60	0.040	9.73
	Error	5	899,895	179,979			6.40
	Total	11					100.00
Automation-Supported	Cut of speed	5	3,215,320	643,064	30.05	0.001	78.81
	Cutting depth	1	757,519	757,519	35.40	0.002	18.57
	Error	5	106,996	21,399			2.62
	Total	11					100.00

The analysis of variance showed that the measurement of the total power consumption and the measurement method did not significantly change the effect of the machining parameters on the result. However, experimental test results show that the measurement method changes the effect of processing parameters on the amount of current drawn by the spindle motor (Table 4).

The error of variance analysis shows the difference between an observed variable and the estimated value calculated by the model. Variance analysis results show the effect of the measurement method on the power consumption of spindle motors, especially those responsible for the cutting process. It was insufficient to explain the optimization-oriented variance of the power consumption of spin engines through machining parameters. While the error rate of machining parameters in describing the power consumption of spindle motors was 34.17% in measurements made with the Unconsidered method, this rate decreased to 2.7% in measurements made with the Automation-Supported method. This result shows that the measurement results produced with the Unconsidered method are more affected by factors other than machining parameters.

Table 4. Analysis of variance of power consumption in spindle.

	Factor	Dof	SS	MS	*f*-Value	*p*-Value	Contribution (%)
Unconsidered	Cut of speed	5	1,020,083	204,017	1.12	0.454	38.10%
	Cutting depth	1	742,588	742,588	4.06	0.100	27.73%
	Error	5	914,859	182,972			34.17%
	Total	11					100.00%
Automation-Supported	Cut of speed	5	3,193,667	638,733	29.09	0.001	78.51%
	Cutting depth	1	764,346	764,346	34.82	0.002	18.79%
	Error	5	109,772	21,954			2.70%
	Total	11					100.00%

R-squared (R^2) is a statistical measure indicating the variation in a dependent variable due to an independent variable. In other words, R^2 indicates how well a regression model predicts observed data [37]. At the same time, the results for the measurement performed with the Unconsidered method were calculated as R^2 = 24.83%, and for the Automation-Supported measurement method, R^2 = 94.06%. These values show that the results obtained with the Unconsidered method do not explain the relationship between machining parameters and spindle energy consumption values.

In short, Tables 2–4 demonstrate a significant difference between the proposed and conventional methods. The difference was slight in the Indirect measure but significant in the Unconsidered measure. Although the Unconsidered measurement was performed through the servo driver, the difference in the result increases due to the variable frequency phenomenon (True-RMS effect) not being handled. However, the Indirect measurement via the CNC main phase (with a constant 50 Hz) performed more closely to the recommended method in capturing electrical variations. Nonetheless, this method may predict the total power consumed by all components of the CNC. Therefore, it cannot predict the power consumed by the axial and spindle motors, which are directly related to the cutting parameter.

4.2.3. Taguchi S/N Ratio Analysis

The Taguchi S/N ratio analysis uses various objective functions to evaluate the system's performance under study [38]. These functions include 'smaller is better,' 'larger is better', and 'nominal is better'. The signal-to-noise (S/N) ratio is a performance measure used to optimize the process. Experimental results were evaluated using the signal factor (S) as the actual value obtained from the system and the noise factor (N) as a factor representing the effect of parameters outside the experimental design affecting the result [39,40]. The noise factor refers to the variables that prevent reaching the targeted optimum result.

In this study, Taguchi S/N ratio analysis was performed to determine the effect of the measurement method on optimizing machining parameters. "Smaller is better" objective functions are selected to minimize the power consumption of the spindle according to the measurement method. Equation (2) illustrates how to calculate the S/N ratio [41]:

$$S\ /\ N = (-10) \times log_{10}\left(\frac{1}{n}\right) \sum_{i=1}^{n} y_i^2 \quad (2)$$

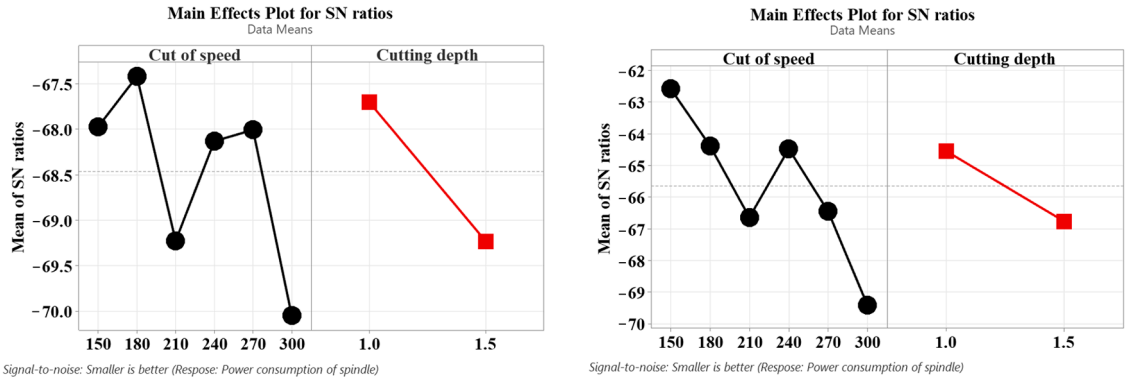
where n represents the number of runs and y_i represents the response for a specific factor-level pattern.

The results of the S/N ratio analyses are shown in Table 5. The tables provide the calculated S/N ratios for different output values. Factor levels determined to obtain optimum output values are in bold in the table. The difference between the largest S/N

ratio and the smallest S/N ratio of each parameter is given in the delta line of the table. The parameter with the largest delta value shows the most influential parameter on the output [42]. The factor level at the top of the S/N ratio analysis plots in Figure 13 gives the effective factor level to obtain the optimum output value.

Table 5. S/N ratio analysis for power consumption of spindle.

Response	Level	Cut of Speed	Cutting Depth	Level	Cut of Peed	Cutting Depth
Power consumption of spindle	1	−67.97	−67.70	1	−62.59	−64.55
	2	−67.42	−69.23	2	−64.39	−66.77
	3	−69.23		3	−66.64	
	4	−68.13		4	−64.49	
	5	−68.01		5	−66.45	
	6	−70.05		6	−69.41	
	Delta	2.63	1.53	Delta	6.82	2.22
	Rank	1	2	Rank	1	2
Measurement method		Unconsidered			Automation-Supported	



(**a**) (**b**)

Figure 13. Main effect plot for S/N of spindle power consumption according to measurement method: (**a**) Unconsidered and (**b**) Automation-Supported.

The S/N ratio graphs show the effect of the measurement method in optimizing the amount of energy consumed by the spindle via machining parameters. According to the results of the analysis carried out using the Unconsidered method and the S/N ratio analysis, the optimum cutting speed was determined to be 180 mm/rev. In comparison, the optimum cutting speed was calculated as 150 mm/rev for the analysis carried out according to the Unconsidered method (Figure 13). These results show that the correct choice of measurement method is essential for optimizing machining parameters.

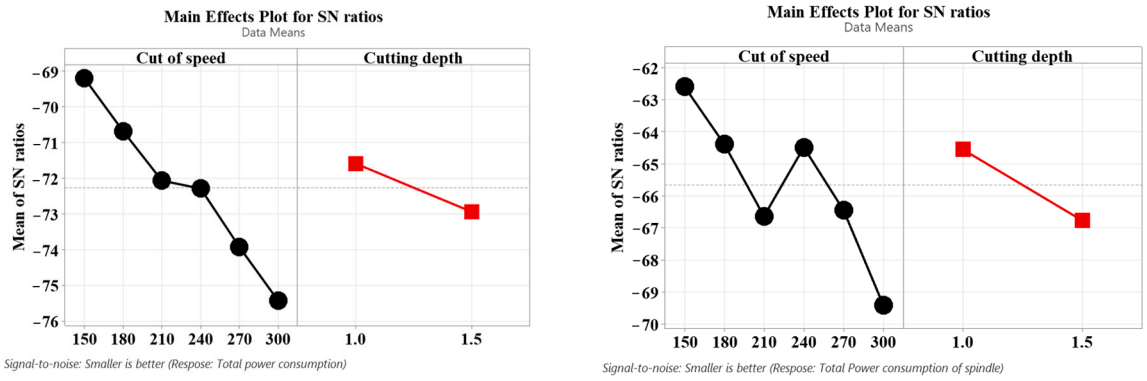
The results of the S/N ratio analyses performed for total power consumption measurements are given in Table 6. The results show that the measurement method does not change the optimum machining parameter level for optimizing the total power consumption. However, the measuring method mainly determined the effect of different levels of cutting speed on energy consumption (Figure 14).

The Unconsidered method showed the least successful results in optimizing the machining parameters for the lowest electricity consumption using statistical analysis (Figure 13 vs. Figure 14). This is because the servo variable frequency was not considered in this measurement method, leading to an increased error rate in the results and reducing the success of the optimization. However, the variable frequency effect does not need to be considered since the Indirect measurement was conducted at a constant frequency (50 Hz). This can result in more accurate predictions of the results. It is important to note that the

Indirect measurement, which measures total consumption, may differ from the proposed method of estimating the S/N ratio. The variation in electrical consumption of components other than the servo drive for each chip removal operation may cause differences in S/N ratio estimation. This difference can naturally affect the optimization performance.

Table 6. S/N ratio analysis for total power consumption.

Response	Level	Cut of Speed	Cutting Depth	Level	Cut of Speed	Cutting Depth
Total power consumption		−69.19	−71.58		−62.67	−64.65
		−70.68	−72.94		−64.48	−66.84
		−72.06			−66.72	
		−72.28			−64.61	
		−73.92			−66.52	
		−75.43			−69.47	
	Delta	6.24	1.35	Delta	6.80	2.18
	Rank	1	2	Rank	1	2
Measurement method		Indirect			Automation-Supported	



(**a**) (**b**)

Figure 14. Main effect plot for S/N of total power consumption according to measurement method: (**a**) Indirect and (**b**) Automation-Supported.

The limitations of this study may be attributed to the complex components of the Automation-Supported measurement scheme. This complexity may also cause difficulties in applying this method, as it is based on a combination of many disciplines, such as software, electronics, and mechanics. However, sustainable production needs and technological advancements may allow for the development of compact power analyzers that communicate with CNC machines, making them user-friendly. The present study may significantly contribute to the literature in this field.

5. Conclusions

Accurate measurements of CNC power consumption provide valuable insights into the efficiency of machining processes, allowing manufacturers to optimize cutting parameters. By precisely monitoring power usage during CNC operations, engineers can identify ideal cutting speeds, feeds, and tooling strategies to maximize productivity, minimize energy consumption, and extend the lifespan of equipment, contributing to both cost savings and sustainable manufacturing practices.

This study presents a measurement method based on advanced automation technologies to take real-time measurements by communicating with the CNC. This communication can correlate electrical consumption data with CNC process data. The effectiveness of

this proposed method has been demonstrated by comparing it with traditional measurement methods. The comparison procedure was achieved by performing statistical and optimization studies. The outcomes of this study can be summarized as follows.

- The independent sample *t*-test showed that the measurement method had a statistically significant effect on the measurement results for all axis motors ($p < 0.05$).
- The analysis of variance showed that for the measurement of the total power consumption, the measurement method did not significantly change the influence of the machining parameters on the result.
- The analysis of variance performed for the measurement of the current drawn by the spindle motor showed that the measurement method significantly influenced the effect of the machining parameters on the result.
- While the error rate of machining parameters in explaining the power consumption of spindle motors was 34.17% in measurements made with the Unconsidered measurement method, this rate decreased to 2.7% in measurements made with the Automation-Supported method. This result shows that the measurement results produced with the Unconsidered method are more affected by factors other than machining parameters.
- In this study, Taguchi S/N ratio analysis was performed to determine the effect of the measurement method on the optimization of machining parameters. S/N ratio values showed that the measurement method changes the optimum machining parameters to optimize the amount of energy consumed by the spindle through machining parameters.

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Abbreviations

The following abbreviations are used in this manuscript:

CNC	Computer numerical control	V	Cutting speed (m/min)
PC	Personal computer	f	Feed rate f (mm/rev)
RMS	Root mean square	a	Depth of cut a (mm)
SEC	Specific Energy Consumption	R^2	Correlation coefficient
HSSB	High-Speed Serial Bus	F-test	The frequency test
PLC	Programmable Logic Controller	p-value	Significance level
API	Application Programming Interface	t-value	Size of the difference relative to the variation
ANOVA	Analysis of variance	DoF	Degree of freedom
SS	The sum of squares	S	Signal
MS	Mean squares	N	Noise

MRR	Material removal rate	*t*-cutting	Cutting time
DLL	Dynamic link library	*t*-standby	Standby time
Mi	Current in main grid	*t*-air	Air-cutting time
Mv	Voltage in main grid	Zi	Current in Z-axis
Xi	Current in X-axis	Zv	Voltage in Z-axis
Xv	Voltage in X-axis	Si	Current in spindle motor
		Sv	Voltage in spindle motor

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