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Enhancing production effectiveness of the K-58 crankcase machining line through integrated TPM–FMEA approach

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Abstract

On the Crankcase K-58 machining line, several performance gaps were identified, including inconsistent cycle time, frequent unplanned downtime, and tool-change irregularities that caused the output to fall below the company targets. This study aims to enhance the production effectiveness of the K-58 crankcase machining line by applying an integrated Total Productive Maintenance (TPM) and Failure Mode and Effects Analysis (FMEA) approach. The initial performance evaluation, using Overall Equipment Effectiveness (OEE) in 2024, showed an average score of 76.2%, indicating significant losses in availability and performance rates. Quantitative analysis was conducted through OEE and Six Big Losses assessments, while FMEA was used to prioritize failure points based on Risk Priority Number (RPN). Improvement actions implemented included autonomous maintenance reinforcement, scheduled preventive maintenance, operator skill development, coolant-condition control, and quick-change adjustments. After implementation, the OEE of the machining line increased to 85.5%, meeting its target. Reduced speed losses improved by more than 45%, while setup and adjustment losses decreased by over 50%. These results confirm that the integrated TPM–FMEA approach is effective for enhancing machining-line performance and reliability.

Keywords:
Crankcase machining, TPM, FMEA, OEE, process improvement.

1 Introduction

Manufacturing industries are continuously challenged to maintain high levels of productivity, reliability, and product quality. Modern production systems require equipment that operates with minimal downtime and stable process capability to meet increasing global competitiveness. In machining operations, equipment inefficiencies such as unplanned stoppages, prolonged cycle time, and tool-related disturbances can significantly reduce output and raise operational costs. Therefore, achieving high equipment effectiveness is essential for ensuring sustainable manufacturing performance [1][2].

In the context of this study, the Crankcase K-58 machining line exhibits several recurring operational issues. These include inconsistent cycle times, frequent insert changes, pneumatic disturbances, and machine stoppages at critical stations such as fine boring and leak testing. These issues contributed to low availability and performance rates, resulting in overall productivity below the internal company target. This condition highlights the importance of structured maintenance and systematic problem prioritization to support machine stability and production continuity [3][4][5].

This research focuses exclusively on the Crankcase K-58 machining line and does not include the assembly process. The machining line was selected due to its high production volume and its significant contribution to engine manufacturing throughput. A clear understanding of the equipment behavior and dominant loss categories is required to perform effective improvement planning [6].

Several studies have demonstrated that combining Total Productive Maintenance (TPM) with Failure Mode and Effects Analysis (FMEA) is effective in improving equipment reliability and minimising production losses. However, the specific operational characteristics of the Crankcase K-58 machining line require a tailored improvement strategy that addresses its unique failure modes. Therefore, this study aims to integrate TPM and FMEA to identify critical failure points, prioritize root causes, and design targeted improvement actions [7][8][9].

The expected contributions of this research are as follows: (1) providing the company with a structured approach to reduce downtime and improve machining stability, (2) supporting operators with clearer autonomous-maintenance standards, and (3) offering researchers a practical case study on TPM-FMEA implementation in high-volume machining operations [10][11][12][13].

2 Method

2.1 Research design

This research was conducted at the Crankcase K-58 machining line of PT XYZ Manufacturing Indonesia. The study was carried out from January 2024 to April 2025 and involved continuous monitoring of machine performance, downtime, and maintenance activities.

The data collected consisted of both primary and secondary sources. Primary data included direct observations of machine operation, cycle-time measurements, maintenance logs, breakdown records, and operator interviews. Secondary data consisted of production reports, historical OEE data, maintenance manuals, and internal standard operating procedures. [2][14]. The research methodology followed sequential steps as outlined below:

(1) Identify the initial performance gap through OEE analysis.
(2) Classify losses using the Six Big Losses framework.
(3) Conduct detailed failure analysis based on breakdown frequency and duration.
(4) Apply FMEA to determine the most critical failure modes based on RPN.
(5) Formulate and implement TPM-based improvement actions.
(6) Evaluate post-improvement performance through updated OEE indicators.

2.2 Research object

The object of this research is the K-58 crankcase machining line, as Fig. 1, which consists of a sequence of operations, including drilling, tapping, milling, reaming, and fine boring. The process begins with dowel pressing and concludes with final leak testing. The crankcase is a high-precision aluminum part that requires multiple machining stations (OP20–OP130) to meet product specifications.

Fig 1. Illustration of crankcase K-58

2.3 Machining process flow

The crankcase machining line consists of a sequential process starting from dowel pressing to final leak testing, as illustrated in Figure 2. Each machining step is divided into operational processes (OP20-OP130) with designated workstations.

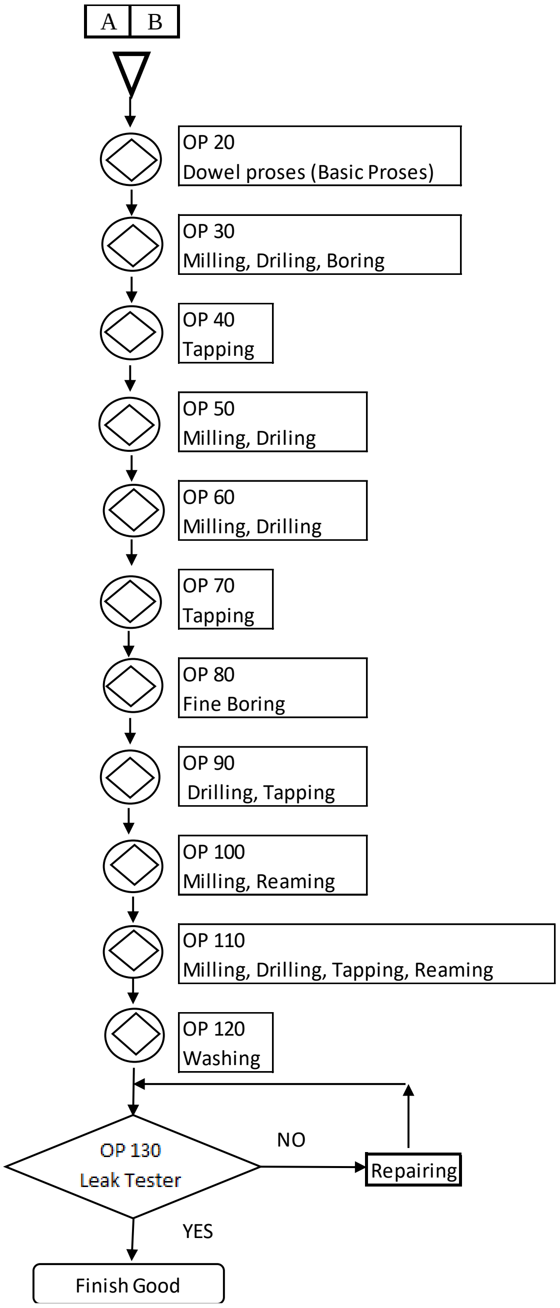

Fig 2. Machining process flow of crankcase K-58

2.4 Data processing

2.4.1 OEE calculation

Overall Equipment Effectiveness (OEE) is calculated using three key indicators: availability, performance, and quality (Eq. 1-3). This metric is widely used to evaluate equipment efficiency in manufacturing operations [15]. According to [16], the OEE framework enables consistent benchmarking of equipment performance across production shifts and lines.

$$Availability = \left(\frac{Operating\ Time}{Loading\ Time}\right) x100\% \qquad (1)$$

$$Performance = \left(\frac{Ideal\ Cycle\ Time\ x\ Total\ Output}{Operating\ Time}\right) x100\% \qquad (2)$$

$$Quality = \left(\frac{Good\ Products}{Total\ Products}\right) x100\% \qquad (3)$$

2.4.1 Six big losses analysis

This method identifies and categorizes six major loss types that reduce equipment effectiveness: breakdowns, setup and adjustments, idling and minor stoppages, reduced speed, process defects, and reduced yield. Each category is quantified to determine which factors contribute most significantly to production losses [6].

2.4.2 FMEA and RPN calculation

FMEA is used to analyze potential failure modes in the production process. Each failure mode is assessed based on severity, occurrence, and detection. The Risk Priority Number (RPN) is calculated as Eq. 4:

$$RPN = Severity\ x\ Occurrance\ x\ Detection \qquad (4)$$

This approach helps prioritize which failure modes should be addressed first to prevent system breakdowns [8]. FMEA-based prioritization has also proven effective in reducing reactive maintenance efforts, as shown by [16] in their study on metal part machining.

2.5 TPM and FMEA integration

The integration of Total Productive Maintenance (TPM) and FMEA enables proactive and systematic improvements. TPM focuses on preventive maintenance and involving operators in maintaining equipment, while FMEA ensures that the most critical failure modes are identified and mitigated through corrective actions. Combining both approaches improves reliability, reduces unplanned downtime, and supports sustainable productivity improvement [7]. This synergy is further validated by [17], who noted that integrating TPM pillars with FMEA significantly reduced OEE losses in assembly lines.

2.6 Analysis framework

This study follows a systematic framework to identify, analyze, and improve machine performance in the crankcase K-58 machining line. The stages are outlined as follows:

1. OEE Evaluation:
   Measure the baseline effectiveness of the machining line using Availability, Performance, and Quality indicators.
2. Six Big Losses Identification:
   Break down production losses into six categories to determine the dominant contributors to inefficiency [6].
3. Pareto Analysis:
   Visualize the frequency of machine-related failures to prioritize issues with the highest occurrence [4].
4. FMEA Application:
   Assess failure modes based on Severity, Occurrence, and Detection to calculate RPN and prioritize corrective actions [8].
5. TPM-FMEA Integration:
   Combine preventive maintenance actions with prioritized failure mitigation strategies to reduce downtime and improve OEE [7].
6. Post-Improvement Evaluation:
   Recalculate OEE after implementing improvements and compare it with initial conditions to assess impact.

3 Result and discussion

3.1 Data collection and production output

The research was conducted on the K-58 crankcase machining line, which operates within a manufacturing facility producing engine components for two-wheeled vehicles. The production line consists of multiple automated and semi-automated stations performing operations such as milling, drilling, tapping, boring, and leak testing. Each operation is assigned a code ranging from OP20 to OP130, where both the left and right crankcase variants are processed in a linear sequence without changing the line configuration.

To understand the baseline performance of the line, production output data from January to December 2024 was collected. The data includes total production targets, actual finished goods, and rejected units. The monthly averages are summarized in Table 1.

Table 1. Average monthly production output

Category	Quantity (units)
Target Output	27,264
Finished Goods	24,305
Rejected Parts	293

From the recorded data, the line achieved an average output rate of approximately 89.2% compared to the monthly target, indicating a performance shortfall. Although the defect rate (rejected parts) appears relatively low at 1.2%, the cumulative effect of cycle time deviations, frequent insert replacements, and minor stoppages contributed significantly to overall performance degradation.

This data serves as a critical input for calculating the Overall Equipment Effectiveness (OEE) as well as identifying major sources of efficiency losses, which are further explored in the following subsections.

3.2 Machine downtime and net production time

The machining line's availability is strongly influenced by unplanned downtime events. Throughout 2024, several machines experienced breakdowns with varying frequency and duration. Downtime records included both minor stoppages and major breakdowns requiring component replacement or maintenance intervention. The machines with the most significant downtime were the fine boring and leak test stations, with individual events lasting from 15 minutes up to 2.5 hours.

In addition, the net production time, defined as the actual machining duration excluding breaks and downtimes, was monitored monthly. On average, each working shift recorded approximately 386.55 minutes of net productive time out of a total 480-minute shift. This corresponds to an average availability rate of 80.53%, reflecting the impact of both scheduled and unscheduled interruptions.

3.3 Cycle time in the crankcase K-58 machining line

Cycle time consistency is a crucial factor affecting the line's performance rate. The machining process was designed with a target cycle time of 68.40 seconds per unit, including transfer time. However, based on observation and time study analysis, the actual average cycle time was recorded at 78.40 seconds, exceeding the design cycle time by approximately 10 seconds.
This deviation was largely due to:

1. Frequent tool changeovers (especially inserts on fine boring machines),
2. Operator delay during part loading and unloading,
3. Minor interruptions not classified as full downtime (e.g., chip cleaning, alignment checking).

The prolonged cycle time contributed to a significant performance loss, which is accounted for in the subsequent OEE analysis.

3.4 Breakdown frequency in the machining line

Failure frequency analysis was conducted to determine the most critical equipment and identify patterns in mechanical or operational failures. Table 2 summarizes the monthly breakdown of events by machine type. Breakdown frequency in machining line K-58 in the Pareto chart is shown in Fig. 3.

Table 2. Breakdown frequency on the machining line

Machine/Station	Monthly Breakdown Events
Fine Boring	12
Leak Test	8
CNC Drilling Center	7
Index Table	5
Tapping Unit	4

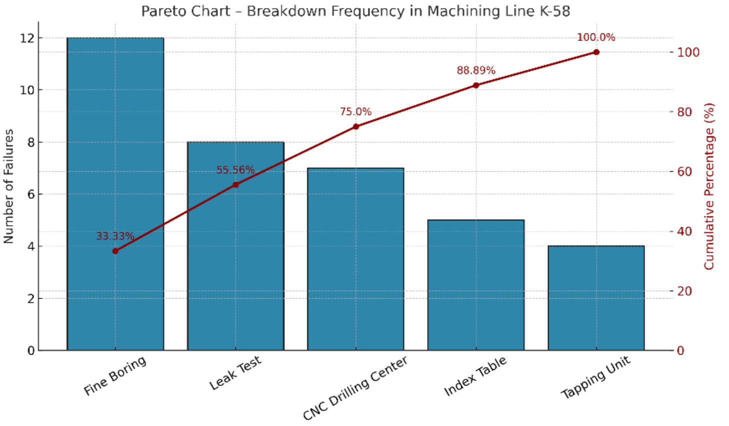

Fig. 3. Breakdown frequency in machining line K-58

The fine boring machine exhibited the highest failure rate, largely associated with insert wear, improper tool seating, and inconsistent coolant delivery. These frequent breakdowns not only disrupted the flow but also increased the time required for diagnosis and recovery. The leak testing station also experienced recurring pneumatic seal failures that led to machine unavailability and production delays.

The breakdown frequency data supports the need for a structured approach to maintenance prioritization using FMEA and TPM, as further explained in the discussion on Six Big Losses and failure risk assessment.

3.5 OEE calculation and analysis

The evaluation of equipment performance on the K-58 machining line was carried out using the Overall Equipment Effectiveness (OEE) framework, which integrates three key metrics: Availability, Performance, and Quality. Data was collected monthly throughout 2024 to analyze trends and determine areas for improvement.

The monthly average values of the OEE components are shown in Fig. 4, representing 12 months of continuous operation.

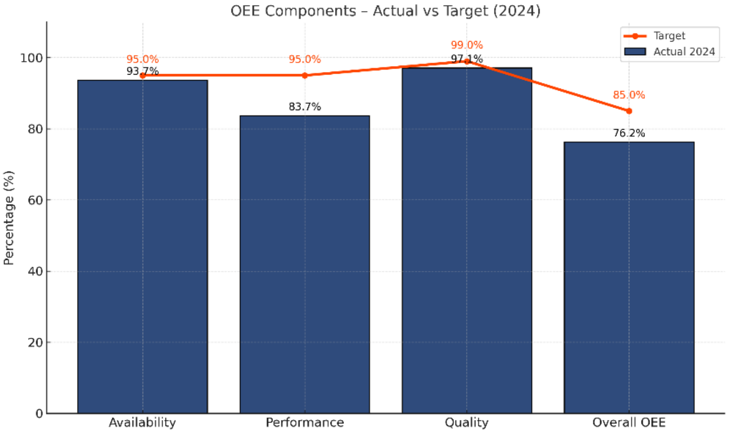

Fig. 4. Average OEE components in 2024

The OEE values show that:

1. Availability remained relatively stable throughout the year, averaging 93.7%. This indicates that the line experienced minimal unplanned downtime, although frequent tool changeovers and short stops still occurred.
2. Performance, however, consistently stayed below the ideal level, averaging 83.7%. This reduction was primarily caused by prolonged cycle times due to insert replacements, chip cleaning, and slow part handling-similar to findings in previous machining studies [6].

3. Quality averaged 97.1%, which is considered acceptable by internal quality standards, though still slightly below world-class levels (>99%).

The cumulative OEE result for 2024 was 76.2%, significantly lower than the global benchmark of 85% for world-class manufacturing performance [4]. This result reflects similar findings reported by [18], who found that machining cells with inconsistent setup times and tool change delays rarely exceeded 80% OEE. This indicates that although machine uptime was sufficient, actual productive output was hindered by efficiency and quality losses.

The analysis also revealed that:

1. The performance rate was the most critical loss factor, driven by deviations in actual cycle time compared to the standard (78.4 seconds vs. 68.4 seconds).
2. The reduced speed loss category was found to have the highest impact on overall performance loss, as confirmed in the following Six Big Losses analysis.

These findings serve as a diagnostic foundation for targeted improvement actions using TPM and FMEA in the subsequent stages.

3.6 Six Big Losses Analysis

The six major categories of production loss were evaluated on the K-58 machining line using the Six Big Losses framework, which is integral to the TPM methodology. This analysis quantifies the primary causes of efficiency losses beyond simple machine uptime.

In 2024, the largest contributor to total loss was Reduced Speed Losses, which accounted for 14.21% of available time. This was followed by Set Up and Adjustment Losses (4.30%), and Defect Losses (2.81%). The complete breakdown is shown in Table 3 and Fig. 5.

Table 3. Six big losses K-58 machining line

Loss Category	Loss (%)
Reduced Speed Losses	14.21
Set Up and Adjustment	4.30
Defect Losses	2.81
Idling & Minor Stoppage	2.09
Breakdown Losses	1.97
Reduced Yield Losses	0.06

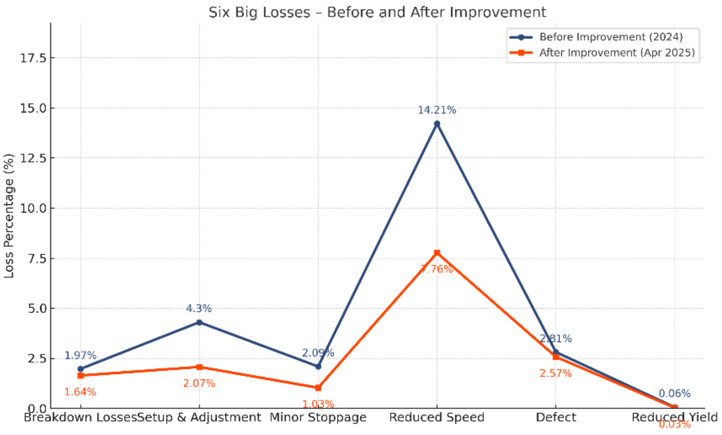

Fig. 5. Six big losses before and after improvement

The high level of reduced speed losses was primarily caused by:

- Manual insert replacement processes requiring machine stops.
- Inconsistent chip evacuation.
- Operators working below standard cycle time due to repeated visual checks.

Comparable dominant losses were observed by [19] in their TPM-based study on CNC assembly lines, where reduced speed and adjustment times consistently ranked highest. Set up and adjustment losses were mainly triggered by manual tool setting activities that lacked clear work instructions or visual standards. Minor stoppages also occurred frequently during rechecking or repositioning of workpieces, typically not recorded in downtime logs.

After the improvement interventions implemented in April 2025, which included TPM-based autonomous maintenance, coolant optimization, and standardized tool setting procedures, the total loss percentage dropped significantly. The Reduced Speed Losses were nearly halved to 7.76%, while Setup Losses fell to 2.07%, and Defect Losses slightly decreased to 2.57%.

This outcome supports previous findings by [15], who emphasized that operator-driven causes such as tool wear and handling speed contribute significantly to productivity erosion in CNC-based machining.

3.7 FMEA analysis and risk prioritization

To systematically identify and mitigate critical failure points on the K-58 machining line, a Failure Mode and Effect Analysis (FMEA) was conducted. Fourteen failure modes were identified from historical breakdown records and observations, then evaluated using three key parameters:

1. Severity (S): Impact level on the production process if the failure occurs.
2. Occurrence (O): Likelihood of the failure happening.
3. Detection (D): Probability that the failure can be detected before affecting the output.

Each failure mode was scored on a scale of 1 to 10, and a Risk Priority Number (RPN) was calculated. The results were then ranked to determine which failures required urgent corrective action. The top five high-risk failures are presented in Table 4.

Table 4. Top 5 failure modes based on RPN

No.	Failure Mode	S	O	D	RPN	Category
1	Frequent insert replacement in fine boring	9	8	3	216	Reduced Speed Loss
2	Manual insert setting without fixture	8	7	3	168	Setup/Adjustment Loss
3	Coolant concentration instability	7	6	4	168	Defect Loss
4	Pneumatic failure in leak test unit	8	5	4	160	Breakdown Loss
5	Manual deburring delays	7	6	3	126	Minor Stoppage Loss

The most critical failure was the frequent insert replacement on the fine boring machine (RPN=216). This failure not only caused speed reduction but also forced additional inspections due to burr formation. Manual insert setting (RPN=168) ranked second, primarily because the absence of a positioning fixture increased tool misalignment risks and setup time. This is consistent with results from [20], who identified tool-related failures as major contributors to performance degradation in turning operations.

Instability in coolant concentration contributed to surface defects and tool wear, indicating a need for more reliable coolant monitoring and control systems.

The high RPN scores validate the importance of integrating FMEA with Total Productive Maintenance (TPM), which allows teams to shift from reactive to preventive actions, as also emphasized by [7].

The insights gained from this FMEA served as the foundation for targeted improvements, which are elaborated in the following section.

3.8 TPM-based improvement actions

Based on the results of the OEE analysis, Six Big Losses evaluation, and FMEA prioritization, a set of improvement actions was developed and implemented using the principles of Total Productive Maintenance (TPM).

The TPM improvement activities were implemented through four key aspects:

1. Autonomous Maintenance: Operators were trained to perform routine cleaning, lubrication, and basic inspections such as insert wear checks and coolant-level verification. Visual controls were strengthened using colored indicators and standardized inspection checklists.
2. Planned Maintenance: The maintenance team established a weekly preventive-maintenance schedule targeting common failure points, including pneumatic valves, coolant-flow regulators, and fine boring tool holders.
3. Skill Development: Training sessions were conducted to enhance operator competency in setup adjustments, insert installation, torque setting, and troubleshooting of minor abnormalities.
4. Quality and Coolant Control: Coolant concentration and flow were monitored daily to reduce the likelihood of tool burning and dimensional inconsistencies.

These improvements were implemented between January and March 2025 and closely monitored for impact on key performance indicators (KPIs).

The approach reflects effective integration of TPM and FMEA as complementary tools for sustainable production efficiency, as suggested by studies such as [7][8].

3.9 Post-improvement performance evaluation

Following the implementation of TPM-based corrective actions and FMEA-informed prioritization, the K-58 machining line was re-evaluated in April 2025 to measure the impact of the improvement program.

A comparative analysis of the key performance indicators before and after implementation is shown in Table 5.

Table 5. Comparison of OEE metrics before and after improvement

Metric	**2024 (Average)**	**April 2025**	**Δ Change (%)**
Availability Rate	93.7%	96.3%	+2.6%
Performance Rate	83.7%	91.2%	+7.5%
Quality Rate	97.1%	97.4%	+0.3%
Overall OEE	**76.2%**	**85.5%**	**+9.3%**

The Overall Equipment Effectiveness (OEE) increased from 76.2% to 85.5%, surpassing the company's target and aligning with world-class standards. This improvement was primarily driven by:

- A 7.5% increase in performance, due to reduced insert setup frequency and stabilized cycle times.
- A 2.6% increase in availability, attributed to reduced unplanned downtime and better preventive maintenance execution.
- A slight quality improvement, resulting from optimized coolant control and enhanced setup accuracy.

In addition, losses associated with the Six Big Losses framework were also significantly reduced, as visualized in Fig. 6.

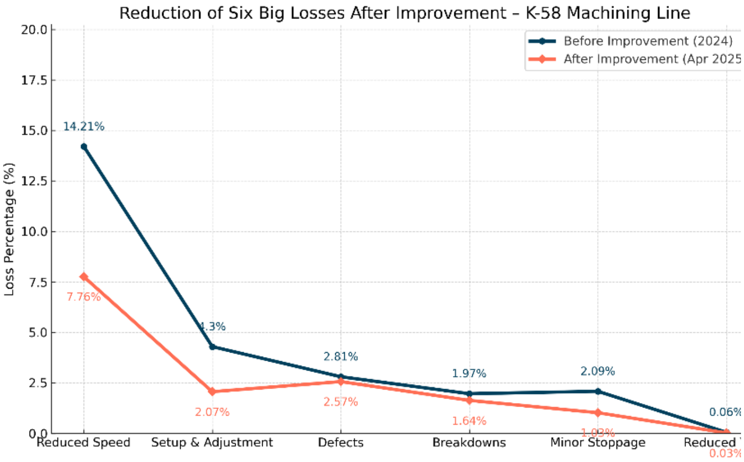

Fig. 6. Reduction of six big losses

The most significant reductions were observed in:

- Reduced Speed Losses: decreased from 14.21% to 7.76%
- Setup and Adjustment Losses: from 4.30% to 2.07%
- Minor Stoppage Losses: from 2.09% to 1.03%

These results confirm that integrating TPM and FMEA led to a measurable and sustainable improvement in production efficiency on the K-58 line. The approach can be recommended for replication in other high-precision machining cells within the same facility or similar environments. A similar impact was reported by [21], where TPM-FMEA integration resulted in a 7% OEE improvement in a valve machining cell.

The improvement in OEE after TPM–FMEA implementation demonstrates that the dominant losses were successfully addressed. The reduction in Reduced Speed Losses was primarily due to more stable cycle times achieved through improved insert-change procedures and controlled coolant conditions. Meanwhile, the reduction in Setup and Adjustment Losses resulted from operator skill enhancement and faster tool alignment. These findings are consistent with previous studies reporting that TPM combined with structured failure analysis can significantly improve machining stability and equipment reliability.

6 Conclusion

This study successfully improved the production effectiveness of the Crankcase K-58 machining line through the integrated application of TPM and FMEA. The initial performance evaluation revealed that the line achieved an OEE of 76.2% in 2024, with significant losses attributed to reduced speed and setup activities. After implementing a series of TPM-based improvements, the OEE increased to 85.5%, meeting the company's operational target. Reduced Speed Losses decreased by more than 45%, while Setup and Adjustment Losses were lowered by over 50%.

These results confirm that combining TPM and FMEA provides a structured approach for identifying critical failure modes, prioritizing improvement actions, and enhancing overall machining-line reliability. Future research may incorporate predictive maintenance analytics and sensor-based monitoring to further enhance the long-term performance of machining operations.

References

[1] L. Lukmandono, A. Setiawan, and E. Purwanto, "Analysis of total productive maintenance (TPM) and failure mode and effect analysis (FMEA) to improve machine effectiveness: A study on Indonesia's sugar mills," *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 885, no. 1, p. 012063, 2020. doi: 10.1088/1757-899X/885/1/012063.

[2] Y. Sari, E. W. Santoso, and A. S. Pratama, "Implementation of failure mode and effect analysis (FMEA) and overall equipment effectiveness (OEE) in SMEs: A case study in manufacturing," *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 1072, no. 1, p. 012068, 2021. doi: 10.1088/1757- 899X/1072/1/012068.

[3] N. Nordin, B. H. Ahmad, M. Z. Hassan, and M. A. Emran, "Increasing overall equipment effectiveness in automotive company using DMAIC and FMEA method," *J. Eng. Sci. Appl.*, vol. 53, no. 1, pp. 70–85, 2020. doi: 10.18280/jesa.530107.

[4] P. Tsarouhas, "Overall equipment effectiveness (OEE) evaluation for an automated ice cream production line: A case study," *Int. J. Prod- uct. Perform. Manage.*, vol. 69, no. 5, pp. 1009–1032, 2020. doi: 10.1108/IJPPM-03-2019-0126.

[5] P. Viveros Gunckel, R. Amigo, and F. Kristjanpoller, "OEE im- provement in manufacturing systems: A case study in the min- ing industry," *J. Manuf. Syst.*, vol. 63, pp. 298–310, 2022. doi: 10.1016/j.jmsy.2022.04.005.

[6] M. Suryaprakash, M. V. S. Kumar, and R. S. Kumar, "Evaluation of overall equipment effectiveness in a manufacturing industry using fuzzy and AHP approach," *Mater. Today: Proc.*, vol. 46, pp. 8964–8970, 2021. doi: 10.1016/j.matpr.2020.12.1040.

[7] S. Sahoo and S. Yadav, "Overall equipment effectiveness (OEE) improvement through automated monitoring in manufactur-ing," *Procedia Manuf.*, vol. 51, pp. 1455–1461, 2021. doi: 10.1016/j.promfg.2020.10.202.

[8] A. Kushwaha, S. K. Sharma, and R. K. Mishra, "Enhancing OEE through total productive maintenance in a manufacturing setup," *Int. J. Adv. Manuf. Technol.*, vol. 124, no. 3, pp. 943–956, 2023. doi: 10.1007/s00170-022-10678-5.

[9] M. H. Badli Shah, "Improvement of overall equipment effectiveness of machining centre using TPM," *Mater. Today: Proc.*, vol. 50, no. 5, pp. 1975–1980, 2022. doi: 10.1016/j.matpr.2020.02.042.

[10] B. R. Borkar, P. S. Talankar, and S. S. Kulkarni, "Optimization of overall equipment effectiveness using design of experiments in a manu- facturing setup," *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 954, no. 1, p. 012017, 2020. doi: 10.1088/1757-899X/954/1/012017.

[11] K. Antosz, D. Stadnicka, and R. M. C. Ratnayake, "Development of a model to integrate the TPM and OEE concepts for improving mainte- nance management in manufacturing companies," *Appl. Sci.*, vol. 10, no. 18, p. 6538, 2020. doi: 10.3390/app10186538.

[12] O. Durán and P. A. Durán, "Prioritization of maintenance tasks in a manufacturing system using FMEA and TOPSIS," *Int. J. Adv. Manuf. Technol.*, vol. 108, no. 5, pp. 1801–1815, 2020. doi: 10.1007/s00170-020-05471-8.

[13] M. Singh, R. K. Yadav, and V. K. Soni, "Lean Six Sigma implementation in manufacturing industry: A case study on process improvement," *J. Ind. Eng. Int.*, vol. 16, no. 1, pp. 145–157, 2020. doi: 10.1007/s40092-019-00332-6.

[14] S. Bajpai, A. K. Sharma, and R. K. Gupta, "Critical factors influencing OEE in automated manufacturing systems," *Mater. Today: Proc.*, vol. 46, pp. 8971–8977, 2021. doi: 10.1016/j.matpr.2020.12.1041.

[15] P. Tsarouhas, "Overall equipment effectiveness (OEE) improve- ment through integrating lean maintenance and quality control ac- tivities," *Qual. Eng.*, vol. 34, no. 2, pp. 245–258, 2022. doi: 10.1080/08982112.2022.2084397.

[16] T. Ferreira, A. A. Baptista, S. G. Azevedo, and S. I. Antunes, "TPM implementation in SMEs: A case study from Portugal," *Int. J. Product. Perform. Manage.*, vol. 71, no. 8, pp. 3285–3307, 2022. doi: 10.1108/IJPPM-01-2021-0039.

[17] V. Patel and R. Patel, "Analyzing barriers to total productive mainte- nance (TPM) implementation using interpretive structural modeling," *Int. J. Qual. Reliab. Manage.*, vol. 39, no. 6, pp. 1412–1432, 2022. doi: 10.1108/IJQRM-07-2021-0228.

[18] K. C. Ng, K. E. Chong, and G. G. G. Goh, "Improving overall equipment effectiveness (OEE) of thick film printing machine using lean six sigma approach," *Int. J. Integr. Eng.*, vol. 11, no. 9, pp. 204–215, 2019. doi: 10.30880/ijie.2019.11.09.022.

[19] A. Almaiman and S. Ahmad, "Evaluation of overall equipment effec- tiveness in a food processing industry: A case study," *Procedia Manuf.*, vol. 51, pp. 1469–1475, 2020. doi: 10.1016/j.promfg.2020.10.204.

[20] A. Costa, J. C. F. Silva, and J. P. Sousa, "Implementation of total productive maintenance in a manufacturing SME: A case study," *Procedia Manuf.*, vol. 51, pp. 1462–1468, 2020. doi: 10.1016/j.promfg.2020.10.203.

[21] A. Chiarini and E. Vagnoni, "TQM, JIT and TPM: Their impact on op- erational and financial performance in manufacturing companies," *Total Qual. Manage. Bus. Excellence*, vol. 32, no. 7-8, pp. 777–791, 2021. doi: 10.1080/14783363.2019.1641078.