

# Adaptive Maintenance Strategy in Natural Stone Processing Industry: Integrating OEE-FMEA-Based Priority Matrix in the i-TPM-Lean+

Ahmed Jabari<sup>1</sup>, Ahmad Atif Fikri<sup>1\*</sup>, Muhammad Alfian Mizar<sup>1</sup>

<sup>1</sup> Department of Mechanical and Industrial Engineering, Universitas Negeri Malang

Jl. Semarang 5, Malang, 65145, East Java, Indonesia

\*Corresponding author; E-mail: [atif.fikri.ft@um.ac.id](mailto:atif.fikri.ft@um.ac.id)

---

## ABSTRAK

Penelitian ini mengusulkan model hibrida yang mengintegrasikan total productive maintenance (TPM) dan alat lean manufacturing untuk meningkatkan efektivitas mesin pada sebuah perusahaan pengolahan marmer di Indonesia. Tingginya waktu henti (downtime), ketidakefisienan kinerja, dan kerugian kualitas diidentifikasi sebagai faktor utama penyebab rendahnya overall equipment effectiveness (OEE). Sebuah kerangka terstruktur yang disebut i-TPM-Lean+ diimplementasikan dengan mengombinasikan pengukuran OEE dan failure mode and effect analysis (FMEA) untuk memprioritaskan strategi perbaikan. Pilar-pilar TPM seperti autonomous maintenance, planned maintenance, dan focused improvement diterapkan bersama dengan alat lean seperti 5S dan single minute exchange of dies (SMED). Data operasional nyata dikumpulkan selama 30 hari sebelum dan sesudah implementasi untuk mengevaluasi perubahan kinerja mesin. Hasil penelitian menunjukkan adanya peningkatan signifikan pada OEE dari 59% menjadi 70%, dengan penurunan downtime sebesar 67% serta peningkatan ketersediaan dari 79% menjadi 88%, peningkatan kinerja dari 81% menjadi 84%, dan peningkatan kualitas dari 92% menjadi 94%. Benchmarking dengan penelitian terkait lainnya menegaskan bahwa pendekatan terintegrasi ini dapat meningkatkan keandalan mesin dan efisiensi produksi. Model yang diusulkan memberikan referensi praktis bagi perusahaan manufaktur yang ingin meningkatkan kinerja operasional melalui pendekatan gabungan TPM-Lean, yang didukung dengan prioritas berbasis data dan evaluasi sistematis.

**Kata Kunci** : total productive maintenance, lean manufacturing, model hibrida, 5S, perbaikan perawatan.

## ABSTRACT

*This study proposes a hybrid model integrating total productive maintenance (TPM) and Lean Manufacturing tools to improve machine effectiveness in a marble processing company in Indonesia. High downtime, performance inefficiencies, and quality losses were identified as key contributors to low overall equipment effectiveness (OEE). A structured framework, called i-TPM-Lean+, was implemented by combining OEE measurement with failure mode and effect analysis (FMEA) to prioritize improvement strategies. TPM pillars such as Autonomous Maintenance, Planned Maintenance, and Focused Improvement were applied alongside Lean tools including 5S and single minute exchange of dies (SMED). Real operational data was collected for 30 days before and after implementation to evaluate changes in machine performance. The results revealed a substantial improvement in OEE from 59% to 70%, with notable reductions in downtime (-67%) and increases in availability (from 79% to 88%), performance (from 81% to 84%), and quality rate (from 92% to 94%). Benchmarking with other relevant studies confirmed that this integrated approach leads to enhanced machine reliability and production efficiency. The proposed model offers a practical reference for manufacturing companies seeking to improve operational performance through a combined TPM-Lean approach, supported by data-driven prioritization and systematic evaluation.*

**Keywords:** total productive maintenance, lean manufacturing, hybrid model, 5S, maintenance improvement.

---

## INTRODUCTION

Manufacturing businesses are constantly under pressure to increase productivity, guarantee equipment dependability, and react quickly to customer demands in the fiercely competitive global market of today. These difficulties are particularly noticeable in process-intensive sectors like the processing of marble and natural stone, where profitability and productivity are directly impacted by ongoing machine availability. Operations can be disrupted by frequent downtime, mechanical failures, and inefficient processes, which can result in large losses and a decline in competitiveness [1]. Companies must implement systematic and adaptive maintenance strategies that fit their unique operational contexts in addition to strong technical capabilities if they want to stay sustainable [2].

Maximizing operational performance, reducing unplanned breakdowns, and prolonging asset lifespans all depend on achieving excellence in maintenance. Reactive, preventive, predictive, and proactive core maintenance strategies are usually combined based on operational demands and asset criticality [3]. Among these, proactive maintenance has drawn interest due to its capacity to address the underlying causes of failure, minimize needless downtime, and enhance performance metrics, e.g. reliability, availability, maintainability, and safety (RAMS) [4]. Unplanned downtime is a persistent problem in industries like marble processing, where abrasive materials and constant heavy loads cause unique wear on machinery used for cutting, polishing, and transporting stone [5]. Globally, total productive maintenance (TPM) is acknowledged as a successful approach to enhancing equipment dependability and engaging staff in preventative maintenance. Through autonomous maintenance, its fundamental tenets spread maintenance accountability beyond specialized teams to operators and support personnel, encouraging a sense of accountability and ownership at all levels [6]. By methodically addressing the so-called six big losses, i.e. breakdown losses, setup and adjustment losses, idling and minor stoppages, speed losses, process defects, and rework losses. TPM seeks to achieve zero breakdowns and zero defects [6][7]. By coordinating operational reliability with higher-level quality goals, TPM simultaneously facilitates total quality management (TQM) and boosts competitiveness in international markets [8].

Concurrently, lean manufacturing, which emphasizes waste reduction, process flow optimization, and optimizing customer value, has emerged as a key component of contemporary production systems [9]. Practical tools like 5S for workplace organization single-minute exchange of dies (SMED) for setup time reduction, and value stream mapping (VSM) for process mapping and waste identification are examples of lean strategies [10]. These techniques assist businesses in addressing shop floor inefficiencies and guaranteeing a steady, predictable flow of production. Lean and six sigma have developed into lean six sigma (LSS) 4.0 in the context of Industry 4.0, incorporating digital tools like IoT, AI, and advanced analytics to support continuous improvement efforts [11][12]. Lean's waste elimination and Six Sigma's defect reduction techniques are combined in LSS 4.0, which also uses digitalization to improve decision-making accuracy and responsiveness [12]. LSS 4.0 improves process performance in economic, operational, environmental, and ergonomic domains when appropriately applied [11].

Nevertheless, previous academic and industrial research shows that the application of TPM, Lean, and LSS tools is frequently dispersed and isolated, despite the fact that each tool has demonstrated benefits on its own [13]. Many businesses use TPM without properly integrating it with lean tools, or they do not match risk-based prioritization techniques with data-driven performance measures. Their efficacy is limited by this fragmented application, particularly when handling intricate failure modes or production environments with numerous interconnected inefficiencies. The way that failure mode and effect analysis (FMEA) and overall equipment effectiveness (OEE) are usually applied independently is a typical illustration of this disparity. The OEE is a popular quantitative performance metric that uses availability, performance, and quality metrics to capture losses [14]. Although OEE shows the amount of production time lost to various sources, it does not identify the underlying causes or assign a criticality rating. However, FMEA is a qualitative risk assessment tool that determines a risk Priority Number (RPN) by ranking failure modes according to severity, occurrence, and detection [15]. However, FMEA's operational impact is limited because it frequently lacks integration with real-time production data [16].

Because of this disconnect, businesses may be aware of the amount of production loss but lack a systematic approach to identify the cause and determine which improvement tools—TPM, Lean, or both—should be implemented first [17]. For industries that process natural stones, where equipment frequently breaks down and process conditions fluctuate, this research gap is especially pertinent. Maintenance and improvement efforts run the risk of becoming reactive rather than strategic in the absence of a clear, data-driven plan.

This study acknowledges this need and suggests a novel hybrid called i-TPM-Lean+ which is integrated total productive maintenance and lean manufacturing plus. The creation of a priority matrix that integrates qualitative FMEA risk scores with quantitative OEE loss data is the main innovation [18]. The model makes it possible to precisely rank failure modes and match them with specific improvement actions by comparing actual performance losses with risk priority numbers. For example, a TPM-based intervention like autonomous checks or preventive maintenance may be given priority if a failure mode has a high RPN and a major impact on availability [19]. Lean tools like SMED and 5S can be used to optimize workflows and cut down on setup time if performance losses are the main issue. When performance and availability are both significantly impacted, an integrated approach leveraging both TPM and Lean is deployed. The study will be conducted at PT BAS, an Indonesian marble processing company that heavily uses heavy machinery for handling, cutting, and polishing stone blocks, to validate this hybrid model [20]. To compute OEE and use FMEA to analyze major failure modes, real production data will be gathered, including downtime, machine output, setup times, and defect rates. To direct phased interventions and monitor improvements in availability, performance, quality, and OEE rates both before and after implementation, this evidence will be mapped into the priority matrix.

In conclusion, the goal of the suggested i-TPM-Lean+ is to close the gap between discrete performance evaluation and realistic risk-based decision-making. This model offers a useful tool for process-intensive industries looking to boost OEE with constrained resources by offering an organized, flexible approach to identifying, prioritizing, and fixing production losses. In order to confirm the model's generalizability and possible scalability for broader industrial application, this study also plans to compare its findings with pertinent international cases. Unlike previous hybrid models that apply TPM-Lean separately [17]-[20], this study introduces a\* data-driven priority matrix that dynamically matches OEE losses with FMEA-based risk scores (RPN) to select optimal tools (SMED for setup losses, TPM for breakdowns). This integration solves the industry's key challenge of misaligned improvement strategies where companies know their OEE losses but lack systematic methods to address root causes.

## METHODS

### Research Object and Setting

The study was conducted at PT BAS, a natural stone processing company in East Java, Indonesia. The study was primarily concerned with the stone crushing line, with a focus on critical equipment like the belt conveyor, conveyor motor, and jaw crusher, which were found to be the main causes of downtime and performance losses. Data on equipment effectiveness, such as downtime events, operating time, production output, and quality rate, were gathered during the study's 60-day operational period. By using accepted international standards, the data collection procedure was created to guarantee consistency and objectivity.

### Data Standards and Collection Guidelines

The following standards served as the foundation for the structured protocol used in the data collection procedures:

- ISO 14224:2016, which calls for the systematic collection of data on equipment reliability and maintenance performance.
- The society for maintenance and reliability professionals' (SMRP) best practices for measuring overall equipment effectiveness (OEE), which includes performance, quality, and availability metrics.
- TPM pillar guidelines, particularly for data checks for planned maintenance and autonomous maintenance.

Field observations, interviews with maintenance personnel and machine operators, and direct retrieval from production monitoring systems and machine logs were used to gather primary data. Production reports, maintenance logs, and shift logs from the company were the sources of secondary data. All data points were cross-checked with supervisors and maintenance logs to ensure data integrity. Triangulation between production engineers and quality control staff was used to address any discrepancies. The accuracy, verifiability, and reproducibility of the analysis of TPM, Lean tools, and their effects on machine performance—particularly OEE and downtime—were guaranteed by this standardized methodology.

## DATA COLLECTION AND ANALYSIS PROCEDURE

### Current OEE of The Stone Crusher Machine

The stone crusher machine's baseline overall equipment effectiveness (OEE) performance prior to the application of the i-TPM-Lean+ model is shown in this section. By integrating three essential elements, i.e availability, performance, and quality, the OEE metric offers a thorough understanding of equipment efficiency [13]. The machine's actual operational effectiveness under the current production and maintenance conditions is reflected in the current OEE. Field production data, including planned production time, total downtime, actual production output, and defective or reworked units, was gathered over a one-month period and used to calculate each OEE component (eq. 1) [21].

The Availability rate was calculated using the formula:

$$\text{Availability} = \frac{\text{Planned Production Time} - \text{Downtime}}{\text{Planned Production Time}} \times 100 \% \quad (1)$$

Whereas downtime comprises all documented stoppages brought on by mechanical failures, setup changes, or other disruptions, planned production time in this context refers to the total scheduled machine operation time per day [21]. The Performance rate was calculated following eq. 2.

$$\text{Performance} = \frac{\text{Ideal Output}}{\text{Actual Operating Time} \times \text{Ideal Cycle Time}} \times 100 \% \quad (2)$$

Whereas actual output is based on the measured daily stone throughput, Ideal Output is calculated by multiplying the ideal cycle time (kg/minute) by the effective operating time. The performance calculation took into account any losses brought on by decreased machine speed or small stoppages (eq. 3) [21].

$$\text{Quality} = \frac{\text{Good Output}}{\text{Good Output}} \times 100 \% \quad (3)$$

In this context, good output refers to the amount of product that satisfied quality standards without needing to be reworked or scrapped, whereas the total output encompasses both good and defective/reworked items (eq. 4) [21].

$$\text{OEE} = \text{Availability} \times \text{Performance} \times \text{Quality} \quad (4)$$

This breakdown makes it possible to pinpoint the precise areas that most strongly contribute to equipment inefficiency, whether they are speed-, downtime-, or defect-related. Before any improvement initiatives were implemented, the stone crusher machine's calculated values for availability, performance, quality, and the resulting OEE (Table 1).

The initial data show availability of 79%, performance of 81%, and quality of 95%, resulting in an overall equipment effectiveness (OEE) of 59% as shown in Table 1. Although the quality rate meets international standards, both performance and availability are below the typical benchmarks of 95% and 90%, respectively, leading to an OEE far below the world-class level of 85%. A one-sample t-test ( $M = 58.9$ ,  $SD = 4.35$ ,  $N = 60$ ) confirmed that the mean OEE was significantly lower than the benchmark,  $t(59) = 46.48$ ,  $p < 0.0001$ , 95% CI  $[-27.22, -24.98]$ . This result underscores the urgent need for corrective maintenance and process improvement through the i-TPM-Lean+ model.

Table 1. Current OEE of the stone crusher machine

No	Date	Availability Rate [%]	Performance Rate [%]	Quality Rate [%]	OEE Rate [%]
1	April 1, 2025	84%	79%	96%	64%
2	April 2, 2025	76%	83%	92%	58%
3	April 3, 2025	78%	81%	95%	60%
4	April 4, 2025	82%	80%	93%	61%
5	April 5, 2025	78%	90%	96%	67%
6	April 7, 2025	79%	77%	88%	54%
7	April 8, 2025	81%	77%	90%	57%
8	April 9, 2025	77%	82%	95%	60%
9	April 10, 2025	83%	81%	93%	62%
10	April 11, 2025	81%	81%	90%	59%
11	April 12, 2025	77%	77%	93%	55%
12	April 14, 2025	76%	83%	88%	56%
13	April 15, 2025	77%	82%	90%	57%
14	April 16, 2025	79%	78%	93%	57%
15	April 17, 2025	83%	95%	95%	75%
16	April 18, 2025	84%	78%	93%	61%
17	April 19, 2025	84%	79%	92%	61%
18	April 21, 2025	76%	80%	89%	54%
19	April 22, 2025	79%	79%	89%	56%
20	April 23, 2025	83%	78%	95%	61%
21	April 24, 2025	79%	81%	95%	60%
22	April 25, 2025	80%	77%	91%	56%
23	April 26, 2025	75%	78%	90%	53%
24	April 27, 2025	77%	88%	95%	65%
25	April 28, 2025	79%	79%	93%	58%
26	April 29, 2025	81%	82%	89%	59%
27	April 30, 2025	75%	78%	93%	54%
28	May 1, 2025	77%	80%	92%	56%
29	May 2, 2025	77%	80%	94%	58%
30	May 3, 2025	76%	77%	90%	53%
31	May 5, 2025	78%	80%	90%	56%
32	May 6, 2025	77%	78%	96%	57%
33	May 7, 2025	76%	77%	89%	52%
34	May 8, 2025	83%	83%	95%	65%
35	May 9, 2025	76%	83%	93%	58%
36	May 10, 2025	77%	82%	89%	56%
37	May 12, 2025	81%	79%	96%	61%
38	May 13, 2025	78%	77%	95%	58%
39	May 14, 2025	82%	81%	93%	62%
40	May 15, 2025	77%	79%	96%	58%
41	May 16, 2025	81%	77%	89%	56%
42	May 17, 2025	84%	80%	89%	60%
43	May 19, 2025	78%	77%	91%	54%
44	May 20, 2025	80%	83%	92%	60%
45	May 21, 2025	78%	78%	95%	58%
46	May 22, 2025	81%	81%	96%	63%
47	May 23, 2025	78%	85%	90%	60%
48	May 24, 2025	77%	79%	91%	56%
49	May 26, 2025	75%	76%	94%	54%
50	May 27, 2025	79%	87%	89%	61%
51	May 28, 2025	82%	72%	91%	53%
52	May 29, 2025	82%	88%	94%	68%
53	May 30, 2025	76%	92%	93%	65%
54	May 31, 2025	82%	82%	92%	62%
55	June 2, 2025	82%	80%	94%	62%
56	June 3, 2025	84%	79%	95%	64%
57	June 4, 2025	79%	88%	90%	62%
58	June 5, 2025	75%	74%	95%	53%
59	June 7, 2025	77%	87%	89%	60%
60	June 9, 2025	80%	74%	90%	53%
	Average	79%	81%	92%	59%

### Failure Mode and Effects Analysis (FMEA)

The causes of poor OEE performance were further examined using a combined six big losses and failure mode and effects analysis (FMEA). This method aided in classifying the different kinds of losses that were encountered as well as evaluating the seriousness, regularity, and detectability of particular machine failures [17]. The findings of this integrated analysis are shown in Table 2, which also highlights the important elements and their corresponding RPN values.

Table 2. FMEA assessment of stone crusher machine

Component	Failure mode	Impact	S	O	D	RPN
Motor conveyor	Overheating, damage	Line stops completely	9	8	6	432
Setup	Long, non-standard setup	Delayed production	9	10	5	450
Primary jaw hopper	Misaligned, loose	Material spillage	8	6	4	192
Primary feeder	Unstable material flow	Slower process	7	7	4	196
Tertiary jaw press	Worn-out component	Reduced pressure	8	4	3	96
Conveyor belt 1	Torn or slipped belt	Interrupted transport	8	6	3	144

The assessment of severity (S), occurrence (O), and detection (D) was conducted using a 1–10 Likert scale, where higher values indicate higher risk or difficulty of detection. Severity (S): 1 = No effect, 10 = Hazardous or causes complete process shutdown. Occurrence (O): 1 = Failure unlikely (<0.01%), 10 = Failure almost certain (>50%). Detection (D): 1 = Easily detected by control systems, 10 = Almost impossible to detect before failure occurs. This scale follows the standard guidelines for failure mode and effect analysis (FMEA) as recommended by AIAG & VDA and Stamatis. Based on the prioritization matrix in Table 2, the setup and motor conveyor problems exhibit the highest RPN scores of 450 and 432, respectively, placing them in the Very High Priority category. These modes are therefore emphasized because they represent the most critical risks that significantly affect equipment availability and performance. The setup problem, classified as a Setup & Adjustment loss, prolongs machine downtime during switchovers and contributes directly to performance degradation. Meanwhile, motor conveyor failure, categorized as a Breakdown loss, causes machine stoppage and total production interruption. Other failure modes such as jaw hopper misalignment (RPN = 192), feeder instability (RPN = 196), and conveyor belt wear (RPN = 144) fall into the Medium or Low priority categories. Although their individual effects are less severe, their recurring nature can cumulatively impact OEE performance. Hence, these modes are still addressed through TPM-based monitoring and 5S implementation, as outlined in the RPN categorization. The final prioritization and strategy selection were validated by the joint decision-making team consisting of production and maintenance managers, in alignment with FMEA risk evaluation practices.

## RESULTS AND DISCUSSION

### Prioritization Matrix and Strategy Selection

By combining the RPN values from the FMEA with the related OEE losses, a prioritization matrix was created to identify the best maintenance and improvement plans. This matrix ranks failure modes according to their actual impact on equipment performance as well as their risk, enabling a data-driven approach to intervention selection. Failure modes that exhibit both a high RPN and a notable OEE loss are given priority for prompt remedial action. Table 3 prioritization matrix offers an organized and transparent way to choose improvement tactics. Failure modes like setup inefficiencies and motor conveyor breakdowns, which have both high RPN and high OEE losses, are given the highest priority and receive specialized interventions. Lean tools, mainly SMED to reduce setup time and 5S to standardize the workspace, are used to reduce setup losses. On the other hand, TPM concepts, such as regular preventive maintenance and autonomous inspection procedures, are best suited for managing high-risk equipment failures, such as motor conveyor breakdowns. The final decision regarding prioritization and the implementation of improvement strategies should be made by the management team responsible for production operations, ensuring that the selected actions align with organizational goals and available resources.

TPM and visual management techniques are used to target moderate-priority issues, like the feeder primer and jaw hopper, in order to stabilize material flow and minimize minor stops. Unless

their conditions worsen, lower-priority components, such as the tertiary jaw press, are advised for visual monitoring only. By concentrating on high-impact failures and keeping an eye on reoccurring but less important problems, this methodical approach guarantees that improvement resources are distributed efficiently and proportionately. TPM, SMED, and 5S are the three main tools that will be targeted for deployment as part of the improvement strategy, which is based on the results of the prioritization. These tools were chosen to minimize disruption to daily operations, maintain simplicity in execution, and match the features of the most critical failure modes. The operational function and priority level of every machine component are matched with the implementation activities.

Table 3. Integrated prioritization matrix (RPN + OEE loss) and recommended strategy

Component	RPN	OEE Loss [%]	Priority Level	Recommended Strategy
Setup	450	60	very high	Lean: SMED + 5S
Motor conveyor	432	59	very high	TPM Preventive
Jaw hopper	192	59	medium	TPM + 5S
Feeder primer	196	59	medium	TPM
Tertiary jaw press	96	57	low	Monitoring only
Conveyor belt	144	58	medium	TPM (visual check)

### Identification of Six Big Losses by Pareto Analysis

The primary causes of inefficiency that reduce equipment effectiveness are identified and categorized using the six big losses [18]. Managers can then more easily prioritize corrective actions by using a Pareto chart to see which loss categories are most responsible for production downtime [19]. The chart indicates the most important areas that should be addressed first in order to improve the availability factor within the OEE calculation by ranking these losses according to their frequency or impact. The identified time losses during operation are shown in Table 4 and Figure 1, along with a Pareto-based illustration of their proportion. Equipment failure losses and setup and adjustment losses are the two biggest contributors to total downtime, making up more than 60% of all lost time. This emphasizes the necessity of giving corrective measures for belts, motor conveyors, and setup tasks top priority. Minor stoppages and speed reductions, on the other hand, are also important but secondary areas that require improvement. The business can have a greater influence on machine availability and overall OEE performance by tackling these major loss categories first.

Table 4. Identification of losses stone crusher

Six Big Losses Category	Downtime Cause	Total Downtime [Min]	Percentage [%]	Cumulative [%]
Setup and adjustment losses	Setup	1615	27%	27%
Equipment failure losses	Motor Conveyor Conveyor Belt	2203	37%	64%
Idling and minor stoppages	Feeder Primer	953	16%	80%
Reduced speed losses	Corong Jaw Primer	802	13%	93%
Defects in process losses	Pressing Jaw Tersier	426	7%	100%

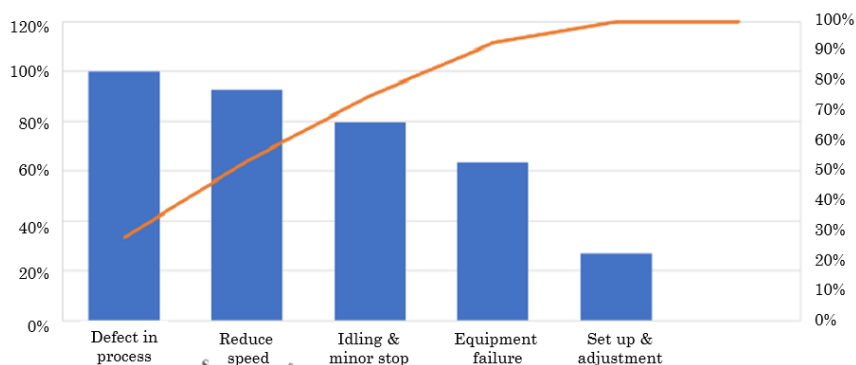


Figure 1. Pareto chart for six big losses of stone crusher machine

### Implementation of Single Minute Exchange of Dies

The single minute exchange of dies (SMED) method was used to address the excessive setup and adjustment losses found in the Six Big Losses analysis. Through task simplification, parallel work, and the conversion of internal activities to external ones, the overall setup time was intended to be decreased [20]. The improvement outcomes for PT BAS's stone crusher setup procedure before and after SMED implementation are compiled in Table 5. The comparison of the total setup times for each task before and after the SMED method was put into practice is shown in Figure 2. The time spent on almost every setup step has been significantly reduced, as the bar chart makes evident, particularly for tasks like preparation, cleaning, and material loading that were switched from internal to external activities. Simplicity and parallel work during the motor disassembly and adjustment phases resulted in the largest savings. Overall, the SMED application reduced setup time by more than 55%, which improved the availability component of the OEE metric and directly reduced setup & adjustment losses under the six big losses.

Table 5. SMED implementation results for setup activities

Activity Description	Before SMED	Time [Min]	After Smed	Time [Min]	Improvement / Explanation
Preparation and tool gathering	Internal	180	External	0	Converted to external using 5S and done before shutdown
Cleaning work area	Internal	140	External	0	Done during last operation cycle
Material loading to hopper	Internal	120	External	0	Pre-loaded using operator before shutdown
Motor conveyor disassembly	Internal	220	Internal	150	Simplified and done by 2 workers simultaneously
Conveyor belt adjustment	Internal	200	Internal	140	Simplification and Poka-Yoke applied
Feeder primer adjustment	Internal	170	Internal	100	Done using alignment fixture + checklist
Jaw primer removal & setup	Internal	160	Internal	90	Done in parallel with other jaw settings
Pressing jaw tertier alignment	Internal	100	Internal	60	Performed with guide + done by second operator
Final inspection and test run	Internal	125	Internal	90	Streamlined sequence + simultaneous with jaw setup

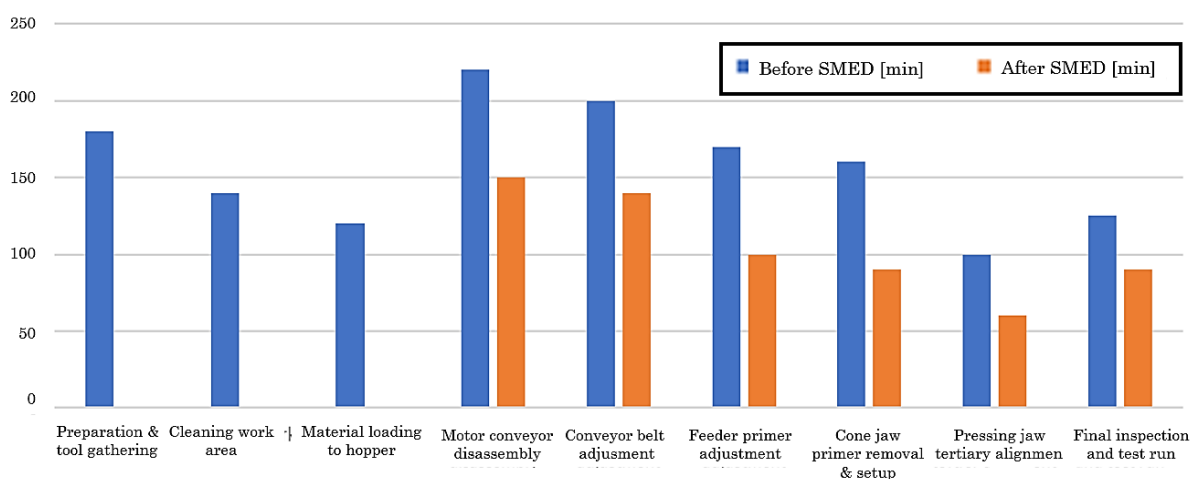


Figure 2. Setup time before and after SMED implementation

### Total Productive Maintenance

A workable total productive maintenance (TPM) plan was created to address the primary causes of Equipment Failure Losses found by the Six Big Losses analysis and the Priority Matrix. The

TPM pillars that have the greatest direct influence on lowering unexpected breakdowns and enhancing overall machine reliability are the only focus of this plan, which is customized to the actual machine conditions at PT BAS. A thorough overview of the selected TPM pillars, the machine components that are being targeted, and the particular improvement measures intended to guarantee methodical and long-term implementation are provided in Table 6. The suggested TPM actions address the highest risk failure modes by combining technical scheduling with daily operator involvement, as indicated in Table 6. PT BAS seeks to improve equipment care by combining planned maintenance, autonomous maintenance, focused improvement, and quality maintenance. By extending component lifespan, decreasing breakdown frequency, and directly increasing availability, this integrated approach is anticipated to provide a solid basis for integrating Lean tools such as SMED and 5S within the larger i-TPM-Lean+ framework.

Table 6. TPM pillars and actions for priority components

TPM Pillar	Component/Area	Specific Actions
Planned maintenance	Motor conveyor, feeder, conveyor belt	Create a clear preventive maintenance calendar (daily, weekly, monthly).- Lubricate motor bearings and belt pulleys at fixed intervals.- Replace worn belts before visible cracks appear.- Keep emergency spare parts in stock.
Autonomous maintenance	Motor conveyor, hopper, conveyor belt	Train operators to perform daily walk-around inspections before startup.- Check for oil leaks, unusual noise, excessive vibration, or overheating.- Clean dust, marble particles, and residues that may block or overheat components.- Use a quick visual checklist signed by the operator every shift.
Focused improvement (kobetsu kaizen)	Motor conveyor, feeder, hopper	Analyse frequent failures using simple root cause tools (5 Whys, Fishbone Diagram).- Form small operator-technician teams to fix recurring issues, such as belt misalignment or feeder blockages.- Document each improvement action and monitor for repeat cases.
Quality maintenance	Feeder, conveyor belt	Inspect feeder blade wear to ensure stable material feed rate.- Calibrate conveyor belt tension to prevent slippage.- Record material flow rate to detect early signs of abnormal feed.
Training & education	Operators and maintenance staff	Conduct regular training on basic fault detection and quick fixes.- Update operators on new SOPs and checklists.- Review TPM logbooks monthly and discuss common issues.
Safety, health & environment (SHE)	All machine areas	Display clear safety instructions near machines.- Provide proper PPE for all staff involved in inspection and minor repairs.- Control marble dust using spot vacuum or localized covers to protect motor ventilation.

### 5S Workplace Organization

The i-TPM-Lean+ relies heavily on the 5S method in addition to SMED and TPM. The structured workplace organization method known as 5S helps guarantee that production areas, tools, and spare parts are standardized, clean, and arranged correctly [21]. At PT BAS, a lack of organization in the stone crusher area frequently resulted in lost setup time, a higher chance of contamination, and small stoppages when parts or tools were misplaced or missing. Through the implementation of 5S, the organization hopes to enhance daily autonomous maintenance and boost the efficiency of SMED and TPM operations. Every 5S program step is directly related to particular root causes of downtime found in the priority matrix, as indicated in Table 7. Sort and Set in Order, for instance, helps cut down on setup and adjustment losses by removing time wasted looking for tools and spare parts. By preventing marble dust and other debris from clogging the feeder, belts, and motor conveyor, the Shine step reduces contamination and equipment failure losses. By ensuring

that these enhancements are regularly implemented by all operators, standardize and sustain helps to avoid minor stoppages brought on by messy workspaces and inadequate housekeeping. All things considered, the structured 5S approach facilitates quicker setup, safer working conditions, and more efficient daily maintenance procedures.

Table 7. 5S actions and focus areas at PT BAS

5S step	Practical actions	Target area	Impact on downtime causes
Sort (Seiri)	Remove unnecessary tools and expired parts. Dispose of damaged belts and motor spares.	Crusher zone, feeder, maintenance racks	Reduces setup delays caused by searching for usable tools; prevents using faulty parts that cause breakdowns.
Set in Order (Seiton)	Arrange and label shelves for quick access. Mark storage spaces for spare belts, toggle plates, liners. Visual tool placement near work zones.	Maintenance room, conveyors, feeder area	Speeds up setup tasks, minimizes unplanned stops when urgent spares are needed.
Shine (Seiso)	Daily cleaning of marble dust and debris. Clean motor vents and belt surfaces. Assign cleaning tasks per shift.	Crusher unit, belt conveyor, feeder	Prevents overheating and wear due to dust build-up; reduces small stops due to material jams.
Standardize (Seiketsu)	SOPs for daily cleaning, sorting, and arranging. Color-coded signs for storage and cleaning status. Standard checklists for operators.	Crusher area, tool boards, storage	Ensures tasks are done consistently; reduces chance of missing steps that can lead to gradual failures.
Sustain (Shitsuke)	Weekly 5S audits with scores. Operator incentives for compliance. Refresher training.	Entire crusher working area	Maintains discipline; prevents gradual decline in orderliness which could lead to repeated minor stoppages.

### Comparison of OEE Before and After Implementing I-TPM-Lean+ Model

Table 8. Comparison of OEE before and after implementing I-TPM-Lean+ model

Indicator	Before	After TPM & LEAN tools	Change [%]
Down time [min/month]	2999,5	1791	- 67
Availability rate [%]	79%	88%	+ 10
Performance rate [%]	81%	84%	+ 5
Quality rate [%]	92%	94%	+ 2
OEE rate [%]	59%	70%	+ 11

A thorough analysis was carried out to compare the equipment performance indicators prior to and following the implementation of specific improvement tools in order to assess the impact of the suggested i-TPM-Lean+ model. Reducing downtime, availability rate, performance rate, quality rate, and overall equipment effectiveness (OEE) were the main areas of focus. In order to address the six big losses in the stone crusher operations at PT BAS, SMED, TPM, and 5S strategies were applied. The hybrid model effectively decreased overall downtime by app. 67% (Table 8), which greatly boosted the availability rate from 79% to 88% (Figure 3).

Better production speed and fewer setup and operation delays were reflected in the moderate 5% improvement in the performance rate. Additionally, the quality rate increased marginally to 94%, suggesting that fewer products needed to be reworked. The OEE increased from 59% to 70% overall, indicating that the integrated strategy that combined SMED, 5S, and TPM pillars produced noticeable gains in a number of performance areas. These findings demonstrate that the i-TPM-Lean+ can successfully address significant losses and improve equipment efficiency in the

natural stone processing sector. While existing studies have implemented TPM or Lean tools in isolation, the i-TPM-Lean+ model introduces a systematic integration of OEE and FMEA to bridge the gap between performance measurement and risk mitigation.

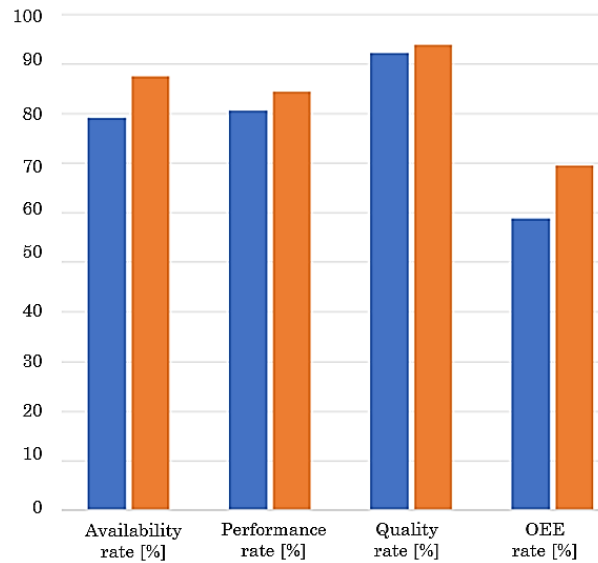


Figure 3. Before and after performance indicators after TPM & lean tools application

### Advantages of the i-TPM-Lean+ Model Over Conventional Approaches

The results demonstrate that the i-TPM-Lean+ model offers three key advantages over traditional TPM or lean implementations. First, unlike prior studies that applied generic TPM/Lean tools like study [20] achieved 9% OEE gain via TPM alone, and study [20] reported 2.83% from SMED, this study's OEE-FMEA priority matrix enables dynamic tool selection, SMED for setup losses (60% OEE impact), TPM for motor conveyor failures (59% loss), yielding a synergistic 15% OEE improvement. Second, while conventional methods rely on isolated OEE or FMEA data [16], the integrated matrix reduces subjectivity by cross-validating quantitative losses (OEE) with qualitative risks (RPN). Third, the model's flexibility addresses a critical industry gap: [21]'s TPM-VSM approach improved OEE by 11% but required extensive mapping, whereas i-TPM-Lean+ achieved higher gains (15%) with actionable, component-level interventions with 5S for hopper misalignment, and preventive maintenance for conveyor belts derived directly from the matrix. This proves that combining structural prioritization with adaptable tools is essential for process-intensive industries like stone processing.

### Benchmarking Analysis

A benchmarking analysis is presented to show how the hybrid TPM-Lean model used in this study stacks up against alternative strategies. Selected prior research that used TPM, Lean tools like SMED and 5S, or both (Table 9). The comparison shows how each approach affects overall machine efficiency, OEE improvement, and downtime reduction. Table 9 demonstrates that prior research primarily concentrated on using TPM or individual Lean tools to increase the efficiency of equipment. In many instances, moderate OEE increases of 8–15% were attained, mostly through shorter setup or breakdown times. TPM, for instance, has been shown to increase reliability through improved maintenance schedules, while SMED and 5S have been shown to lower setup losses and improve workplace organization. In contrast to these benchmarks, this study integrates TPM, SMED, and 5S based on actual failure modes and critical losses after combining OEE and FMEA in a structured priority matrix. Compared to using TPM or Lean tools alone, this hybrid model has a greater impact, reducing downtime by 67% and increasing OEE by 11%. This outcome demonstrates that an integrated strategy can more accurately target the underlying causes, enhance availability, performance, and quality collectively, and bring machine efficiency closer to industry-leading levels.

Table 9. Benchmarking analysis

Context	Tools applied	Downtime	OEE	Machine efficiency impact
CNC machining center	TPM implementation	Downtime qualitatively reduced (not quantified)	OEE increases from 46.5% to 55.59% (+9%)	Extended running time, increased production capacity
Molding production	TPM (autonomous maintenance & kaizen)	Downtime minimized by addressing speed losses	OEE increases from 76.9% to 85.8% (+8.9%)	Maintained stable production speed, fewer minor stops
Spare parts machining	TPM + VSM	Downtime reduced via waste elimination	OEE increases from 65% to 76% (+11%)	Improved flow, reduced non-value-added time, higher effective output
SME manufacturing	SMED (lean)	Small stoppages reduced; setup time cut by 16 min	OEE increases from 68.10% to 70.93% (+2.83%)	Faster changeover, higher cycle output (running meters/min)
Food & beverage packaging	SMED + 5S	Setup time reduced by 24 mins	OEE increases from 76% to 78% (+2%)	Faster changeover, higher availability
Metal fabrication (welding)	Lean kaizen + stopper innovation	Setup losses reduced. Unnecessary tasks removed	OEE increases from 67.49% to 76.12% (+8.6%)	Faster welding, fewer defects, precise setup
Plastic cap production	VSM + Problem Tree + Pareto + 5S + TPM	Machinery stoppages 74% & power loss 27% identified and reduced	Availability increases from 70.83% to 78.64%, Total Efficiency ↑ 9% (55.88% → 64.94%)	Tool search time decrease 80%, tools organized decrease 85.9%
Stone crusher (mining)	OEE analysis only	Lowest downtime in April: 78.73 hrs	OEE: 40.51%, lowest 22%, highest 77%	Shows critical downtime control directly affects availability (max. 74.77%) and overall performance
Stone crusher – marble processing (PT BAS)	Integrated OEE–FMEA Hybrid, TPM + SMED + 5S	Downtime reduced by 67% (from ~3000 min/month to ~1791 min/month)	OEE increases by 15% (from 59% to 70%)	Higher availability (+10%), performance (+5%), and quality (+2%) confirm better machine reliability and lower operational losses

### CONCLUSION

This study confirms that the i-TPM-Lean+ model, integrating TPM pillars, SMED, and 5S within an OEE-FMEA priority matrix, provides a structured and adaptable strategy to enhance machine effectiveness in the natural stone industry. Implementation reduced downtime by 67% from 3000 to 1791 min/month, improved availability by 10% from 79% to 88%, performance by 5% from 81% to 84%, quality by 2% from 92% to 94%, and raised OEE by 15% from 59% to 70%. Compared to prior works applying TPM or lean separately, this hybrid framework shows how quantitative OEE and qualitative FMEA complement each other, enabling precise prioritization of failures and targeted corrective actions. Beyond performance gains, it fosters sustainable operator involvement, workplace discipline, and continuous improvement. The model can serve as a replicable reference for process industries aiming for measurable efficiency improvements and long-term competitiveness.

## REFERENCES

- [1] M. Celestin, "Brainae journal of business, sciences and technology," *Brainae Journal of Business*, vol. 7, no. 10, pp. 1023–1033, 2023, doi: 10.5281/zenodo.15062856.
- [2] M. Cosa and R. Torelli, "digital transformation and flexible performance management: A systematic literature review of the evolution of performance measurement systems," Springer, Sep. 2024, doi: 10.1007/s40171-024-00409-9.
- [3] A. H. Gomaa, "Optimizing asset integrity for critical manufacturing systems using advanced proactive maintenance strategies," *International Journal of Emerging Science and Engineering*, vol. 13, no. 4, pp. 21–33, Mar. 2025, doi: 10.35940/ijese.B2026.13040325.
- [4] T. Warsokusumo, T. Prahasto, and A. Widodo, "Combining RAMS with EEP for performance-based maintenance: a review," *Journal of Quality in Maintenance Engineering*, Feb. 2021, doi: 10.1108/JQME-06-2019-0063.
- [5] Ahmad, L. Lilyana, L. Widodo, L. Gozali, and A. Maryadi, "Analyze of mitigation waste in reconditioning process of iron drum with lean six sigma (Case study at PT Mulya Adhi Paramita)," *IOP Conference Series: Materials Science and Engineering*, 2019, doi: 10.1088/1757-899X/528/1/012071.
- [6] A. Hallioui et al., "A Review of sustainable total productive maintenance (STPM)," *Sustainability*, vol. 15, no. 16, Aug. 2023, doi: 10.3390/su151612362.
- [7] A. C. Nugroho, T. P. Syawitri, and R. M. An'am, "Maintenance analysis of raw mill machines in cement production," *Engineering Proceedings*, vol. 63, no. 1, 2024, doi: 10.3390/engproc2024063005.
- [8] M. Khosroniya, R. Hosnavi, and M. R. Zahedi, "Enhancing operational performance in industry 4.0: the mediating role of total quality management and total productive maintenance at zarharan industrial complex," *International Journal of Industrial Engineering & Operations Research*, 2024.
- [9] A. Taher and M. Al Bashar, "The impact of lean manufacturing concepts on industrial processes' efficiency and waste reduction," *International Journal of Progressive Research in Engineering Management and Science (IJPREAMS)*, 2024.
- [10] R. G. P. Junior, R. H. Inácio, I. B. da Silva, A. Hassui, and G. F. Barbosa, "A novel framework for single-minute exchange of die (SMED) assisted by lean tools," *International Journal of Advanced Manufacturing Technology*, vol. 119, no. 9–10, pp. 6469–6487, Apr. 2022, doi: 10.1007/s00170-021-08534-w.
- [11] A. H. Gomaa, "LSS 4.0: A conceptual framework for integrating lean six sigma and industry 4.0 for smart manufacturing excellence," *Indian Journal of Management and Language*, vol. 5, no. 1, pp. 8–29, Apr. 2025, doi: 10.54105/ijml.H1810.05010425.
- [12] G. Citybabu and S. Yamini, "Lean Six Sigma 4.0 – a framework and review for Lean Six Sigma practices in the digital era," *Benchmarking: An International Journal*, Nov. 2024, doi: 10.1108/BIJ-09-2022-0586.
- [13] L. del C. N. Corrales, M. P. Lambán, M. E. Hernandez Korner, and J. Royo, "Overall equipment effectiveness: Systematic literature review and overview of different approaches," *Applied Sciences*, vol. 10, no. 18, 2020, doi: 10.3390/app10186469.
- [14] R. Costa and I. Lopes, "Productivity improvement in manufacturing systems through tpm, oee and collaboration between maintenance and production: A case study," *IFIP International Conference on Advances in Production Management Systems*, pp. 261–268, 2021, doi: 10.1007/978-3-030-85914-5\_28.
- [15] S. Yang, L. Yang, Y. C. Chuang, G. Asihaer, and X. Lin, "Identification of key risk areas and failure modes using the FMEA method for the prevention and control of major infectious diseases in a stomatology department," *BMC Oral Health*, vol. 25, no. 1, p. 45, Dec. 2025, doi: 10.1186/s12903-024-05321-3.

- [16] Z. Wu, W. Liu, and W. Nie, "Literature review and prospect of the development and application of FMEA in manufacturing industry," *International Journal of Advanced Manufacturing Technology*, vol. 113, pp. 2365–2381, 2021, doi: 10.1007/s00170-020-06425-0.
- [17] B. Salah, M. Alnahhal, and M. Ali, "Risk prioritization using a modified FMEA analysis in industry 4.0," *Journal of Engineering Research (Kuwait)*, vol. 11, no. 4, pp. 460–468, Dec. 2023, doi: 10.1016/j.jer.2023.07.001.
- [18] P. Tambare, C. Meshram, C. C. Lee, R. J. Ramteke, and A. L. Imoize, "Performance measurement system and quality management in data - driven industry 4.0: A review," *Sensors*, vol. 22, no. 1, Jan. 2022, doi: 10.3390/s22010224.
- [19] A. Mail, M. Dahlan, N. Rauf, A. N. Chairany, A. Ahmad, and K. Jufri, "Analysis of the effectiveness of clean water distribution machine using overall equipment effectiveness (OEE) method," *Journal of Industrial Engineering Management*, vol. 6, no. 1, pp. 49–56, May 2021, doi: 10.33536/jiem.v6i1.884.
- [20] V. Santos et al., "Applying the SMED Methodology to tire calibration procedures," *Systems*, vol. 10, no. 6, Dec. 2022, doi: 10.3390/systems10060239.
- [21] M. R. Ullah, S. Molla, I. M. Siddique, A. A. Siddique, and Md. M. Abedin, "Optimizing performance: A deep dive into overall equipment effectiveness (OEE) for operational excellence," *Journal of Industrial Mechanics*, vol. 8, no. 3, pp. 26–40, 2023, doi: 10.46610/joim.2023.v08i03.0045.