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Analytical Study on the Implementation of Total Productive Maintenance (TPM) in CNC Machines - A Case Study: PT XYZ

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Abstract: *Ensuring machine efficiency is essential for maintaining optimal productivity in manufacturing industries. This study investigates the implementation of Total Productive Maintenance (TPM) in CNC Milling machines at PT XYZ, aiming to assess machine effectiveness through Overall Equipment Effectiveness (OEE), analyze production losses using the Six Big Losses framework, and identify failure modes via Failure Mode and Effects Analysis (FMEA). The research methodology includes data collection from February 2023 to January 2024, statistical analysis of machine performance, and root cause identification. The results indicate that the average OEE value for CNC Milling machines is 66.335%, which falls within the industry-standard range but does not meet world-class benchmarks. Reduced Speed Losses (26.653%) is the primary contributor to inefficiencies, followed by Idling and Minor Stoppages (6.397%). The FMEA analysis identifies the damaged spindle bearing as the most critical failure mode, with an RPN value of 320, primarily caused by excessive workload and inadequate maintenance. This study highlights the necessity of improving key TPM pillars, including Autonomous Maintenance, Planned Maintenance, and Training & Education, to enhance machine effectiveness. The company can reduce downtime, improve OEE, and increase overall production efficiency by addressing these areas. Future research should explore advanced predictive maintenance techniques like IoT-based monitoring to optimize machine performance.*

Keywords: Total Productive Maintenance, CNC Milling, Overall Equipment Effectiveness, Six Big Losses, Failure Mode and Effects Analysis

1. INTRODUCTION

In today's highly competitive market, every industry strives to deliver high-quality products to maintain a strong market position. In the manufacturing sector, machinery is a fundamental component of the production process. The efficient and effective utilization of machinery directly impacts productivity, while inefficiencies can lead to operational disruptions, reduced output, and financial losses. Consequently, ensuring the optimal performance of production machinery is a fundamental requirement for sustaining smooth operations and achieving long-term business success.

This study focuses on the production process at PT XYZ, which manufactures spare metal parts. The company employs various types of machinery, including CNC Milling machines, as components of its production system. Given the critical role of these machines, proper maintenance is essential to prevent unexpected operational failures that could negatively affect production continuity. Maintenance in manufacturing is as crucial as production itself, as it ensures the reliability and efficiency of equipment, ultimately contributing to overall operational effectiveness. Therefore, assessing machine efficiency and effectiveness through a structured and data-driven approach is imperative.

One widely recognized method for evaluating equipment performance in the manufacturing industry is the Overall Equipment Effectiveness (OEE) framework. OEE is a comprehensive performance metric that quantifies machine productivity by analyzing three key factors: availability, performance efficiency, and quality rate. This metric provides insights into equipment utilization and is a benchmark for identifying areas requiring improvement. Companies can enhance machine efficiency, reduce losses, and optimize production processes by systematically monitoring OEE.

An analysis of production data and operational observations at PT XYZ from February 2023 to January 2024 revealed recurring production challenges primarily related to excessive CNC Milling machine downtime due to frequent breakdowns. These machine failures necessitated corrective maintenance, involving repair activities and the procurement of replacement components. Persistent machine downtime significantly impacts production schedules, increases operational costs, and reduces overall efficiency. Implementing a structured maintenance system such as Total Productive Maintenance (TPM) is essential to mitigate these challenges and maintain production stability. TPM optimizes machine effectiveness through proactive maintenance strategies and operator involvement in basic equipment care.

The objective of this study is to systematically assess the effectiveness of CNC Milling machines by applying the OEE methodology, identify sources of production inefficiencies using the Six Big Losses framework, determine underlying causes of machine failures through Fishbone Diagram analysis, and evaluate failure modes using the Failure Mode and Effects Analysis (FMEA) method. Additionally, this study aims to provide actionable recommendations for machine performance improvement based on the principles of TPM. By addressing these key areas, the research seeks to contribute to developing a more reliable and efficient manufacturing system, ultimately enhancing productivity and competitiveness in the industry.

2. Research Methods

This study was conducted at PT. XYZ from February 2023 to January 2024, focusing on CNC Milling machines. This research aims to provide recommendations for improving the CNC Milling machines used by the company to minimize downtime. The study involves four key stages of data processing [6,7,8,9]: (1) identifying the Total Productive Maintenance (TPM) pillars related to machine issues within the company, (2) calculating the effectiveness of CNC Milling machines using the Overall Equipment Effectiveness (OEE) method, (3) analyzing production losses through the Six Big Losses framework using a fishbone diagram, and (4) conducting failure analysis using the Failure Mode and Effects Analysis (FMEA) method.

Total Productive Maintenance (TPM) is a machine maintenance strategy aimed at minimizing losses within the manufacturing system, thereby reducing production costs by integrating the Overall Equipment Effectiveness (OEE) approach [5]. TPM consists of eight key pillars [10]:

1. Autonomous Maintenance (AM). A machine maintenance concept where basic maintenance tasks are performed by production operators [11].
2. Focused Maintenance. A system improvement approach that addresses critical issues through data analysis [12].
3. Planned Maintenance. A structured maintenance strategy is designed to identify and address the root causes of machine failures [11].
4. Quality Maintenance. A maintenance approach ensures machines prevent defects during production processes [11].
5. Education & Training. The knowledge and skills operators require to operate and maintain machinery efficiently [11].
6. Safety, Health & Environment. Corporate efforts to create a safe and sustainable working environment [11].
7. Office TPM. A company-wide approach to ensure a shared understanding and commitment to TPM implementation [11].
8. Development Management. Leveraging past maintenance activities to achieve optimal machine performance [12].

The Overall Equipment Effectiveness (OEE) method is a widely used measurement technique for assessing machine productivity and identifying improvement areas [13]. The primary objective of the OEE method is to maximize overall machine effectiveness and enhance production efficiency [13,14]. OEE calculations are based on three key performance ratios: Availability (A), Performance Efficiency (PE), and Rate of Quality Product (ROQP) [15].

Availability represents the ratio that reflects the utilization of available time for machine operations. The measurement formula for Availability is expressed in Equation (1):

$$A = \frac{Operation\ Time}{Loading\ Time} \times 100\% \qquad (1)$$

Performance Efficiency refers to the ratio that represents the capability of equipment to produce a given output. The formula for calculating the Performance Efficiency ratio is expressed in Equation (2):

$$E = \frac{\text{Processed amount} \times \text{Ideal cycle time}}{Operation\ Time} \times 100\% \qquad (2)$$

The rate of Quality Product represents the ratio that reflects the ability of equipment to produce products that meet the required quality standards. The formula for calculating the Rate of Quality Product ratio is expressed in Equation (3):

$$ROQP = \frac{\text{Processed amount} - \text{Defect Amount}}{\text{Processed amount}} \times 100\% \qquad (3)$$

The Overall Equipment Effectiveness (OEE) calculation is performed once the values for the three key ratios—Availability, Performance Efficiency, and Rate of Quality Product—are obtained. The formula for measuring OEE is expressed in Equation (4):

$$OEE = A \times PE \times ROQP \qquad (4)$$

The Six Big Losses Method is used to identify significant losses that impact machine effectiveness by categorizing six types of losses that contribute to reduced machine performance [8,13]. These six significant losses include **Setup and Adjustment Losses, Idling and Minor Stoppages Losses, Defect Losses, Reduced Speed Losses, Breakdown Losses,** and **Reduced Yield Losses.**

Setup and Adjustment Losses refer to losses due to extended setup or adjustment times required to prepare machinery for operation. The formula for measuring Setup and Adjustment Losses (SAL) is expressed in Equation (5):

$$SAL = \frac{\text{Set Up Time}}{Loading\ Time} \times 100\% \qquad (5)$$

Idling and Minor Stoppage Losses refer to losses arising from brief machine stoppages, idle time, and similar interruptions. The formula for measuring Idling and Minor Stoppage Losses (IMSL) is expressed in Equation (6):

$$IMSL = \frac{\text{Nonproductive Time}}{Loading\ Time} \times 100\% \qquad (6)$$

Defect Losses refer to losses incurred due to products that fail quality control and cannot undergo rework. The formula for measuring Defect Losses (DL) is expressed in Equation (7):

$$DL = \frac{\text{Ideal cycle time} \times \text{total defect}}{Loading\ Time} \times 100\% \qquad (7)$$

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Reduced Speed Losses arise when machines do not operate at optimal performance due to wear and degradation, causing the actual machine speed to be lower than the normal speed. The formula for measuring Reduced Speed Losses (RSL) is expressed in Equation (8):

$$RSL = \frac{\text{Actual processing time} - \text{Ideal processing time}}{Loading\ Time} \times 100\% \qquad (8)$$

Breakdown Losses are categorized as downtime losses caused by machine and equipment failures, rendering the machines inoperable and resulting in significant production time losses. The formula for measuring Breakdown Losses (BL) is expressed in Equation (9):

$$Breakdown\ Losses = \frac{\text{Downtime}}{Loading\ Time} \times 100\% \qquad (9)$$

Reduced Yield Losses refer to losses caused by defects occurring at the initial stages of the production process. The formula for measuring Reduced Yield Losses (RYL) is expressed in Equation (10):

$$RYL = \frac{\text{ideal cycle time} \times \text{total reduced yield}}{Loading\ Time} \times 100\% \qquad (10)$$

The **Failure Mode and Effects Analysis (FMEA) method** identifies potential system failures before they reach the consumer [9]. In conducting FMEA analysis, several key parameters are considered, including **Severity, Occurrence,** and **Detection.**

3. RESULT AND ANALYSIS

3.1 ANALYSIS OF TOTAL PRODUCTIVE MAINTENANCE (TPM) IMPLEMENTATION IN CNC MILLING MACHINES

The company faces several challenges in effectively implementing the pillars of Total Productive Maintenance (TPM), which impacts the overall efficiency of its CNC Milling machines.

The Autonomous Maintenance pillar has not been correctly executed, as machine operators only conduct superficial cleaning before machine usage without thoroughly inspecting the equipment’s condition. This inadequate inspection process leads to a lack of awareness regarding potential machine issues, increasing the risk of unexpected failures during operation. Proper implementation of Autonomous Maintenance requires operators to take an active role in basic maintenance tasks, such as routine inspections, lubrication, and minor adjustments to prevent unforeseen breakdowns.

The Planned Maintenance pillar is also not effectively enforced due to the absence of a structured maintenance schedule based on historical failure rates and predicted breakdown occurrences. Additionally, routine replacement schedules for critical components have not been systematically implemented. This lack of a proactive approach to maintenance can lead to unanticipated machine failures, reducing productivity and increasing downtime. A well-structured planned maintenance system should incorporate preventive and predictive maintenance strategies to minimize unplanned stoppages.

Similarly, the Quality Maintenance pillar remains underdeveloped, as evidenced by the prolonged neglect of critical machine components. For instance, the scrap conveyor, a vital part of the CNC Milling machine, has not been repaired over an extended period, potentially affecting the machine’s overall efficiency and product quality. Quality Maintenance aims to prevent defects by ensuring that equipment is maintained in optimal working condition, reducing the likelihood of defective products and improving manufacturing reliability.

The Training and Education pillar is another area requiring improvement. Operant training is limited to the initial onboarding process, leading to insufficient machine operation and maintenance knowledge. Continuous training programs are essential for equipping operators with up-to-date technical skills and enhancing their ability to identify and address minor issues before they escalate into significant failures. A comprehensive training framework should include periodic workshops, hands-on training, and assessments to ensure operators maintain a high level of competency.

Conversely, the Focused Improvement pillar is relatively well implemented, as employees actively collaborate to identify machine-related issues and develop solutions when CNC machine problems arise. This approach fosters a culture of continuous improvement, where team members work together to enhance operational efficiency through systematic problem-solving techniques.

The Safety, Health, & Environment (SHE) pillar has been successfully enforced, as evidenced by the low occurrence of workplace accidents. This demonstrates the company's commitment to maintaining a safe and comfortable working environment. The practical implementation of the SHE pillars ensures that employees adhere to safety protocols, use appropriate personal protective equipment (PPE), and follow environmental sustainability practices.

The Office TPM pillar is also well-established. It ensures that operators receive accurate and timely information while integrating the 5S methodology (Sort, Set in Order, Shine, Standardize, Sustain) into workplace management. This structured approach promotes workplace organization, reduces inefficiencies, and enhances overall productivity.

Additionally, the Development Management pillar has been effectively adopted, with the company utilizing historical maintenance data to enhance its machine maintenance strategies. By analyzing past maintenance activities, reducing downtime, and improving overall equipment performance, the company can optimize its predictive maintenance efforts.

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3.2 OVERALL EQUIPMENT EFFECTIVENESS (OEE) ANALYSIS

Based on the Overall Equipment Effectiveness (OEE) calculations for CNC Milling machines conducted from February 2023 to January 2024, as presented in Table 1, the performance metrics are as follows: an average Availability of 91.33%, an average Performance Efficiency of 71.374%, and an average rate of Quality Product of 99.236%. These values result in an overall OEE score of 66.335%, positioning the company's performance within the industry-standard range. However, this score falls short of the world-class benchmark, which is generally considered above 85%.

The relatively high Availability rate suggests that the machines are operational for a significant portion of the scheduled production time, indicating minimal downtime due to breakdowns or planned maintenance. However, the lower Performance Efficiency suggests that the machines are not operating at their optimal speed, potentially due to tool wear, improper cutting parameters, or operator inefficiencies. Despite a high Rate of Quality products, which suggests that most produced items meet the required quality standards, the suboptimal Performance Efficiency significantly impacts the overall OEE score.

The company must prioritize strategies that minimize production losses and optimize machine utilization to enhance CNC Milling operations and achieve a world-class OEE level. This can be accomplished through targeted improvements in key areas, including reducing Reduced Speed Losses, addressing minor stoppages, and implementing more effective Planned Maintenance practices. Investing in operator training, real-time performance monitoring, and predictive maintenance technologies can help enhance machine efficiency and production effectiveness. By focusing on these improvement areas, the company can increase its OEE score and achieve higher productivity, reduced downtime, and improved manufacturing competitiveness.

Tabel 1. Overall Equipment Effectiveness of CNC Milling Machines

No	Month	*Availability*	*Performance Efficiency*	*Rate of Quality Product*	OEE
1	Feb 2023	94,614%	95,104%	99,310%	89,362%
2	Mar 2023	90,038%	79,787%	99,200%	71,264%
3	Apr 2023	91,004%	55,498%	98,875%	49,937%
4	May 2023	92,239%	92,661%	99,550%	85,085%
5	Jun 2023	93,398%	96,169%	99,389%	89,271%
6	Jul 2023	91,643%	57,486%	99,273%	52,299%
7	Aug 2023	90,032%	48,581%	99,259%	43,415%
8	Sep 2023	91,810%	47,992%	99,130%	43,678%
9	Oct 2023	90,543%	54,053%	98,965%	48,435%
10	Nov 2023	92,509%	52,854%	99,247%	48,527%
11	Des 2023	90,519%	77,178%	99,357%	69,411%
12	Jan 2024	94,850%	99,121%	99,273%	93,333%
Rata-Rata		91,933%	71,374%	99,236%	65,335%

3.3 OVERALL EQUIPMENT EFFECTIVENESS (OEE) ANALYSIS

Table 2 summarizes the calculation results of the Six Big Losses for CNC Milling machines from February 2023 to January 2024. The data reveals that Reduced Speed Losses contribute the highest percentage, at 26.653%, making them the most significant source of inefficiency in the production process. This is followed by Idling and Minor Stoppages at 6.397%, Breakdown Losses at 0.886%, Set-up and Adjustment Losses at 0.783%, and Defect Losses at 0.473%, while Reduced Yield Losses account for 0.000%.

The predominant contribution of Reduced Speed Losses suggests that machines are operating below their optimal speed, which may be attributed to several factors. These include improper cutting parameters, excessive tool wear, mechanical inefficiencies, or inadequate machine calibration. Such inefficiencies result in prolonged machining times, reduced productivity, and increased operational costs. Additionally, idle and minor stoppages, which account for 6.397% of the total losses, indicate frequent but brief interruptions in machine operation, possibly caused by unoptimized workflow, material handling issues, or operator delays.

To mitigate these inefficiencies and enhance machine performance, a comprehensive root cause analysis will be conducted using Fishbone Diagrams (Ishikawa Diagrams), as illustrated in Figure 1. This method will enable the identification of underlying causes of Reduced Speed Losses and other significant inefficiencies, facilitating the development of targeted corrective actions. Potential improvements may include optimizing machining parameters, implementing preventive maintenance strategies, upgrading tooling systems, and enhancing operator training programs. By systematically addressing these issues, the company can significantly improve CNC Milling machine efficiency, reduce production losses, and move towards achieving a higher Overall Equipment Effectiveness (OEE) score.

Tabel 2. Percentage of Six Big Losses in CNC Milling Machines

No	Month	*Set Up and Adjustment Losses*	*Idling and Minor Stoppages Losses*	*Defect Losses*	*Reduced Speed Losses*	*Breakdown Losses*	*Reduced Yield Losses*
1	Feb 2023	0,598%	4,654%	0,621%	4,632%	0,133%	0,000%
2	Mar 2023	0,599%	7,184%	0,575%	18,199%	2,179%	0,000%
3	Apr 2023	0,915%	6,345%	0,568%	40,499%	1,736%	0,000%
4	May 2023	0,838%	6,731%	0,385%	6,769%	0,192%	0,000%
5	Jun 2023	0,838%	5,614%	0,549%	3,578%	0,150%	0,000%
6	Jul 2023	0,958%	7,112%	0,383%	38,961%	0,287%	0,000%
7	Aug 2023	0,599%	7,228%	0,276%	52,739%	2,141%	0,000%
8	Sep 2023	0,718%	7,016%	0,383%	47,749%	0,455%	0,000%
9	Oct 2023	1,077%	7,182%	0,506%	41,602%	1,197%	0,000%
10	Nov 2023	0,838%	6,423%	0,368%	43,614%	0,230%	0,000%
11	Des 2023	0,823%	6,986%	0,449%	20,659%	1,672%	0,000%
12	Jan 2024	0,598%	4,295%	0,684%	0,833%	0,256%	0,000%
Rata – Rata		0,783%	6,397%	0,473%	26,653%	0,886%	0,000%

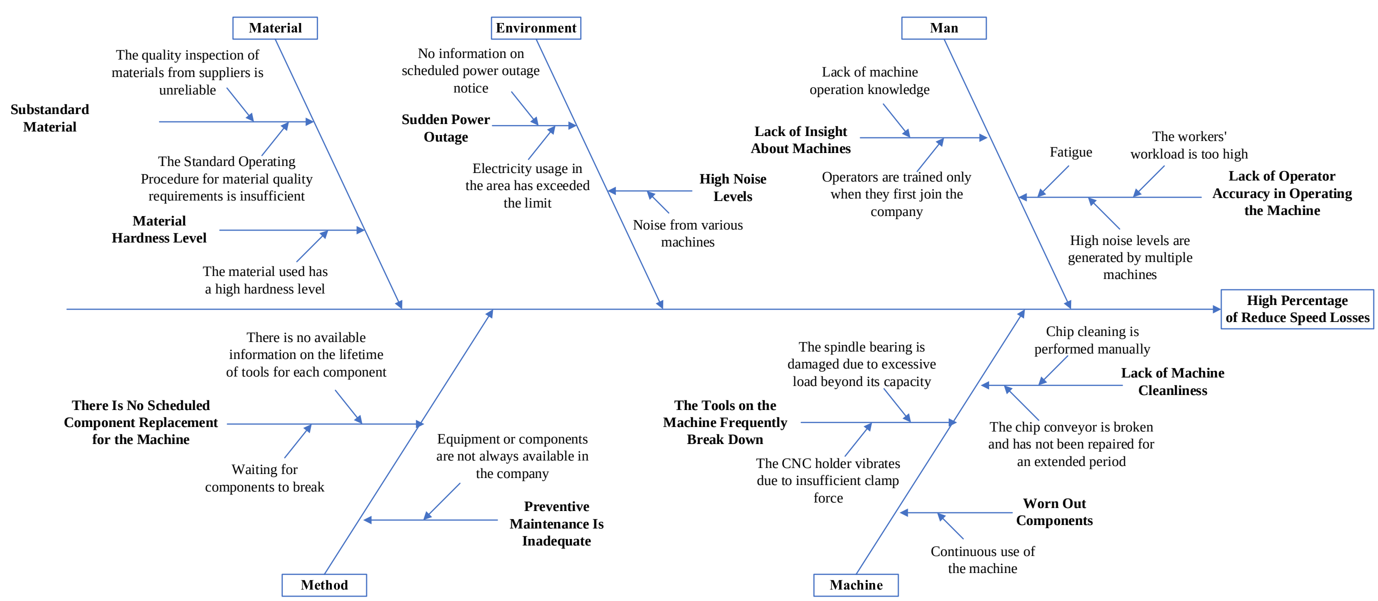

Figure 1 Fishbone Diagram

3.4 Failure Mode and Effects Analysis (FMEA)

Based on the calculation of CNC Milling machine losses, an in-depth analysis was conducted using the Failure Mode and Effects Analysis (FMEA) method to systematically identify and assess the root causes of machine failures. The FMEA approach allows for the evaluation of failure modes based on three key parameters: Severity (S), Occurrence (O), and Detection (D), which are then used to calculate the Risk Priority Number (RPN). This prioritization helps in identifying the most critical failure points that require immediate attention.

The FMEA results, as presented in Table 3, highlight several critical failure modes along with their potential effects and corresponding corrective actions. Among these, the most significant issue identified is the damaged spindle bearing, which has the highest RPN value of 320. This failure mode leads to complete machine inoperability, significantly disrupting production efficiency. The root causes of this issue are an excessive workload, inadequate maintenance, and delayed replacement of worn-out components. Other notable failure modes include misalignment in spare part machining, prolonged setup and repair times, and ineffective preventive maintenance, all contributing to reduced machine availability and performance.

Targeted corrective actions must be implemented to address these failure modes and enhance CNC Milling machine performance. This includes establishing a predictive maintenance program, improving machine calibration processes, enforcing routine inspections, and ensuring the timely replacement of critical components. Additionally, integrating real-time monitoring systems and training operators in advanced troubleshooting techniques can reduce the likelihood of recurring failures.

By systematically applying the insights gained from the FMEA analysis, the company can significantly improve machine reliability by proactively addressing potential failure points before they escalate into severe issues. Implementing predictive maintenance, supported by real-time data analysis and condition-based monitoring, will allow for early detection of abnormalities, enabling timely interventions and minimizing unexpected breakdowns. Furthermore, adopting an optimized spare parts management system will ensure the availability of critical components, reducing delays in repair and maintenance operations.

Minimizing unplanned downtime requires a shift toward a proactive maintenance strategy. This can be achieved by adopting Total Productive Maintenance (TPM) principles, emphasizing operator involvement in routine inspections and minor repairs. Continuous training programs for employees will enhance their technical proficiency, allowing them to detect and address issues early. Moreover, implementing a robust maintenance scheduling system will help plan periodic overhauls, ensuring that machines remain in peak operating condition.

Tabel 3. *Failure Mode and Effect Analysis*

Failure Mode	Failure Effect	S	Failure Cause	O	Control	D	RPN
The spare part machining process does not align with the initial reference point	The workpiece does not meet quality standards (reject)	6	The CNC Milling holder is unstable and not securely fastened, with insufficient clamp force	5	Conduct machine inspections before starting the production process	4	120
The spindle bearing is damaged	The machine cannot operate	8	Damaged components are not promptly repaired, exacerbated by a workload exceeding capacity	5	The technician performs machine disassembly for analysis and repair	8	320
Machine breakdown occurs	The production process is disrupted	7	Routine maintenance scheduling has not been effectively implemented	4	Conduct a visual inspection of the machine's condition	5	140
Machine components experience wear	A machine breakdown occurs	7	The company does not provide spare components for repairs	7	Perform a direct inspection of each machine component	5	245
Setup and repair processes take a long time	The production process is disrupted	6	The chip conveyor is damaged	8	Conduct a direct visual inspection, considering excessive machine downtime	5	240
Preventive maintenance has not been	A machine breakdown occurs	8	The company's equipment and components are incomplete	4	Perform testing and direct inspection of each component	2	64

effectively implemented							
There is a leakage in the air hose	The spindle movement is not optimal	8	Prolonged machine usage under high workloads accelerates wear and tear	5	Conduct a direct inspection of the machine	3	120

Enhancing overall production efficiency involves optimizing machine utilization, improving process standardization, and streamlining workflow operations. Lean manufacturing techniques, such as value stream mapping and bottleneck analysis, can be integrated to identify inefficiencies and eliminate unnecessary delays. Additionally, automated data collection systems will provide real-time insights into machine performance, enabling swift decision-making to optimize production output.

These corrective measures will contribute to a more sustainable maintenance strategy, ultimately leading to higher productivity by ensuring that machines operate optimally. Proactive maintenance will minimize downtime, reduce defect rates, and extend equipment lifespan, reducing operational costs. As a result, the company will strengthen its market competitiveness by maintaining a highly reliable and efficient production system, fostering continuous improvement, and maximizing overall equipment effectiveness (OEE).

4. Conclusion

This study provides an in-depth analysis of Total Productive Maintenance (TPM) implementation in CNC Milling machines, focusing on OEE assessment, production loss analysis, and failure mode evaluation. The findings indicate that while specific TPM pillars, such as Safety, Health and Environment, and Office TPM, are well-implemented, other areas require significant improvement, including Autonomous Maintenance, Planned Maintenance, and Training and Education.

The OEE analysis reveals that the company's CNC Milling machines operate at an efficiency level of 66.335%, which meets standard industry benchmarks but falls short of world-class performance (above 85%). The most significant production loss is due to Reduced Speed Losses (26.653%), suggesting inefficiencies in machine operation, tool wear, and inadequate process optimization. The FMEA results identify the damaged spindle bearing as the most critical failure mode, necessitating proactive maintenance measures to prevent further breakdowns.

The implications of these findings emphasize the importance of structured maintenance strategies in improving manufacturing efficiency. Implementing enhanced TPM measures, such as real-time monitoring and predictive maintenance, can help mitigate losses and optimize machine effectiveness. This study contributes to existing knowledge by providing a practical framework for identifying key inefficiencies in CNC Milling operations. Future research should explore integrating innovative maintenance technologies, such as IoT-based predictive analytics, to enhance OEE and overall productivity further.

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