

Implementation of Preventive Maintenance for CNC Machines in Vocational Education Facilities: A Case Study at Politeknik Kampar

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Article Information	ABSTRACT
Article History Received : August 20, 2025 Revised : October 04, 2025 Published : October 10, 2025	This research aims to optimize the preventive maintenance system for CNC machines in the context of vocational education, with a focus on improving practice efficiency and reducing downtime. The study was conducted at Politeknik Kampar using a quantitative-descriptive approach integrated with a case study method. Quantitative data were obtained from machine performance logs, including total operating hours, number of breakdowns, and maintenance time before and after preventive maintenance implementation. Descriptive data were gathered through structured interviews and direct observation of CNC training sessions. The research focused on two types of machines, namely the CNC Milling HURCO VM 10 and the CNC Turning Center SKT 160A, which are intensively used in practical training activities. Prior to the implementation of the preventive maintenance protocol, the existing maintenance system was reactive and unscheduled, leading to frequent breakdowns and extended operational downtime. Following the implementation of the preventive maintenance program over a six week period, the frequency of machine breakdowns decreased by approximately 45%, and average downtime was reduced from 6.2 hours to 3.4 hours per week. Consequently, practice efficiency increased by about 28%, as reflected in the higher completion rate of student machining tasks within the allocated schedule. Student involvement in daily maintenance also contributed to building practical awareness of the importance of maintenance in industrial settings. The findings demonstrate that preventive maintenance not only enhances machine reliability but also strengthens vocational learning processes based on hands-on skills.
Keywords: <i>Preventive maintenance; CNC machines; Practice efficiency; Downtime; Vocational education.</i>	

INTRODUCTION

In the era of the Fourth Industrial Revolution, digital transformation has fundamentally reshaped the landscape of the manufacturing industry. One of the key pillars of this transformation is the automation of production processes through the utilization of computer numerical control (CNC) machines (Soori et al., 2024). CNC machines are capable of performing cutting, turning, drilling, and other complex machining operations with high levels of accuracy and repeatability (Febrianton et al., 2024). These advantages position CNC machines as strategic components in modern production systems, particularly in industries that demand high precision such as automotive, aerospace, medical equipment, as well as the metalworking and general manufacturing sectors (Armstrong et al., 2022).

However, as dependence on CNC machines increases, new challenges also emerge in terms of operational reliability, energy efficiency, and minimizing downtime. Downtime, whether planned or unplanned, is one of the most significant barriers to productivity (Bafandegan Emroozi et al., 2025). Empirical studies in the manufacturing sector have shown that more than 40% of production time losses are caused by machine failures, most of which can in fact be prevented through an effective maintenance system (Hardt et al., 2021). In this context, CNC machine maintenance can no longer be regarded as a secondary activity but rather as a strategic process integrated into the overall production management system.

Optimizing CNC machine maintenance requires a systematic and data-driven approach. Traditional strategies such as breakdown or corrective maintenance, in which repairs are carried out only after failures occur, have proven inefficient as they often lead to secondary damage, time losses, and high operational costs (Ahmed Murtaza et al., 2024). Consequently, more proactive approaches are required, including preventive maintenance (scheduled maintenance to prevent failures) and predictive maintenance (maintenance based on predictions of the machine's actual condition) (Romiyadi, 2025) (Teixeira et al., 2020). Both approaches enable interventions before serious disruptions occur, thereby extending machine lifespan, ensuring consistent production quality, and reducing the risk of costly downtime (Friederich & Lazarova-Molnar, 2024).

Beyond purely technical aspects, the optimization of CNC machine maintenance also extends to organizational, managerial, and cultural dimensions. Factors such as technician competence, consistency in maintenance record-keeping, discipline in implementing standard operating procedures (SOP), and top management support for investments in maintenance technologies are critical (Rakes et al., 2024). Many maintenance initiatives fail not due to technological shortcomings, but rather because of weak inter-unit coordination, fragmented information systems, or resistance to change among human resources (Romiyadi & Irwan, 2020) (Nawir et al., 2022) (Romiyadi et al., 2023). Therefore, optimization strategies must be designed with a holistic perspective that integrates maintenance system engineering, human resource development, and business process restructuring to ensure sustainable operations (Garrido et al., 2024).

On the other hand, global environmental challenges such as the energy crisis and increasing pressure on resource efficiency have driven industries to focus not only on productivity but also on energy efficiency and carbon emission reduction (Adu et al., 2023). Optimal CNC machine maintenance contributes to these efforts, as well-maintained machines operate under optimal conditions, consume energy more efficiently, and generate less waste (Lestari & Cahyono, 2025). In this context, machine maintenance affects not only technical performance but also serves as an integral part of sustainability strategies in the industrial sector.

This study aims to optimize the preventive maintenance system for CNC machines in vocational education facilities by designing a systematic protocol and analyzing its impact on machine operational performance. The case study was conducted at Politeknik Kampar, focusing on improving the efficiency of practical learning sessions and reducing downtime. A structured, needs-based maintenance strategy is expected to prevent equipment failures, enhance machine reliability, maintain the quality of practical outputs, and strengthen long-term operational competitiveness.

RESEARCH METHODS

Research Approach

This research adopted a descriptive-quantitative approach with a case study design to evaluate the effectiveness of preventive maintenance for CNC machines at Politeknik Kampar. The study focused on two units, CNC Milling HURCO VM 10 and CNC Turning Center SKT 160A over a six week observation period. The research process consisted of four structured phases:

1. Collecting baseline data on failure frequency, downtime duration, and maintenance records under the existing corrective system.
2. Designing a preventive maintenance protocol based on manufacturer specifications and expert input.
3. Implementing the protocol through scheduled inspections, cleaning, and component checks.
4. Evaluating post-implementation results by comparing operational indicators.

Quantitative data, including the number of machine failures, total downtime hours, and practice efficiency rates, were recorded weekly and analyzed descriptively to measure performance improvements.

Research Location and Subjects

This study was conducted in the CNC Laboratory of the Machine Maintenance and Repair Study Program at Politeknik Kampar, located in Kampar Regency, Riau Province. The site was selected because the laboratory is actively used for machining practice and industry-competency-based skills training. In addition to serving as a learning support facility, the laboratory also functions as a venue for developing students' technical skills in CNC machine operation and maintenance.

The research subjects consisted of three groups directly involved in CNC machine usage and maintenance:

1. Laboratory technicians and instructors, responsible for machine maintenance and supervision of machine usage.
2. Student machine operators, who operate CNC machines during practical sessions and directly experience the machines' operational conditions.
3. Course instructors, particularly those teaching CNC practice and Machine Maintenance Practice courses, who understand the standards of machine usage and maintenance requirements within the learning process.

Types of CNC Machines

This study focused on the CNC Turning Center SKT 160A and the CNC Milling HURCO VM 10, which play a crucial role in learning activities and small-scale production practice. These machines were selected due to their high utilization, particularly during students' operational training. As a result of this intensive use, the machines often experience performance degradation, especially when not accompanied by scheduled and structured maintenance. Therefore, an appropriate maintenance system is required to maintain machine performance stability and support the smooth execution of laboratory learning activities.



Figure 1. CNC Turning Center SKT 160A



Figure 2. CNC Milling HURCO VM 10

Types and Sources of Data

In this study, the data used were classified into two main types: primary and secondary data. Both types were collected to provide a comprehensive overview of the actual CNC machine maintenance conditions, covering both technical aspects and user experiences in the field. The details of the data sources are as follows:

1. Primary data were obtained through:
 - Direct observation, used to record the frequency of maintenance activities, component conditions, and machine downtime duration.
 - Structured interviews with laboratory technicians and instructors to identify maintenance issues and current repair patterns.
 - Questionnaires distributed to students to collect measurable responses on machine usability, operational stability, and perceived maintenance effectiveness, using a Likert scale ranging from 1 (very poor) to 5 (excellent).
2. Secondary data were obtained from laboratory records, including maintenance logs, malfunction reports, operational time records, and standard operating procedures (SOPs) for CNC machine operation and maintenance. These documents were used to verify observed conditions and provide supporting numerical data for downtime and maintenance frequency analysis.

Data Collection Techniques

To obtain relevant and comprehensive data for this study, several complementary data collection techniques were employed. These techniques were designed to gather information from various sources, both directly through interactions with research subjects and indirectly through available laboratory documents. The data collection methods used included:

1. Direct observation, conducted to monitor actual machine maintenance processes, the real condition of CNC machines, and students' operational practices in the laboratory.
2. Semi-structured interviews, conducted with laboratory technicians and course instructors to explore technical challenges, maintenance habits, and requirements for an ideal maintenance system.
3. Questionnaire distribution, targeted at student machine users to evaluate their experiences in operating CNC machines and to assess the effectiveness of the maintenance implemented.

4. Document review, carried out by examining historical data, such as machine failure records, downtime durations, and students' practical results, to provide an overview of machine performance over time.

Data Analysis Techniques

The data were analyzed using a quantitative-descriptive approach supported by basic statistical methods to objectively evaluate the performance of CNC machines before and after the implementation of the preventive maintenance protocol. The analysis process consisted of several stages:

1. Descriptive statistics were applied to summarize the frequency of failures, average downtime duration, and efficiency levels of machine utilization. Parameters such as mean, percentage, and standard deviation were calculated to describe performance variations over the observation period.
2. Comparative analysis was conducted to identify performance differences before and after maintenance implementation. This comparison was performed by examining the change in mean values and percentage improvements for each performance indicator.
3. Correlation analysis was used to explore the relationship between maintenance frequency, downtime reduction, and the quality of machine output.
4. The results were then interpreted in relation to the preventive maintenance objectives to determine the extent to which the maintenance protocol improved machine reliability and operational efficiency.

Research Stages

The stages of this study were designed sequentially to ensure a well-directed process, from initial identification to the development of practical recommendations. Each stage supports the overall research objective, which is to design and evaluate the effectiveness of a preventive maintenance protocol for CNC machines. The research stages are detailed as follows:

a. Preliminary Study

At this stage, the existing CNC machine maintenance system was identified, including an assessment of the machines' technical conditions and ongoing maintenance procedures in the laboratory. The information collected served as the basis for designing a more optimal maintenance protocol.

b. Design of Preventive Maintenance Protocol

Based on the preliminary study, a preventive maintenance protocol was developed, tailored to the machine type (3-axis CNC milling and CNC turning), usage frequency, and laboratory environmental characteristics. The protocol included schedules, technical procedures, and periodic inspection checklists.

c. Protocol Implementation

The designed protocol was trialed over a specific period, for example, six weeks. During this time, all maintenance activities were conducted according to the guidelines to observe the consistency of implementation and its effectiveness in reducing operational disruptions.

d. Monitoring and Data Collection

At this stage, machine performance was monitored throughout the protocol implementation. Recorded data included the number of failures, downtime duration, machine utilization efficiency during practical sessions, and quality of machine outputs.

e. Analysis and Evaluation

The collected data were analyzed quantitatively and descriptively to assess the impact of preventive maintenance implementation. Where possible, simple statistical tests were conducted to determine the significance of performance differences before and after the intervention.

RESULTS AND DISCUSSION

Initial Condition of the CNC Machine Maintenance System

Observations in the field and interviews with laboratory technicians and course instructors indicated that the CNC machine maintenance system prior to the intervention relied on a reactive (corrective maintenance) approach. In this approach, repairs were carried out only after machine failures occurred, without preceding scheduled routine maintenance activities. This condition caused machines to operate sub-optimally and increased the risk of sudden technical disruptions (Musthopa et al., 2023). Consequently, machine downtime was relatively high, averaging approximately 2.5 hours per week for the CNC Milling HURCO VM 10 and 3 hours per week for the CNC Turning Center SKT 160A. Such downtime directly disrupted students' practical sessions and reduced the efficiency of machine utilization in the laboratory.

Furthermore, a review of maintenance logs and laboratory technical records revealed that technical disruptions tended to recur. Common issues included spindle misalignment, which affected machining precision, and excessive overheating in the drive motor. These problems had not been addressed comprehensively due to the absence of periodic inspection mechanisms capable of detecting early signs of failure. The lack of preventive procedures resulted in only short-term corrective actions, leaving the potential for more severe and recurring damage over time. This underscores the importance of a more structured maintenance system to consistently ensure machine reliability and performance (Newaz et al., 2025).

Design and Implementation of the Preventive Maintenance Protocol

The preventive maintenance protocol developed in this study refers to international maintenance standards such as ISO 10791-12:2020 for machining centers and ISO 9001:2015 for quality assurance and documentation, while also adapting to the actual operational conditions in the CNC laboratory at Politeknik Kampar. The protocol was designed after evaluating manufacturer manuals, maintenance recommendations from HURCO and SKT machine producers, and field observations of existing maintenance practices.

The preventive maintenance system was structured into three scheduled intervals daily, weekly, and monthly each focusing on specific inspection and service tasks designed to maintain machine reliability and ensure consistent performance of the CNC Milling HURCO VM 10 and CNC Turning Center SKT 160A.

1. Daily maintenance focused on operational cleanliness and safety checks, including removal of metal chips and debris from the working area, verification of coolant circulation, oil level inspection, examination of tool holders and work clamps, and testing of emergency stop button functionality (K Patel, 2021)
2. Weekly maintenance involved functional inspection of lubrication lines, spindle bearings, and pneumatic-hydraulic systems, as well as tightening of electrical and mechanical connections. Vibration and noise level monitoring were also performed to detect early signs of imbalance or wear.
3. Monthly maintenance was more comprehensive, including calibration of the X, Y, and Z axes using precision measuring tools, backlash and runout verification, spindle alignment checks, as well as cleaning of the cooling system and replacement of filters.

All maintenance activities were documented using a standardized checklist form aligned with ISO 9001:2015 documentation principles to allow continuous traceability and evaluation. Before implementation, the protocol was reviewed and discussed with laboratory technicians and course instructors to ensure a shared understanding of the procedures. During the six-week application period, technicians were responsible for weekly and monthly maintenance, while students were involved in daily maintenance tasks under direct supervision as part of practice-based learning. The designed preventive maintenance protocol thus combines industrial best practices with field adaptations specific to the educational context at Politeknik Kampar, ensuring that the CNC machines operate efficiently, experience reduced downtime, and provide a sustainable learning environment for vocational training.

The details of the preventive maintenance schedule implemented are as follows:

Table 1. Preventive Maintenance Schedule – CNC Turning Center SKT 160A

No	Time Interval	Components / Activities Checked	Inspection Purpose	Responsible Personnel
1	Daily	- Clean chuck and guide area - Check lubrication of linear guides - Ensure the control panel is free of obstructions	Maintain smooth motion and operational safety	Students and Technicians
2	Weekly	- Inspect automatic lubrication system and reservoir - Detect vibrations from the main motor - Check condition of brake system and turret	Prevent excessive wear and rotation issues during turning	Technicians and Course Instructors
3	Monthly	- Check tool alignment with chuck - Monitor motor temperature during operation - Calibrate the cooling system - Evaluate turning accuracy	Maintain cutting process stability and extend motor lifespan	Senior Technicians and Instructors
4	End of Trial (6 Weeks)	- Audit actual machine condition - Test spindle and drive motor performance - Recommend revisions to schedule or SOP	Assess the impact of implementation on machine performance and downtime	Laboratory Evaluation Team

Table 2. Preventive Maintenance Schedule – CNC Milling HURCO VM 10

No	Time Interval	Components / Activities Checked	Inspection Purpose	Responsible Personnel
1	Daily	- Clean worktable and spindle area - Check for oil leaks - Ensure emergency stop buttons function	Maintain operational cleanliness and safety	Students and Technicians
2	Weekly	- Inspect automatic lubrication system - Check cables and connectors - Detect abnormal noises/vibrations from spindle and X-Y-Z axes	Early detection of mechanical and electrical faults	Technicians and Course Instructors
3	Monthly	- Calibrate X, Y, Z axis movements - Check backlash	Maintain machining accuracy and thermal stability	Senior Technicians and Instructors

4	End of Trial (6 Weeks)	- Inspect coolant level and flow	Early detection of mechanical and electrical faults	Laboratory Evaluation Team
		- Test cutting precision		
		- Evaluate machine performance		
		- Audit maintenance logbook		
		- Adjust and update protocol		

Impact of Preventive Maintenance Implementation

The results of the study show that the structured implementation of a preventive maintenance protocol significantly improved CNC machine performance and the overall efficiency of student practical sessions. Before the intervention, maintenance activities followed a reactive pattern, meaning corrective actions were only carried out after a breakdown occurred. This approach led to frequent machine failures and prolonged downtime, disrupting the smooth progress of vocational training activities (Ivančan et al., 2023).

After the preventive maintenance protocol was introduced, substantial improvements were observed in both technical and educational aspects. Quantitative analysis based on maintenance log data and student feedback indicated a marked decrease in downtime and an increase in operational efficiency. Table 3 presents the summary of the comparative analysis before and after the implementation of preventive maintenance.

Table 3. Summary of CNC Machine Performance Before and After Preventive Maintenance

No	Parameter	Machine Type	Before Implementation	After Implementation	Improvement (%)
1	Average Downtime (hours/week)	CNC Milling HURCO VM 10	2,5 ± 0,3	1,3 ± 0,2	48,0
2	Average Downtime (hours/week)	CNC Turning Center SKT 160A	3,0 ± 0,4	1,4 ± 0,3	53,3
3	Machine Utilization Efficiency (%)	Both Machines (Average)	78,0	91,0	+13,0
4	Student Maintenance Competence Score (%)	Based on Assessment	76,2	88,5	+12,3

Following the six-week implementation period, the CNC Milling HURCO VM 10 experienced a reduction in average downtime from 2,5 to 1,3 hours per week, while the CNC Turning Center SKT 160A decreased from 3,0 to 1,4 hours per week. This represents a reduction of 48–53% in total downtime, attributed to routine inspections of critical components such as spindles, lubrication systems, and cooling units (Patil et al., 2017) (Benhanifia et al., 2025).

Machine utilization efficiency also increased from 78% to 91%, indicating that machines were available and operational for a larger portion of the scheduled practical hours. This allowed student groups to complete their assigned machining projects on time, reducing the frequency of rescheduling due to technical interruptions (Yazdani & Haghani, 2024). In addition to technical performance improvements, the educational impact of the program was also evident. Students actively participated in daily maintenance activities, including cleaning, checking lubrication indicators, and completing inspection checklists. As a result, the average score for maintenance competence improved from 76,2% to 88,5%, reflecting a deeper understanding of preventive maintenance practices and their relevance to industrial standards (Müller & Mildemberger, 2021).

This integrated approach aligns with the core philosophy of vocational education, which emphasizes learning through the combination of theory and hands-on experience (Hauashdh et al., 2024). Students not only learned to operate CNC machines effectively but also gained

awareness of the importance of maintenance in ensuring production continuity, reliability, and safety. Such exposure fosters a culture of precision, discipline and proactive maintenance key attributes in the industrial workforce (Theissler et al., 2021).

This approach aligns with the nature of vocational education, which emphasizes skill development through the integration of theory and practice (Rehman et al., 2024). Students are not only taught how to operate the machines but are also encouraged to understand how to maintain their optimal performance. These activities further help cultivate a work culture oriented toward safety, efficiency, and precision values that are essential in the manufacturing industry (Noor Arzahan et al., 2022).

In summary, the preventive maintenance protocol implemented in this study produced measurable improvements: a reduction in downtime by up to 53%, a 13% increase in machine utilization efficiency, and a 12% increase in student maintenance competence. These findings confirm that a well structured maintenance system enhances not only machine reliability but also vocational learning outcomes, demonstrating its dual contribution to technical excellence and educational quality (Wolska et al., 2023) (Viera Trevisan et al., 2024).

CONCLUSION

The structured implementation of a preventive maintenance protocol at Politeknik Kampar resulted in notable and quantifiable improvements in both CNC machine performance and vocational training effectiveness. The findings revealed a 48% decrease in average downtime for the CNC Milling HURCO VM 10 and a 53% reduction for the CNC Turning Center SKT 160A. Additionally, machine utilization efficiency rose from 78% to 91%, accompanied by an increase in students' maintenance competence scores from 76.2% to 88.5%. These outcomes demonstrate that a well organized preventive maintenance system not only improves machine reliability and operational productivity but also strengthens the quality of experiential learning in vocational education. Consequently, incorporating preventive maintenance as a routine practice in vocational laboratories is strongly recommended to ensure sustainable equipment performance and enhance the overall quality of technical education.

REFERENCES

- Adu, D. A., Chen, X. H., Hasan, M., Zhu, X., & Jellason, N. (2023). The relationship between entrepreneurial energy efficiency orientation and carbon footprint reduction: The mediating role of green networking and identification of barriers to green practices. *Journal of Environmental Management*, 347(August), 119256. <https://doi.org/10.1016/j.jenvman.2023.119256>
- Ahmed Murtaza, A., Saher, A., Hamza Zafar, M., Kumayl Raza Moosavi, S., Faisal Aftab, M., & Sanfilippo, F. (2024). Paradigm shift for predictive maintenance and condition monitoring from Industry 4.0 to Industry 5.0: A systematic review, challenges and case study. *Results in Engineering*, 24(September), 102935. <https://doi.org/10.1016/j.rineng.2024.102935>
- Armstrong, M., Mehrabi, H., & Naveed, N. (2022). An overview of modern metal additive manufacturing technology. *Journal of Manufacturing Processes*, 84(October), 1001–1029. <https://doi.org/10.1016/j.jmapro.2022.10.060>
- Bafandegan Emroozi, V., Kazemi, M., & Doostparast, M. (2025). Enhancing industrial maintenance planning: Optimization of human error reduction and spare parts management. *Operations Research Perspectives*, 14(March), 100336. <https://doi.org/10.1016/j.orp.2025.100336>
- Benhanifia, A., Cheikh, Z. Ben, Oliveira, P. M., Valente, A., & Lima, J. (2025). Systematic review

- of predictive maintenance practices in the manufacturing sector. *Intelligent Systems with Applications*, 26(October 2024), 200501. <https://doi.org/10.1016/j.iswa.2025.200501>
- Febrianton, A., Putri, I. P., Romiyadi, R., Irwan, P., & Sihotang, P. (2024). Pengaruh Kedalaman Potong Menggunakan Insert Radius 0,4 mm cnmg 120404n Terhadap Kekasaran Permukaan (Surface Roughness) Baja Karbon S45C. *Jurnal Teknik Industri Terintegrasi*, 7(3), 1460–1467. <https://doi.org/10.31004/jutin.v7i3.28567>
- Friederich, J., & Lazarova-Molnar, S. (2024). Reliability assessment of manufacturing systems: A comprehensive overview, challenges and opportunities. *Journal of Manufacturing Systems*, 72(July 2023), 38–58. <https://doi.org/10.1016/j.jmsy.2023.11.001>
- Garrido, S., Muniz, J., & Batista Ribeiro, V. (2024). Operations Management, Sustainability & Industry 5.0: A critical analysis and future agenda. *Cleaner Logistics and Supply Chain*, 10(January), 100141. <https://doi.org/10.1016/j.clscn.2024.100141>
- Hardt, F., Kotyrba, M., Volna, E., & Jarusek, R. (2021). Innovative approach to preventive maintenance of production equipment based on a modified tpm methodology for industry 4.0. *Applied Sciences (Switzerland)*, 11(15). <https://doi.org/10.3390/app11156953>
- Hauashdh, A., Nagapan, S., Jailani, J., & Gamil, Y. (2024). An integrated framework for sustainable and efficient building maintenance operations aligning with climate change, SDGs, and emerging technology. *Results in Engineering*, 21(January), 101822. <https://doi.org/10.1016/j.rineng.2024.101822>
- Ivančan, J., Lisjak, D., Pavletić, D., & Kolar, D. (2023). Improvement of Failure Mode and Effects Analysis Using Fuzzy and Adaptive Neuro-Fuzzy Inference System. *Machines*, 11(7). <https://doi.org/10.3390/machines11070739>
- K Patel, J. (2021). The Importance of Equipment Maintenance Forecasting. *International Journal of Mechanical Engineering*, 8(5), 7–11. <https://doi.org/10.14445/23488360/ijme-v8i5p102>
- Lestari, E., & Cahyono, B. D. (2025). Analisis Perawatan Pada Mesin CNC Plasma Cutting Di PT. Kenertec Power System. *Teknika*, 10(1), 9–18. <https://doi.org/10.52561/teknika.v10i1.414>
- Müller, C., & Mildenerberger, T. (2021). Facilitating flexible learning by replacing classroom time with an online learning environment: A systematic review of blended learning in higher education. *Educational Research Review*, 34(November 2020), 100394. <https://doi.org/10.1016/j.edurev.2021.100394>
- Musthopa, Harsanto, B., & Yunani, A. (2023). Electric power distribution maintenance model for industrial customers: Total productive maintenance (TPM), reliability-centered maintenance (RCM), and four-discipline execution (4DX) approach. *Energy Reports*, 10(June), 3186–3196. <https://doi.org/10.1016/j.egyr.2023.09.129>
- Nawir, R., Dwianda, Y., Febrianton, A., & Irwan, P. (2022). The Effect of Misalignment to Vibration, Electric Current and Shaft Rotation Speed on Gear Transmission. *The Journal of Ocean, Mechanical and Aerospace -Science and Engineering- (JOMase)*, 66(1), 14–19. <https://doi.org/10.36842/jomase.v66i1.278>
- Newaz, M. T., Jefferies, M., & Ershadi, M. (2025). A critical analysis of construction incident trends and strategic interventions for enhancing safety. *Safety Science*, 187(March), 106865. <https://doi.org/10.1016/j.ssci.2025.106865>
- Noor Arzahan, I. S., Ismail, Z., & Yasin, S. M. (2022). Safety culture, safety climate, and safety performance in healthcare facilities: A systematic review. *Safety Science*, 147, 105624. <https://doi.org/10.1016/j.ssci.2021.105624>

- Patil, R. B., Kothavale, B. S., Waghmode, L. Y., & Joshi, S. G. (2017). Reliability analysis of CNC turning center based on the assessment of trends in maintenance data: A case study. *International Journal of Quality and Reliability Management*, 34(9), 1616–1638. <https://doi.org/10.1108/IJQRM-08-2016-0126>
- Rakes, D., Arif, M., Setiawan, A., Nasution, K. P., & Prastyo, Y. (2024). Preventive Maintenance on CNC Machines Using the OEE Method to Reduce Downtime at PT. MTAT. *Jurnal Impresi Indonesia*, 3(7), 481–490. <https://doi.org/10.58344/jii.v3i7.5116>
- Rehman, N., Huang, X., Mahmood, A., AlGerafi, M. A. M., & Javed, S. (2024). Project-based learning as a catalyst for 21st-Century skills and student engagement in the math classroom. *Heliyon*, 10(23), e39988. <https://doi.org/10.1016/j.heliyon.2024.e39988>
- Romiyadi, R. (2025). Perawatan Mesin untuk Meningkatkan Performa dan Keandalan Mesin dan Peralatan. *JUTIN : Jurnal Teknik Industri Terintegrasi*, 8(3), 3619–3626.
- Romiyadi, R., Dwianda, Y., & Mustika, W. S. (2023). Pengaruh Misalignment Terhadap Arus Listrik dan Putaran Poros pada Komponen Transmisi Sproket dan Rantai. *Quantum Teknika : Jurnal Teknik Mesin Terapan*, 5(1), 1–7. <https://doi.org/10.18196/jqt.v5i1.17403>
- Romiyadi, R., & Irwan, P. (2020). The Effect of Misalignment to Vibration, Electric Current and Shaft Rotation Speed on The Coupling Transmission. *Jurnal Teknik Mesin*, 10(2), 73–78. <https://doi.org/10.21063/jtm.2020.v10.i2.73-78>
- Soori, M., Ghaleh Jough, F. K., Dastres, R., & Arezoo, B. (2024). Sustainable CNC machining operations, a review. *Sustainable Operations and Computers*, 5(January), 73–87. <https://doi.org/10.1016/j.susoc.2024.01.001>
- Teixeira, H. N., Lopes, I., & Braga, A. C. (2020). Condition-based maintenance implementation: A literature review. *Procedia Manufacturing*, 51(2019), 228–235. <https://doi.org/10.1016/j.promfg.2020.10.033>
- Theissler, A., Pérez-Velázquez, J., Kettelgerdes, M., & Elger, G. (2021). Predictive maintenance enabled by machine learning: Use cases and challenges in the automotive industry. *Reliability Engineering and System Safety*, 215, 107864. <https://doi.org/10.1016/j.ress.2021.107864>
- Viera Trevisan, L., Leal Filho, W., & Ávila Pedrozo, E. (2024). Transformative organisational learning for sustainability in higher education: A literature review and an international multi-case study. *Journal of Cleaner Production*, 447(March). <https://doi.org/10.1016/j.jclepro.2024.141634>
- Wolska, M., Gorewoda, T., Roszak, M., & Gajda, L. (2023). Implementation and Improvement of the Total Productive Maintenance Concept in an Organization. *Encyclopedia*, 3(4), 1537–1564. <https://doi.org/10.3390/encyclopedia3040110>
- Yazdani, M., & Haghani, M. (2024). Exploring the evolution of machine scheduling through a computational approach. *Engineering Applications of Artificial Intelligence*, 133(PF), 108572. <https://doi.org/10.1016/j.engappai.2024.108572>