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Improving the sustainability index through the implementation of total productive maintenance for the bending process in electrical manufacturing

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ABSTRACT
Significant losses resulting from frequent breakdowns of the bending machine directly impact Company X. Such breakdowns reduce machine efficiency due to the necessity of component replacements, which conflicts with sustainability principles aligned with the United Nations' Sustainable Development Goals (SDGs). This study aims to enhance the sustainability index (SI) by implementing Total Productive Maintenance (TPM) and evaluating Overall Equipment Effectiveness (OEE). These measures are fundamental to driving improvements in the company's productivity, addressing both manufacturing performance and sustainability objectives. The analysis includes calculating machine effectiveness using OEE and assessing company losses based on the Six Big Losses framework. Results reveal that the average OEE over the past year is 55%, which falls below both the international standard and the company's target of 70%. The sustainability index was measured at 82.36%. To address these issues, improvements are proposed focusing on TPM pillars (Safety, Health, Environment; Planned Maintenance; and Autonomous Maintenance) while maintaining alignment with sustainability goals. Additionally, enhancements to the 6S methodology are recommended to support sustainable practices consistent with SDG 12. By adopting these strategies, the sustainability index is projected to improve to 80.91%, and machine effectiveness is expected to increase to 70.34%.

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1. INTRODUCTION

Sustainable Development Goals (SDGs) are a set of 17 global objectives launched in 2015 by the United Nations [1]–[3], aimed at addressing key global challenges in response to environmental, social, and economic changes observed since the early 2000s [4]. Proper machine maintenance aligns with SDG 12, "Responsible Consumption and Production." Effective maintenance enables machines to operate more efficiently, reducing energy and material waste and minimizing hazardous waste and emissions, thereby supporting the goal of reducing environmental harm. Routine maintenance extends the lifespan of machines and their components, reducing the need for new machinery and promoting recycling [5]. Additionally, adhering to environmental standards in machine maintenance ensures compliance with legal regulations. This practice reflects awareness and responsibility towards sustainability, inspiring other companies to follow suit. Therefore, proper machine maintenance significantly contributes to achieving SDG 12.

Total Productive Maintenance (TPM) supports clean and affordable energy by enhancing energy efficiency, reducing emissions, conducting preventive maintenance, and educating employees, all of which contribute to sustainable and reliable energy use [6]. Furthermore, the TPM pillars are closely associated with human factors, specifically safety, health, and environment, as well as autonomous maintenance and ensuring that all employees are included by making a moderate investment in maintenance [7]. Achieving the desired outcomes requires active participation and comprehensive training of employees at all organizational levels [5]. These personnel must possess the necessary skills and knowledge to understand the importance of effective maintenance practices and responsible energy consumption. Moreover, fostering a workplace safety and well-being culture is vital to ensure employee health and productivity. This commitment extends beyond machinery operation to include accident and injury prevention. The successful implementation of TPM within the company can also substantially reduce the need to employ additional workers solely for machine maintenance.

Frequent machine breakdowns significantly affect the company by causing downtime, setup delays, production halts, slower production speeds, lower product quality, and equipment instability during startup [7]–[9]. Frequent breakdowns also negatively affect machine efficiency due to the continual replacement of machine components, which contradicts the principles of sustainability [11]. The sustainability principle advocates for the efficient use of equipment, energy, and resources while minimizing waste [1]. Moreover, reducing excessive energy consumption has positive implications for social, economic, and environmental dimensions, which are integral to the sustainability framework. These three aspects constitute the core pillars of sustainability. In general, maintenance is a crucial step in optimizing the efficiency of a production machine, namely by avoiding sudden machine breakdowns [12]. Proper machine maintenance directly influences the age of the machine used, which can extend its life, thus minimizing the occurrence of breakdowns during use and avoiding work accidents for workers [13], [14], meaning that machines need a regular maintenance to avoid losses [15].

Company X employs a bending machine to produce products such as the Direct APP Box. This machine requires multiple repairs for a year, with each repair event lasting between 60 and 3660 minutes. This duration exceeds the ideal maintenance times, typically 10 minutes for inspections, 240 minutes for minor breakdowns, and 1440 minutes for significant breakdowns. Maintenance activities are intended to prevent machine breakdowns. Currently, the company lacks a machine maintenance strategy that incorporates sustainability principles. By investigating and analyzing the causes of machine breakdowns through the calculation of Overall Equipment Effectiveness (OEE), Six Big Losses (SBL), TPM, and Sustainability Index, a suitable maintenance strategy can be determined to mitigate issues related to machine breakdown [16], thereby reducing losses that affect the company. Maintenance is essential to re-optimize machine performance, ensuring that the machine remains in optimal condition to prevent unexpected breakdowns and ensure its readiness for production [13], [17]. Efficiency management in maintenance is becoming increasingly crucial for improving the sustainability of the industry [18]. Implementing proactive machine maintenance enables companies to reduce costs while enhancing performance across sustainability dimensions: social, economic, and environmental [2], [5], [19], [20] both in terms of operations and machine maintenance practices. This study presents a novel approach by harmonizing two methods, TPM and Sustainability Index, to analyze sustainability performance in the bending process within the electrical manufacturing industry. This integration represents the primary novelty of the research. As shown in Table 1. Several previous studies reference the methodological combination employed in this study. Unlike previous research that focused solely on either OEE or TPM [8], [13]. This study evaluates sustainability through the three core pillars (environmental, economic, and social) and directly links these to machine effectiveness (OEE) and Six Big Losses.

Table 1. Previous research

Author	Sustainability Index	Total Productive Maintenance	Overall Equipment Effectiveness	Six Big Losses
[21]	✓			
[13]		✓	✓	✓
[8]		✓	✓	✓
[22]	✓			
[23]	✓			
Selected Methods	✓	✓	✓	✓

This integrated approach provides a comprehensive perspective on the relationship between machine maintenance and corporate sustainability performance, a dimension largely underexplored in existing literature. By merging technical and sustainability viewpoints through the combined application of TPM, OEE, Six Big Losses, and Sustainability Index aligned with SDG 12, the study offers both practical and academic contributions to developing maintenance strategies that are operationally effective and environmentally sustainable.

The rapid expansion of industrial sector has compelled governments to implement effective environmental protection measures while maintaining regulatory oversight. These efforts aim to minimize the risk of ecological degradation resulting from industrial activities as early as possible [1]. The Sustainable Development Goals represent a global initiative encompassing all countries, without distinguishing between developed and developing nations.

Machine breakdowns can have a direct impact on both productivity and operational efficiency. Such disruptions can result in significant losses for the company in various forms [4]. An effective way to measure the impact of such losses is by employing the Six Big Losses framework, which highlights reductions in production effectiveness due to equipment operating in suboptimal conditions [9]. This framework is a critical tool for identifying and quantifying issues within the production process [10], as it is used to calculate a machine's OEE. Accurate OEE measurement enables the implementation of targeted actions to improve machine performance effectively [24]. By addressing and eliminating the root causes of inefficiency, optimal condition of machinery can be maintained [12], [13], [24]. Six Big Losses are a primary contributor to diminished machine performance [25] and are commonly categorized into three groups, as presented in Table 2.

Table 2. Six big losses

Six Big Losses		
Downtime Losses	Equipment Failures	Are caused by faulty equipment
	Setup and Adjustment Losses	There are times for equipment readjustment.
Speed Losses	Idling and Minor Stoppages Losses	The existing idle time is attributable to minor damage to the machine.
	Reduced Speed	Due to the difference between actual and design machine speed
Defect	Process Defects	Are caused by scrap and defective products that need to be repaired or replaced
	Reduced Yield	There is a period that is required for the machine to reach stability.

Sustainability has emerged as a critical concern in the modern era, reflecting growing awareness of the need to balance present human needs with those of future generations, while preserving ecological integrity [26]. In the context of manufacturing, sustainable development enables industries to pursue economic growth cost-effectively, while simultaneously addressing environmental preservation [17]. The sustainability index serves as a tool to assess sustainability performance across various levels, ranging from companies and organizations to cities and nations [27]. This index encompasses multiple dimensions of sustainability, including environmental, social, and economic factors. It is commonly used to evaluate the extent to which an organization has implemented sustainability practices [28]. The sustainability index is calculated by assessing the individual index values of each sustainability pillar [14], [15].

Maintenance is actions (such as servicing, repairing, replacing, cleaning, adjusting, and inspecting) that are necessary to keep the machine or its components in good working order and repair them to certain acceptable conditions [12]. Two types of maintenance can be performed on the object to be maintained: planned maintenance and unplanned maintenance [19]. Corrective maintenance repairs are performed after the machine breaks down or fails. Preventive maintenance is performed by periodically evaluating equipment, machinery, and plant systems to detect possible problems and immediately schedule maintenance tasks to prevent deterioration or unexpected damage of the operating conditions in a production process [20], [31], and is performed before a breakdown occurs, and repairs are scheduled to address specific breakdowns [32]. The main difference between corrective and preventive maintenance is that corrective maintenance is performed in response to an existing problem. In contrast, preventive maintenance is carried out to prevent problems from occurring [33].

TPM aims to improve manufacturing companies' overall efficiency and effectiveness, and improve reliability where there is an inconsistency between operators and systems through a system-of-care approach [8], [34]. According to Nakajima [17], TPM is defined as "productive maintenance with total participation." Still, it is often misunderstood to mean that only workers are involved and assumes that preventive maintenance activities must be performed independently from the production floor. TPM should be implemented Company-wide [17].

OEE is a method used to measure the overall efficiency of a piece of equipment in evaluating the performance of a machine [5], [17] OEE indicates productivity levels based on a certain level of expected performance. OEE is a measurement index that shows how the equipment is working. OEE not only means the number of products produced but also indicates that the machine is working and the percentage of defective products compared to quality products [35]. OEE can be considered an index of the health of a process or equipment. There are three components involved in the calculation of OEE, which can be seen at the following points:

- The availability rate is the range of the ratio of the available time of a machine in operation to produce products to the available time [17].
- Performance Efficiency is the ratio range of production results on actual machine operations compared to the expected or standard output [17].
- The rate of quality is the sum of the ratio range of products that follow the standard or are suitable for the total production of the whole [17].

2. MATERIALS AND METHODS

The methodology applied in this research is illustrated in Figure 1. This Research methodology reveals a comprehensive research flowchart with a sequential step used to improve the performance and sustainability of a bending machine. The process begins with calculating machine effectiveness using OEE method, with data related to production availability, task efficiency, and product quality to determine machine effectiveness. This is followed by an assessment of Six Big Losses, where loss data from machine breakdowns are categorized and quantified to identify performance barriers, which is essential for quantifying the losses incurred by the company. Subsequently, TPM approach is applied to evaluate foundational TPM elements, including 6S, as well as the pillars of autonomous maintenance, safety, health, environment, and planned maintenance [36], [37]. TPM is analyzed using current maintenance data to develop recommendations for reducing losses through autonomous maintenance, safety and environmental assessments, planned maintenance, and 6S analysis. To identify areas for potential improvement, the company must first evaluate its current sustainability status. This is achieved by calculating a comprehensive sustainability index that assesses the company's overall sustainability performance. The final stage involves comparing the proposed improvement strategies to determine their impact on machine effectiveness (OEE), Six Big Losses, and Sustainability Index. Sustainability Index is calculated by integrating existing indicators and targets across economic, environmental, and social pillars, resulting in an overall index that reflects the company’s sustainability performance.

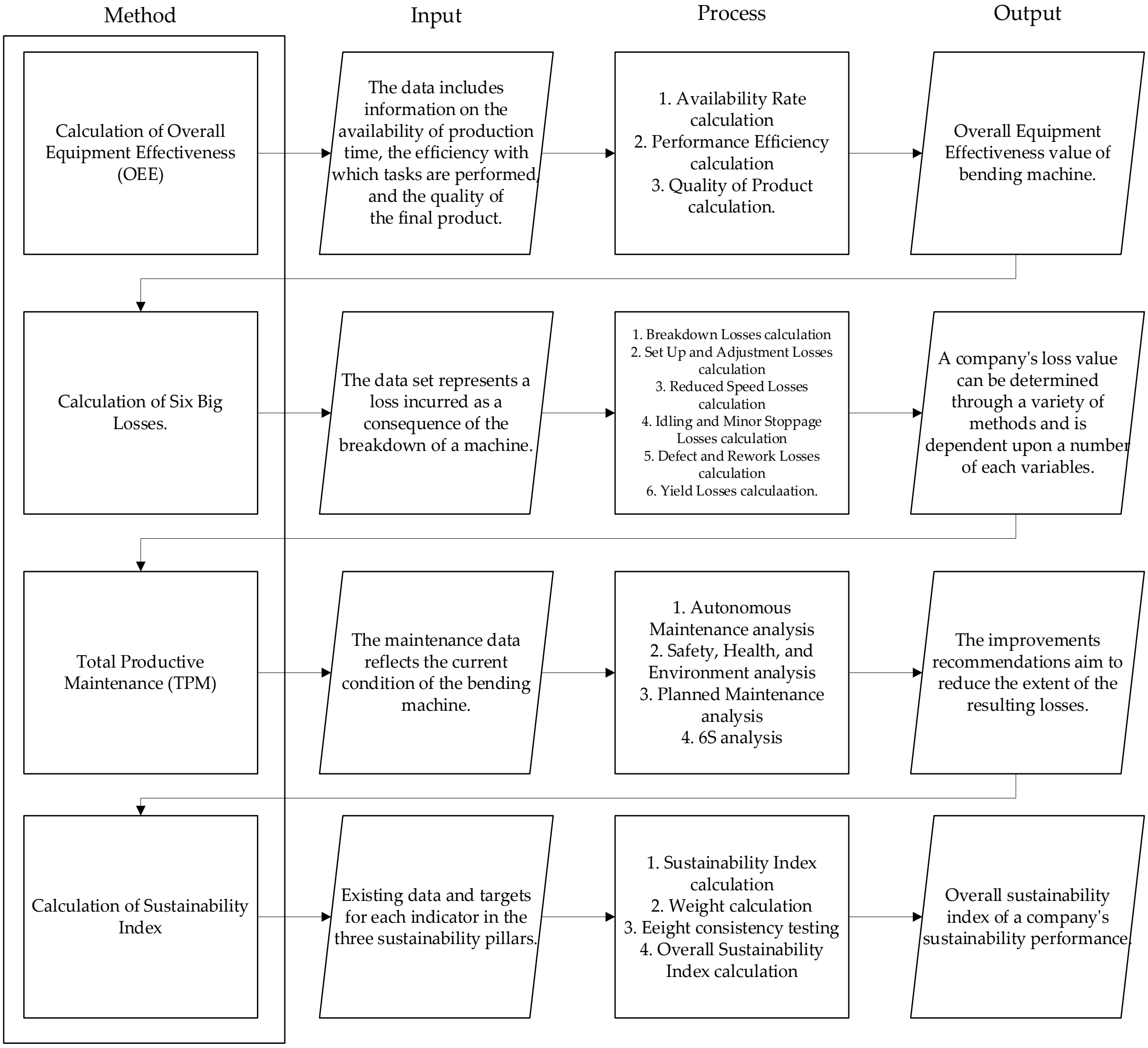


Figure 1. Research Flowchart

3. RESULTS

3.1. Calculation of Overall Equipment Effectiveness (OEE)

OEE is a calculation that includes three components: availability rate, performance efficiency, and rate of quality [3], [38], [39]. OEE is a metric used to measure the effectiveness of a machine or piece of equipment in a production process. The availability rate measures how much of the time planned for production is used for output after accounting for downtime. It indicates that the higher machine with downtime value, the less effective the machine is, which reduces its production output and can result in the company not meeting its targets or consumer demand [16]. The availability rate requires a load time value, which can be obtained by reducing the available time value by the planned downtime.

The next step involves calculating performance efficiency, which measures how effectively a machine or equipment operates relative to its maximum achievable potential. Performance efficiency is determined using the cycle time and the total number of products produced.

The rate of quality indicates how effectively the production process yields products that meet quality standards without defects. Calculating this rate requires data on the number of defective products, good products, and total products produced.

OEE metric is derived from three core components: availability rate, performance efficiency, and rate of quality. As described in the previous section, each factor was calculated monthly. OEE value for each month is then obtained by multiplying the three corresponding components. From these monthly OEE values, the average annual OEE can be determined. Subsequently, the average yearly OEE for the bending machine is calculated, as shown in Table 3.

Table 3. Calculation of overall equipment effectiveness

Month	Availability Rate	Performance Efficiency	Rate of Quality	OEE (%)
Mar-23	86,15	75,19	96,4	62,44
Apr-23	93,62	31,08	98,96	28,79
May-23	87,59	73,09	97,45	62,39
Jun-23	89,69	58,93	97,27	51,41
Jul-23	80,39	88,13	96,88	68,64
Aug-23	98,24	64	98,33	61,82
Sep-23	90,41	57,95	99,09	51,92
Oct-23	97,36	54,24	99,21	52,39
Nov-23	91,64	46,16	98,56	41,69
Dec-23	99,38	68,4	98,24	66,78
Jan-24	98,31	70,78	98,94	68,85
Feb-24	89,05	82,4	98,25	72,09
Average				**55,84**

Over a 12-month production period, the bending machine's effectiveness failed to meet the ideal standard threshold of 85%, with an average OEE of only 55.85%. This low OEE value results from suboptimal performance across its three key components: availability rate, performance efficiency, and quality rate.

By evaluating machine effectiveness, the extent of operational losses can be identified by calculating the Six Big Losses. These losses represent the primary factors contributing to reduced machine performance. The six categories include: breakdown losses, setup and adjustment losses, idling and minor stoppage losses, reduced speed losses, defects in the production process, and reduced yield losses. Company's monthly losses over the one year are summarized in Table 4.

Table 4. Calculation of six big losses

Months	Breakdown Losses (Minutes)	Time Losses Setup Adjustment (Minutes)	Time Losses Idling Minor (Minutes)	Time Losses Reduced Speed (Minutes)	Time Losses Defect in Process (Minutes)	Time Losses Reduced Yield (Minutes)
Mar-23	2599,999753	499,282	1250,082	4718,778	514,298	116,374
Apr-23	819,999896	360,08	900,2	8986,568	42,438	10,288
May-23	2339,999806	520,536	1299,454	5145,008	356,454	41,492
Jun-23	1660,00016	439,53	1099,63	6702,43	262,43	83,72
Jul-23	3540,000295	499,985	1250,865	2171,415	503,595	104,69
Aug-23	519,998528	779,856	1559,712	10634,4	316,078	82,712
Sep-23	2679,999725	749,06	1500,915	11752,975	148,135	36,335
Oct-23	780,000746	779,856	1559,712	13517,504	127,022	62,034
Nov-23	2469,998916	779,856	1559,712	15904,336	194,964	97,482
Dec-23	164,998672	718,768	1440,208	8443,52	323,312	146,96
Jan-24	515,001474	778,752	1560,546	8742,708	225,108	36,504
Feb-24	2680,000893	628,879	1260,205	4013,08	327,898	90,539

Following by calculation of Six Big Losses, Company X was found to experience the most significant loss in the category of reduced speed losses, amounting to a total of 100,732.72 minutes. In contrast, the smallest loss was attributed to reduced yield losses, totalling 909.13 minutes. Reduced speed losses can be attributed to several operator- and equipment-related issues. These include a lack of operator focus during machining, insufficient operator experience, aging machinery, malfunctioning machine components, slow machine response times, disorganized work environments, unclean equipment, ineffective preventive maintenance, and failure to perform pre-production inspections by Standard Operating Procedures (SOPs).

3.2. Calculation of the Sustainability Index

Before conducting the calculations, the first step is to identify sustainability indicators relevant to the company's operational context. This step is crucial to ensuring that the assessment framework is aligned with the actual conditions and challenges encountered by the company. Table 5 provides a compilation of sustainability indicators drawn from previous studies, serving as a reference point for indicator selection. From this list, specific indicators that reflect the company's current sustainability issues are selected to support a more targeted and meaningful analysis.

Table 5. Calculation of sustainability index indicators

Author	Environmental				Economy				Social			
	E1	E2	E3	E4	C1	C2	C3	C4	S1	S2	S3	S4
[22]	✓	✓	✓	✓	✓		✓		✓	✓	✓	✓
[23]	✓	✓	✓	✓		✓	✓		✓	✓	✓	✓
[40]	✓	✓	✓			✓			✓		✓	✓
[41]				✓		✓		✓		✓		✓
[42]		✓	✓						✓			
[43]								✓				
Selected Indicators		✓	✓		✓	✓		✓		✓	✓	

Details:
Environmental: E1: Material Consumption, E2: Material Waste, E3: Waste Recycling, E4: Water Consumption
Economy: C1: Inventory, C2: Quality, C3: Defect, C4: OEE
Social: S1: Satisfaction Level, S2: Noise Level, S3: Safety Level, S4: Employee Training

Indicators were selected based on the three pillars of sustainability. The indicators that significantly impact the company are presented below. Table 6 show the indicators selected from the existing set.

Table 6. Selected sustainability indicators

Sustainability Pillars	Indicator	Units	Calculations
Environment	Material Waste	%	$\frac{\text{Total amount of waste}}{\text{The total amount of input}}$
	Recyclable Waste	%	$\frac{\text{Amount of waste recycled}}{\text{Total waste}}$
Economy	Quality	%	$\frac{Number\ of\ inputs\ -\ number\ of\ rejects}{Number\ of\ inputs}$
	Inventory	Unit	The calculation of the storage capacity of Company X has been carried out by the Company.
	OEE	%	Availability Rate x Performance Efficiency x Rate of Quality
Social	Noise Level	Decibels (DB)	The Company has measured noise levels.
	Safety Level	%	-

Once the indicators have been identified, calculations are made according to Table 7, each indicator has existing and target values. The change value is then calculated, and the result of the Sustainability Index value can be displayed for each pillar.

The results of sustainability index assessment revealed scores of 73.08% for environmental pillar, 85.52% for economic pillar, and 95.62% for social pillar. The results indicate that the company requires 73% effort in environmental area, 85% in economic area, and 95% in social area. The social pillar appears to require a greater degree of effort, suggesting the company to prioritize this area to improve the value of sustainability index.

Table 7. The calculation results of the sustainability index

Pillar	Code	Description	Units	Existing	Target	Value of Change	Log	SI
Environment	E2	Material Waste	%	46,67	30	-16,67	1,22	73,08
	E3	Recyclable Waste	%	10,57	15	4,43	0,65	
Economy	C1	Quality	%	98,28	95	-3,28	0,52	85,52
	C2	Inventory	Unit	3026	2600	-426	2,63	
	C4	OEE	%	55,84	70	14,16	1,15	
Social	S2	Noise Level	DB	87	85	-2	0,30	95,62
	S3	Safety Level	%	95	90	-5	0,70	
Overall Sustainability Index							82,36	

The weighting of each sustainability pillar (environmental, economic, and social) was determined using Pairwise Comparison method based on the Analytical Hierarchy Process (AHP) approach introduced by Saaty [44]. In AHP, each pillar is compared in pairs based on its relative importance toward the ultimate objective [45], [46], which is the enhancement of manufacturing sustainability. It is then necessary to perform a consistency test on the weights obtained by calculating the consistency ratio value. The weight value is obtained as shown in Table 8.

Table 8. Weights of sustainability pillars based on pairwise comparison

Weight		
Environment	Economy	Social
0,31	0,44	0,25

The weight obtained must be consistent. To find out if a weight is consistent, divide the Consistency Index (CI) value by the Random Index (RI) value to obtain the Consistency Ratio (CR) value. The Consistency Index, Random Index, and Consistency Ratio values are obtained in Table 9.

Table 9. Consistency ratio value

n = 3		
CI	RI	CR
0,025	0,52	0,048077
CR Value Matrix 3 by 3 : 0,05		
CR	<	CR 3-3
0,04807692	<	0,05

A weight may be defined as "consistent" when the value obtained from the CR matrix exceeds that derived from the CR weight. In this instance, the CR matrix value exceeds the weight CRs, indicating that the weight value is consistent.

The Sustainability Index value is multiplied by the weight of each pillar to calculate the overall Sustainability Index.

$$\text{Overall SI} = (W_{ec} \times SI_{ec}) + (W_{sc} \times SI_{sc}) + (W_{en} \times S_{en})$$
$$= (0{,}44 \times 85{,}51) + (0{,}25 \times 95{,}62) + (0{,}3 \times 73{,}08)$$
$$= 82{,}36\ \%$$

The overall SI value obtained is 82.36%, indicating that approximately 82.36% of improvements are necessary to improve the company's sustainability performance, particularly in the social pillar, which requires more focused attention due to its relatively low sustainability index value of 95.62%.

3.3. Recommendations

Considering the issues identified in the preceding section, solutions can be proposed to enhance the company's operations. Table 10 and Table 11 below proposed improvements are anticipated to assist the company in reducing the existing impacts and losses and apply the concept of sustainability in production and machine maintenance.

Table 10. Recommendations within the TPM frameworks for handling losses

Framework	TPM Pillar	Improvement Recommendation	Handled Losses
TPM	Autonomous Maintenance	Machine Malfunction Indicator Sensor	Equipment failures, idling, and minor stoppage losses.
	Planned Maintenance	Maintenance Schedule	Equipment failures, Process defects, Reduced yield, Idling and minor stoppages losses
	Safety, Health and Environment	Warning display	Noise Level, Safety Level

Table 11. Recommendations within the 6S frameworks for handling losses

TPM Pillar	Improvement Recommendation	Handled Losses
6S	Seiri	Reduced speed, Process Defects, setup, and adjustment losses
	Seiton	Reduced speed, Process Defects
	Seiso	Equipment failures, setup and adjustment losses
	Seiketsu	Reduced yield, Equipment Failures, Setup and adjustment losses
	Shitsuke	Process defects, equipment failures, idling and minor stoppages losses
	Sensu	Equipment Failures, Setup and adjustment losses

Table 10 and Table 11 summarize improvement strategies based on TPM and 6S, designed to address various production losses in the bending machine. Planned Maintenance and Autonomous Maintenance were selected as the primary TPM pillars because they directly address the most frequent sources of loss, specifically reduced speed and minor stoppages. Planned Maintenance focuses on components with limited-service life, such as solenoid valves and pulleys, common causes of unplanned downtime. On the other hand, Autonomous Maintenance is implemented to prevent minor failures through daily operator checks, aligning with TPM's emphasis on early-stage efficiency. As emphasized by Nakajima [17], these two pillars are foundational for stabilizing equipment performance during the initial phases of TPM implementation.

3.3.1. Recommendation for Autonomous Maintenance

Operators in an autonomous maintenance system are responsible for simple preventive maintenance such as cleaning, lubrication, and routine inspections. However, judging from the high value of machine breakdown, it can be concluded that the operators responsible for performing machine maintenance are still less skilled or thorough in performing simple maintenance. In addition, it could also be due to the lack of resources or equipment needed to perform simple maintenance and the age of the machine, which is older than the age of the machine in its ideal condition

Given the current state of autonomous maintenance within the company, targeted improvements are necessary to enhance operator awareness of their responsibilities—not only toward the machinery but also in relation to environmental, economic, and social sustainability. One appropriate initiative to address the challenges in autonomous maintenance is the implementation of a machine inspection checklist.

Table 12 is a checklist which has to be completed by the operator on duty. It includes essential information such as the inspection date, machine number, operator's name, responsible personnel, and the machine's condition in the production area. The checklist covers routine inspections that must be performed before the machine is powered on. These general checks are conducted by operators trained by maintenance personnel to ensure proper execution of the inspection procedures.

Table 12. Machine inspection check sheet

<table>
<tr><td colspan="2" rowspan="5">Company X</td><td colspan="4">Inspection Date</td></tr>
<tr><td colspan="4">Machine Number</td></tr>
<tr><td colspan="4">Area</td></tr>
<tr><td colspan="4">Operator</td></tr>
<tr><td colspan="4">PIC</td></tr>
<tr><td colspan="6">MACHINE INSPECTION CHECKSHEET</td></tr>
<tr><td rowspan="2">Component</td><td rowspan="2">Standard Condition</td><td colspan="2">Actual Condition (✓)</td><td rowspan="2">Information</td><td rowspan="2">Time</td></tr>
<tr><td>Good</td><td>Bad</td></tr>
<tr><td rowspan="2">Pedal</td><td>Not stuck or stiff</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Normal pedal height</td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Solenoid Valve</td><td>No rattling sound</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Control signal response is good</td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Oil Pump</td><td>Temperature is stable</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Oil is not bubbly</td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Hidrolik Press</td><td>Hydraulic pressure is stable</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Press result is consistent</td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Emergency Socket</td><td>Fast response when pressed</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Machine automatically shuts down when pressed</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="6">Additional Information:</td></tr>
</table>

A bending machine has several internal components with a high downtime, such as the Solenoid Valve, Pulley, and gear. If those components break down, the production process must stop immediately. A machine damage detector can be added to detect minor problems in the machine before they develop into significant damage. This can minimize damage and allow for quick and cost-effective repairs. Machine Malfunction Indicator Sensors also help prevent workplace accidents caused by sudden machine failures; potential hazards can be identified and addressed immediately, creating a safer work environment.

Another suggested improvement to help decrease the high value of breakdown time is to provide a sensor tool on the machine. This tool enables the operator to immediately assess the machine's condition. The sensor tool emits a sound with an intensity of 85 DB when there are problems with the engine condition, and the lights come on according to the indicator's color. The red indicates that the engine has broken down and must be stopped immediately, the yellow indicates a breakdown to the engine which, if left unchecked, will be fatal, while the green shows that the engine system is running to standard.

The Machine Malfunction Indicator Sensor monitors engine conditions that deviate from optimal operating parameters. These conditions may include excessive vibrations, abnormal noise levels, elevated temperatures, and other operational irregularities. The sensor collects data at regular intervals, which are then processed by the system to assess engine performance.

The sensor system compares the actual operating conditions with predefined normal parameters. If a deviation is detected (indicating that the engine is not functioning correctly) the sensor triggers an audible alarm and activates a visual warning system. This system utilizes a three-color light indicator, with each color representing a specific severity level of engine malfunction. Figure 2 shows the Machine Malfunction Indicator Sensor that can be implied to each machine.

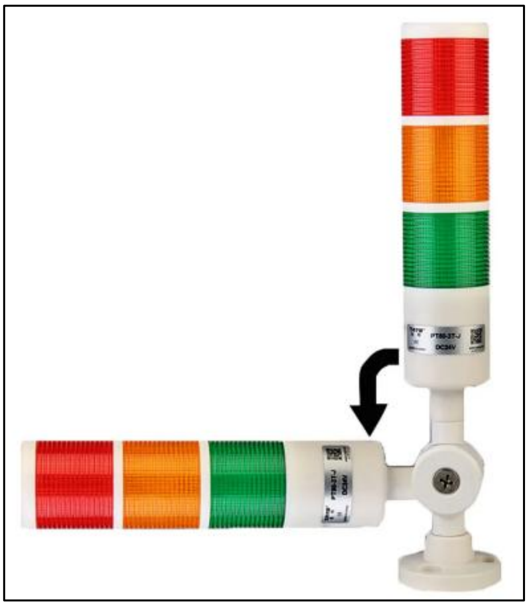


Figure 2. Machine malfunction indicator sensor
Source: AliExpress – Three Color Warning Light

3.3.2. Recommendation for Safety, Health, and Environment (SHE)

Company X has effectively implemented the Safety, Health, and Environment (SHE) pillar, as evidenced by a dedicated SHE department that focuses on creating a healthy and safe work environment for employees. However, there is still no boundary line in the machine area indicating that it has entered the production area, otherwise known as a safety floor mark. This can confuse operators because there are no markings around the work area. There is also no first aid kit in the production area; the first aid kit is in the office, which is far away from the production area.

Based on the analysis, several recommendations can be implemented to enhance the company's safety. Floor marking can provide a strong visual cue to operators. With bright colors, it can easily convey information even in busy environments. It can also help operators understand the workflow arrangements in the production area. Painted or taped lines are commonly used for safety purposes, such as marking pedestrian paths, forklift and equipment paths. However, they are also very useful for delineating work areas, marking locations for pallets, raw materials, finished goods, shipping, and other static locations. By clearly defining the boundaries of these areas, employees and visitors can navigate the space more efficiently. In Table 13 shows several colors with different meanings.

Table 13. Floor marking color code guideline

Color Code	Color	Meaning
Red		Alert people to dangerous equipment or materials (defect/scrap area)
Orange		Caution for parts of machinery or energized equipment.
White		Internal objects (racks, machines, carts, benches)
Yellow		Mark aisle ways and cell area divisions.
Green		Mark safety equipment designation (finished goods)
Blue		Areas for equipment in need of repair and warns against starting equipment under repair (raw materials)
Hazard Stripe		Bring attention to special areas with potential hazards.
White/Black Contrast Stripe		Marks robotic passageways.
Yellow/Black Contrast Stripe		Marks dead ends of passageways.

Source: OSHA Standard for Floor Marking (1910.144) and ISO 7010 Safety Signs.

Each color represents a specific consideration for each work area. For instance, red indicates the presence of potentially dangerous equipment in the marked area, while green indicates that the equipment is safe. This system can enhance workers's awareness of the work area environment as they navigate it daily. The floor marking is shown in Figure 3.

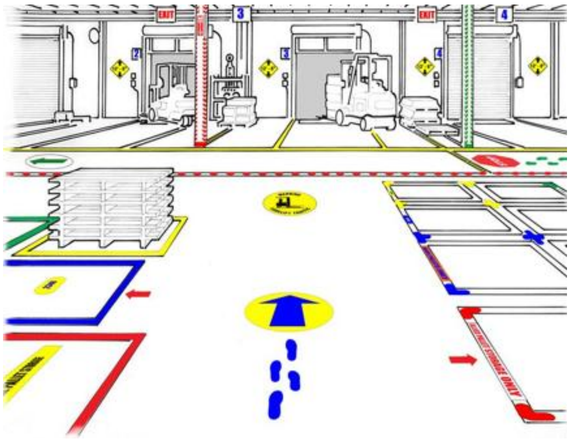


Figure 3. Floor marking application guidelines [47]

Industrial floor tapes are preferred over painted lines because they are more resistant to foot and forklift traffic and do not require long dry times. Additionally, they are easy to clean and require minimal upkeep. These tapes are available in various colors and sizes, enabling the creation of a customized marking system that meets the company's specific needs.

The thickness of floor markings ranges from 0.1 mm to 1 mm, dependent on the type and intensity of traffic in the area, while the width of the marking is between 2 and 10 cm on average. International standards regulate the use of floor tapes, including the Occupational Safety and Health Administration (OSHA) standards in the United States and the International Organization for Standardization (ISO) standards. For instance, OSHA has established regulations regarding the use of colors and materials to delineate work environment floors.

A first aid kit located on the side of the machine can provide immediate aid to operators who are injured during the production process. The distance to the first aid kit must be close, considering that an injury is an emergency that must be resolved immediately, as it relates to the safety and health of the workers. The bending machine on the production floor of Company X is located at the end, adjacent to the wall. Consequently, if the floor plan of the floor marking is described, it will resemble in Figure 4.

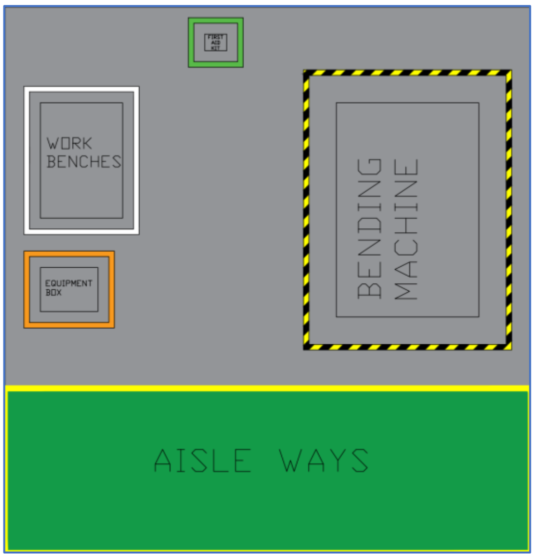


Figure 4. Placement of First Aid Kit and Floor Marking Tape

Placing posters about the importance of safety in the operator's work area can improve the operator's awareness during machining. By displaying posters about the importance of safety at work, it is hoped that operators will be more careful when carrying out work directly related to the machine. Figure 5 shows several design design of the poster which can be placed in production area based on Occupational Safety.

Figure 5. Poster on Occupational Safety
Source: safetysign.co.id (2023) – K3LH Poster Guidelines.

A series of Indonesian safety posters aimed at promoting occupational safety among workers, their English translations, explanations, and objectives are presented in Table 14. Each poster employs relatable metaphors and practical advice to convey the importance of workplace safety measures and promote a culture of vigilance and care among operators.

Table 14. Safety poster explanation

Indonesian Posters Sentences	Persuasive Meaning	Explanation	Goals
"Hargai kedua tangan anda"	Value your arms with the same passion you have for your soulmate!	Keeps the operator using gloves and value their arm, and keeps the operator doing their job carefully and using safety equipment.	To make operators use safety equipment while doing their jobs, such as helmets, safety gloves, safety goggles, masks, and many more.
"Lindungi dengan sarung tangan yang sesuai dengan pekerjaan"	Protect your hands! Use the right gloves for the job to keep your fingers safe and intact.		
"Kepala anda bukan batu, pakai helm sekarang!"	"Hey there! Your head is precious, so make sure to wear your helmet!"	It shows that their heads are prone to accidents and aren't made of stone that can't be broken, so they realize the importance of using helmets to protect their heads.	
"Hindari terpeleset, tersandung, dan jatuh pada saat bekerja"	"Prevent slips, trips, and falls at work. The floors are not softer than the bed."	Realizing the importance of tidying and keeping their workspace clean, and they can avoid accidents that can cause slipping, tripping, and falling, and they will remember that floors aren't softer than beds.	To make operators realize that implementing the rules of 6S will be more efficient with their workstation because it is all sorted, set in order, standardized, shiny, and sustained.
"Bersihkan jalan anda dari peralatan dan sampah yang mengganggu"	"Keep your workspace tidy and free from distractions to improve your happiness."		

3.3.3. Recommendation for Planned Maintenance

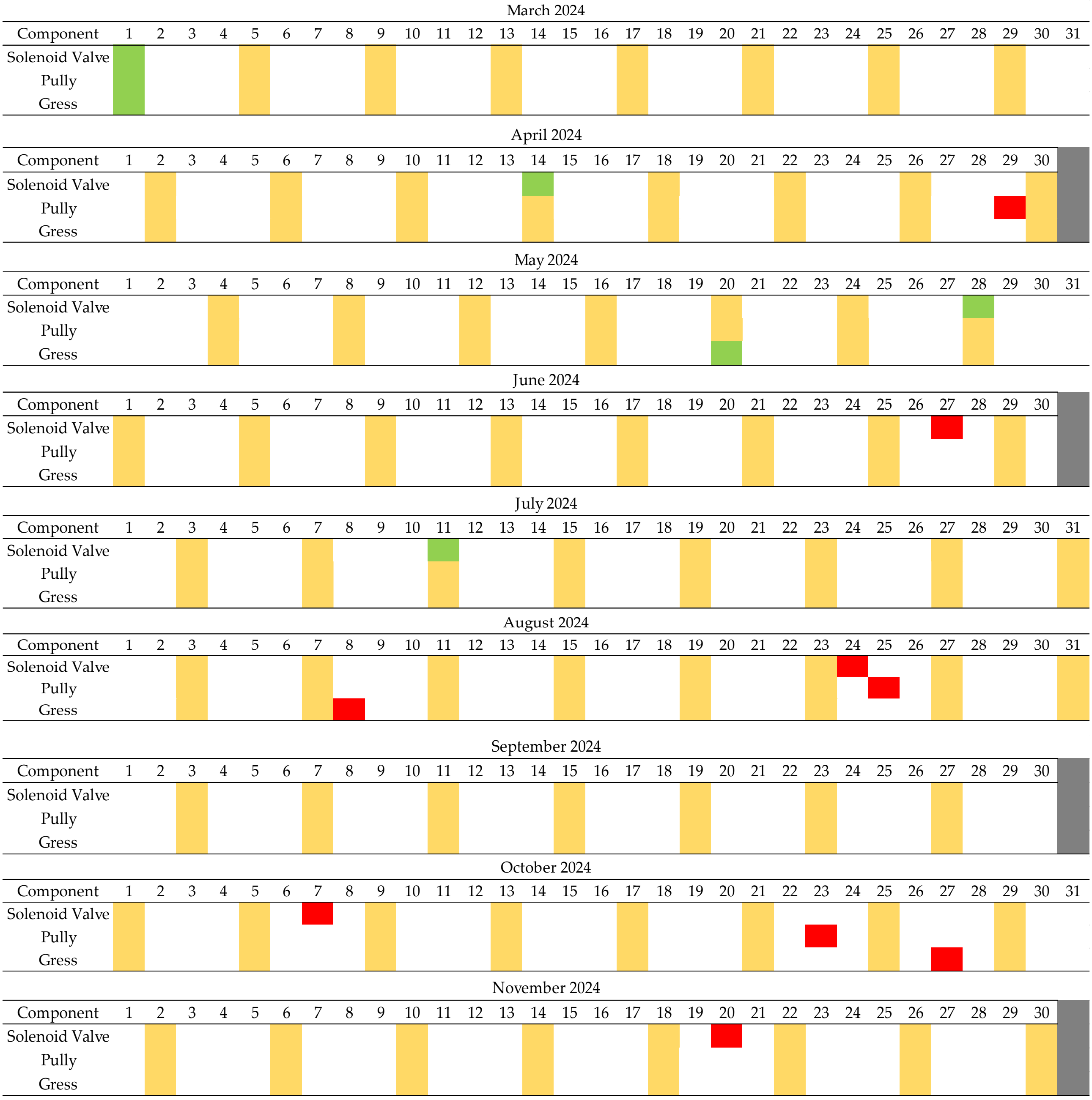
Planned maintenance is a structured and scheduled maintenance approach intended to ensure that equipment and systems remain in optimal working condition, which is carried out before the machine experiences failure [48]. This approach encompasses various types of maintenance, including corrective, predictive, and preventive maintenance. Preventive maintenance is a maintenance strategy that is carried out on a regular and planned basis to prevent the occurrence of equipment breakdowns or failures. The main goal of preventive maintenance is to reduce the probability of unexpected downtime and to increase the operational lifespan of an equipment. Table 15 provides details on the replacement of components in the system with some important parameters. The components analyzed include Solenoid Valve, Pully and Gress with different life replacement times of 1040 hours, 1411 hours and 1919 hours, respectively.

Table 15. Repair and inspection interval for each component

Component	*Age Replacement* (Hours)	*Age Replacement* (Days)	Minimum D (tp)	*Availability* (tp)	Optimal Inspection Frequency	Optimal Inspection Time Interval (Hours)
Solenoid Valve	1040	44	0,035483612	0,964516388	4	200
Pully	1411	59	0,123267321	0,876732679	3	150
Gress	1919	80	0,058555632	0,941444368	2	100

Table 15 also lists the "Minimum D (tp)" and "Availability (tp)" for each component, reflecting its reliability and availability, with availability values ranging from 0.8767 to 0.9645.

Additionally, this table displays the Optimal Inspection Frequency and Optimal Inspection Time Interval by Hour, indicating the optimal frequency and interval for inspecting each component. Each component has a different age replacement value; the Solenoid Valve requires maintenance every 44 days, the Pully 59 days, and the Gress 80 days. This data is essential for scheduling preventive maintenance and ensuring the reliable operation of the system.



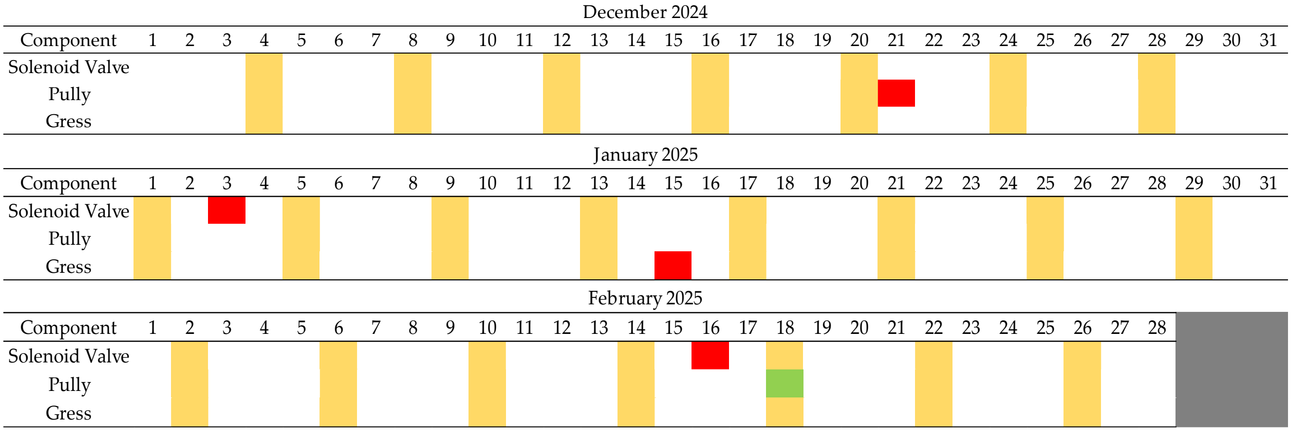


Figure 6. Maintenance schedule

Figure 6 represents the optimal maintenance schedule, obtained by converting the selected MTTF value into units of days. This schedule indicates that the repair time interval for solenoid valve components is 65 days, pulley components 66 days, and gear components 70 days. The length of time required for repairs can be determined by converting the specified MTTR value into units of days. If the MTTR value is 3 days, then the repair time for solenoid valve parts will be 3 days; however, if the MTTR value is 1 day, the repair time for pulley and gears parts will be 1 day. The machine will be maintained autonomously by the operators daily.

3.3.4. Recommendation for 6S

The implementation of 6S methodology plays a critical role in supporting employee health and safety by aiming to reduce waste, enhance workplace hygiene, improve safety, and boost productivity. Visual management further reinforces these goals by making safety standards more accessible and understandable through visual cues and diagrams that guide employees in performing tasks correctly and safely. Although the company intends to apply 6S in its work areas, its execution remains suboptimal, leading to several ongoing issues. Specifically, four of the six major types of equipment-related losses (namely breakdown losses, setup and adjustment losses, idle and minor stoppage losses, and reduced speed losses) can be attributed to the ineffective implementation of 6S. Recommendations for 6S pillars improvement, are presented in Table 16.

Table 16. Overall 6S recommendations

Number	6S	Meaning	Improvement Recommendations
1	*Seiri*	Sort	Sorting components and tools used into a toolbox
			Separating components/tools by material
2	*Seiton*	Set in Order	Make a list of the availability of a component or tool that will be used
			Organize tools and components, both before and after use in the equipment box
3	*Seiso*	Shine	Always clean machines and equipment before and after use
			Provide floor marking so that operators know the work area
			Clean the work area when the shift is over
4	*Seiketsu*	Standardize	Always perform inspection and maintenance before and after starting the engine
			Make adjustments to the machine when before and after using the machine.
5	*Shitsuke*	Self Discipline	Keeping the machine area clean and tidy
			Inspect operators for 5S implementation
6	*Sensu*	Safety	Conduct a risk assessment to identify potential hazards around the machine. Post clear warning signs and safety instructions near the machine.
			Provide and use appropriate APD (Alat Pelindung Diri) when operating machinery.

The application of 6S is crucial for the successful implementation of TPM, as it provides the foundational framework upon which TPM practices are built. Therefore, meticulous attention to detail and rigorous application of 6S principles in the workplace, particularly those related to machinery, is crucial. From the Seiton (orderliness) perspective, one proposed improvement involves introducing an equipment condition check sheet, which can be seen in Table 17, enabling operators to assess the state of the equipment prior to use during production or before initiating machine operations, thereby promoting safety, efficiency, and reliability in daily processes.

Table 17. Equipment availability check sheet

<table>
<tr><td>Company X</td><td colspan="4">Equipment Availability Checksheet</td><td colspan="3">Inspection Date
Machine Number
Area
Person In Charge</td></tr>
<tr><td colspan="8">Tooling inspection should include at least the following:
1. Tools used are appropriate for the scope of the work area
2. Tool handles are well attached
3. In good condition: not loose, sharp cutting edge, no mold.
4. Tools are stored in the box, not outside the equipment box area 4.
Items that fall into the “Poor” or “Very Poor” category should not be used, they should be removed from the work area immediately.</td></tr>
<tr><td rowspan="2">Equipment Details
(hammers, screwdrivers, dies, etc..)</td><td colspan="4">Condition</td><td>PIC</td><td>Information</td><td>Status</td></tr>
<tr><td>Best</td><td>Good</td><td>Bad</td><td>Worst</td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Furthermore, from a seiri (concise) perspective, equipment boxes should be provided so that operators can sort and tidy components, separating them by material type, size, and frequency of use. The equipment box for Seiri Implementation is shown in Figure 7.

Figure 7. Equipment box for Seiri implementation
Source: AliExpress.com – Drawer Tool

Improvements are made to increase the value of the Sustainability Index and Overall Equipment Effectiveness. The result in Table 18, Table 19, and **Table 20** clearly proves the significant improvements achieved. The aspects calculated Table 18 is identical to those previously calculated in Table 3, where the OEE values were calculated. Table 19 presents the same calculation as found in Table 7, and as illustrated in Table 20, the data provides insights into both the pre- and post-implementation phases of the company's suggested improvements. Autonomous maintenance pillar, safety health, and environment pillar, planned maintenance pillar, and also improving the 5S into 6S pillar for reducing downtime of the bending machine.

Table 18. Overall equipment effectiveness value after improvements

Month	Availability Rate	Performance Efficiency	Rate of Quality	OEE (%)
Mar 23	0,8753	0,6956	0,9857	60,0152
Apr 23	0,937	0,306	0,9895	28,3711
Mei 23	0,8934	0,676	0,9805	59,2162
Jun 23	0,9099	0,6434	0,979	57,3136
Jul 23	0,8349	0,9444	0,9745	76,8373
Agt 23	0,9477	0,9956	0,9861	93,0415
Sept 23	0,9249	0,7942	0,9905	72,7577
Okt 23	0,9722	0,846	0,9929	81,6642
Nov 23	0,9232	0,7251	0,9868	66,0576
Des 23	0,9944	1,0492	0,9854	102,8092
Jan 24	0,9842	1,0196	0,9904	99,3857
Feb 24	0,9011	0,9989	0,9843	88,5977
Average				70,34

Table 19. Calculation of the sustainability index after improvements

Pillar	Code	Description	Units	Existing	Target	Value of Change	Log	SI
Environment	E2	Material Waste	%	41,4	30	-11,4	1,0569	70,5
	E3	Recyclable Waste	%	14,41	15	0,59	-0,2291	
Economy	C1	Quality	%	98,55	95	-3,55	0,5502	86,94
	C2	Inventory	Unit	2750	2600	-150	2,1761	
	C4	OEE	%	70,34	70	-0,34	-0,4685	
Social	S2	Noise Level	DB	84	85	1	0	92,6
	S3	Safety Level	%	98	90	-8	0,9031	
Overall Sustainability Index								80,91

Table 20. Sustainability index overall before and after improvements

Sustainability Index	Before Improvements	After Improvements	Variance
OEE	55,84	70,34	14,50
Environment	73,08	70,5	2,58
Economy	85,52	86,94	1,42
Social	95,62	92,6	3,02
Overall SI	82,36	80,91	1,45

The reduction has a significant impact on the OEE value in the breakdown of the bending machine. If the breakdown is reduced, production time can be allocated to manufacturing finished products with greater value. The OEE value of Company X has increased to 70,34%, indicating that the improvement recommendations will positively impact the Company.

The same indicators utilized in calculating the Sustainability Index after improvements will be employed for the calculation of the sustainability index after improvements. For the environmental pillar, indicators pertaining to both material waste and recyclable waste will be considered. The economic pillar will be assessed through quality, inventory, and OEE lenses. Finally, the social pillar, noise level, and safety level indicators will be utilized.

After calculating the sustainability index and OEE following the improvement measures, the next step is to perform a comparative analysis by calculating the variance between the pre- and post-improvement results to assess the effectiveness of the implemented changes.

After implementing improvements, the overall sustainability index value has improved to 80,91%. This indicates that the sustainability aspect has improved compared to the previous state at Company X. According to Sustainalytics, the optimal sustainability index score is typically below 20%, indicating low ESG risks. This suggests that Company X has sustainability practices and policies that effectively manage ESG-related risks.

To maintain and improve its sustainability score, the company must implement effective measures to ensure efficient energy use and reduce emissions and waste that require further processing. Expanding green land is also beneficial in maintaining the company's infrastructure. SDG 12 enables companies to enhance the value of their sustainability index while significantly contributing to achieving sustainability, thereby strengthening their competitiveness, reducing operational risks, and fostering a positive reputation among stakeholders. Moreover, it is imperative to implement autonomous maintenance on a routine basis, in addition to applying and enforcing the TPM pillars related to safety, health, and environment, and planned maintenance, as well as for autonomous maintenance.

However, further analysis indicates that the social aspects are the most pressing area for improvement in the sustainability index. This encompasses several key elements, including the welfare of employees, relations with the broader community, and the implementation of corporate social responsibility. One approach that could be employed to improve social sustainability is providing local communities with access to affordable, reliable, and modern energy. An example of this would be the support of renewable energy projects in local communities and the implementation of company infrastructure with the latest technology to ensure more efficient and environmentally friendly operational practices. It is thus evident that companies should pay greater attention to social issues to achieve long-term sustainability.

4. CONCLUSION

The research results indicate that the OEE value obtained is 55.85%, far from the ideal standard. This suggests that the bending machine is still unproductive in the production process. After calculating the six big losses, the most significant loss experienced is reduced speed, with a total loss of 100.732,72 minutes. The level of the sustainability index is only 82.36%. Improvement recommendations are based on an analysis of the pillars and foundations of TPM to increase the effectiveness and value of the existing sustainability index. These improvements include providing check sheets, installing malfunction sensors on bending machines, placing safety posters in the production area, etc. In addition, the efficient use of energy must be enforced, as well as the reduction of emissions or waste that must be processed further. Increasing the area of green land is also beneficial in maintaining the company's infrastructure, which is correlated with SDG 12. After implementing improvements, the OEE value is increased to 70,34%, and the sustainability index is 80,91%

The improvement model proposed in this study, which integrates TPM, 6S implementation, and sustainability index evaluation, has the potential to be replicated in other manufacturing sectors beyond the electrical equipment industry. Industries such as automotive, food and beverage, and metal processing, which operate continuous or semi-continuous production lines, can adopt this approach to reduce equipment losses and improve sustainable performance. The key to successful replication lies in customizing the selected TPM pillars, adjusting the 6S practices to match workplace characteristics, and redefining sustainability indicators relevant to the sector. By employing a structured method, such as AHP, for weighting and utilizing log-based normalization for evaluation, this model can serve as a flexible framework to guide sustainability-oriented maintenance strategies across various industrial contexts.

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