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APPLICATION OF TOTAL PRODUCTIVE MAINTENANCE IN A MANUFACTURING PROCESS OF CARDBOARD BOXES UNDER LEAN SIX SIGMA DMAIC METHODOLOGY

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ABSTRACT

Two key elements for improving supply chain performance are total productive maintenance (TPM) and overall equipment effectiveness (OEE). This paper proposes a TPM strategy for managing and autonomously maintaining four die-cutting machines for cardboard boxes to enhance production flow. Using the DMAIC cycle (define, measure, analyse, improve, control), maintenance activities were classified and efficiency measured through OEE and sigma metrics. After the first improvement cycle, the OEE and sigma metrics increased by an average of 21%, boosting productivity, quality, and efficiency. The study concludes that strategies based on preventive, predictive, and corrective maintenance significantly enhance supply chain performance in a Lean Six Sigma framework, and could be applied to other processes.

OPSOMMING

Twee sleutelelemente vir die verbetering van voorsieningsketting-prestasie is totale produktiewe instandhouding (TPM) en algehele toerustingdoeltreffendheid (OEE). Hierdie artikel stel 'n TPM-strategie voor vir die bestuur en outonome instandhouding van vier stansmasjiene vir kartondose om produksievloei te verbeter. Deur die DMAIC-siklus te gebruik (definieer, meet, ontleed, verbeter, beheer), is instandhoudingsaktiwiteite geklassifiseer en doeltreffendheid gemeet deur OEE- en sigma-metrieke. Na die eerste verbeteringsiklus het die OEE- en sigma-metrieke met gemiddeld 21% toegeneem, wat produktiwiteit, kwaliteit en doeltreffendheid verhoog het. Die studie kom tot die gevolgtrekking dat strategieë gebaseer op voorkomende, voorspellende en regstellende instandhouding die voorsieningsketting-prestasie aansienlik verbeter in 'n Lean Six Sigma-raamwerk, en op ander prosesse toegepas kan word.

1. INTRODUCTION

Total productive maintenance (TPM) is a methodology that improves equipment efficiency by introducing prevention concepts, zero defects, and the participation and autonomy of operating personnel. In manufacturing, proper maintenance is critical to prevent failures and speed reductions that disrupt production continuity, generate product waste and reprocesses, and increase operating expenses, all of which have a negative impact on supply chain performance [1]. Manufacturers recognise the need to improve operations continually in order to remain competitive. Investments in programmes such as just-in-time (JIT) and total quality management (TQM) aim to enhance organisational capabilities, but their benefits are limited by unreliable or inflexible equipment [2].

Originating in Japan, TPM has spread globally, becoming a methodology for enhancing equipment reliability and plant productivity. TPM eliminates losses caused by unplanned downtime, slowdowns, and quality issues. It uses overall equipment effectiveness (OEE) to measure these losses [3]. Ahuja and Singh [4] emphasise that maintenance must ensure equipment availability to produce the required quantities and quality levels. Shen [5] discusses critical TPM factors such as feasibility studies, effective entry plans, suitable strategies, equipment and product reliability, and personnel training.

This research aims to apply a methodological proposal that is based on the define, measure, analyse, improve, and control (DMAIC) improvement cycle, classifying TPM and maintenance management activities into those five phases. Key indicators, OEE, and sigma metrics (a statistical measure of process variation, often used to assess quality and defect rates in aiming for high consistency and minimal errors in production) were used to evaluate performance from statistical and productivity perspectives in a cardboard box manufacturing process, particularly in the die-cutting department. This highly automated and critical process defines the company's overall productivity.

2. LITERATURE REVIEW

In the state-of-the-art TPM applications, various approaches have been studied, including integrated structural modelling (ISM) for identifying and analysing TPM facilitators [6,7] McKone et al. [8] used structural equation modelling (SEM) to investigate the relationship between TPM and manufacturing performance, finding significant positive relationships with low inventory costs, high quality levels, and strong delivery performance. Analysis hierarchy process (AHP) techniques were applied to rank the importance of the eight TPM pillars based on productivity, cost, quality, and delivery time criteria [9]. Kakkak and Ghodsi [10] used the European Foundation for Quality Management (EFQM) model to assess TPM's impact on organisational excellence, aiming to improve product quality and services.

Amorim et al. [11] applied TPM in autonomous maintenance performance analysis in the manufacturing industry through a qualitative and descriptive survey, identifying machinery and equipment as the critical factors for improving OEE. Other TPM applications include sustainable manufacturing [2,12] and the automotive industry [13]. State-of-the-art TPM approaches also explore online monitoring to support TPM systems [14], intelligent machine learning for minimising unused industrial machinery time [15], and integrating Industry 4.0 technologies in TPM practices [16,17]. Pascal et al. [18] presented a model using survival laws, the hidden Markov model, and support vector machines with sensor data to propose TPM improvement indicators.

The primary metric in TPM research is OEE, which evaluates equipment efficiency and maintenance improvements by focusing on availability, performance, and quality [19-21]. Integrating TPM with total quality management (TQM) techniques optimises preventive maintenance [22,23], focusing on continuous improvement [24] and using OEE as a Lean Six Sigma (LSS) capability metric [25]. The importance of the most recent studies is highlighted, which address the importance and role of Industry 4.0 in TPM [26-28]. In contrast to the state-of-the-art of TPM, this research proposes using TPM techniques and maintenance management within the DMAIC continuous improvement cycle as the main contribution. Conducted in a highly automated section of a cardboard box manufacturing process that is critical to overall productivity, the study also uses OEE and sigma metrics to evaluate performance from various perspectives, providing a better understanding of waste factors.

3. METHODOLOGY

The general methodology proposed for applying the TPM in the process through the phases of the DMAIC cycle is shown in Table 1.

Table 1: Proposed methodology with a focus on TPM

Phase	Activities
Define	Definition of the problem Realisation of the project charter Process mapping at three levels Realisation of SIPOC diagram Determination of causes of stoppage in machines
Measure	Determination of machinery stoppages Work sampling/ sample size determination Classification of causes of downtime Loss records Evaluation of the OEE Indicator and the sigma level of the process
Analyse	Analysis of the maintenance department Management of the maintenance area Stoppages in the cutting area owing to equipment damage Maintenance activities
Improve	Implement autonomous maintenance Perform major cleaning Define equipment cleaning and maintenance routines Apply the seven steps of autonomous maintenance Implement the use of TPM cards
Control	Failure mode and effect analysis (FMEA) Comparison of OEE and sigma level, before and after implementation

The proposed methodology integrates a continuous improvement cycle, using efficiency and quality metrics to achieve productivity objectives. The steps are as described below.

3.1. Define phase

"Identify the causes of machinery stoppages in the die department."

The first step was defining the problem to gather relevant information about the process, describing its characteristics and observed symptoms. An adequate problem description would prevent erroneous assumptions and deviations from the study's original objectives. The die-stamping department was selected as the critical area for this study owing to its essential and expensive equipment. Inefficiencies and stoppages in this department have a significant impact on subsequent processes. The die-cutting area contains four machines for cardboard boxes: Bobst #1, Bobst #3, Brausse #105, and Brausse #145, as shown in Figure 1.

The project charter is a Six Sigma tool that outlines the critical information for a project. It includes a general project description, the initial sigma level, processing capacity, parts per million (PPM), and the affected indicators (such as OEE), as well as details about the region, business unit, and team members (including different belt levels in Six Sigma). This project aims to apply the TPM improvement methodology through a DMAIC cycle in a packaging and cardboard box company. By linking OEE and sigma level measurements, the project seeks to assess and enhance the quality and productivity of the process equipment. The primary goal is to increase the overall process OEE from an initial average of 58.42%, along with individual machine indicators.

Figure 1: Die-cutting department

Three-level process mapping is a graphical tool that is widely used in the Six Sigma definition phase to locate critical-to-quality characteristics (CTQs) efficiently. With the mapping of processes and each of the links that make up the production process, it is possible to demonstrate the existence of strategic, critical, and support processes in which the cardboard box manufacturing process is involved. The administrative and operational process's general activities, inputs, and identifying outputs were at the first level. As a result, the following was obtained:

- Lack of training for operators to operate the machine.
- Lack of preventive, corrective, autonomous maintenance.
- Lack of feedback from planning departments.
- Lack of follow-up to manufacturing/production problems.
- No regular sampling based on production times.

At the second level were the processes involved in the manufacturing area and the relationship between them. The review of the information of the second-level mapping, in which the critical process for the process that includes this project (stamping department), identified and found four machines under study: Bobst # 1, Bobst # 3, Brausse # 105, Brausse # 145.

Most of the problems detected were a lack of preventive maintenance on machines, a lack of training for maintenance technicians, a lack of training in machinery adjustment, and a lack of autonomous maintenance, Forty-two activities were detected in the diecutting process, of which 38 were operational and four were verifications, carried out by two collaborators who manage the machine (operator and feeder/assistant).

The SIPOC diagram offers a comprehensive overview of potential areas for process improvement and the intricate connections between the involved activities. The acronym SIPOC stands for the five core components it encapsulates: supplier, input, process, output, and customer. The 'S' denotes the supplier, who provides the process with information, materials, or other necessary resources; 'I' represents the elements introduced into the process; 'P' encompasses the sequence of steps that transform the input, thereby enhancing the end value; 'O' signifies the outcome derived from the process; and finally, 'C' identifies the customer, the recipient of the process's end result. This model serves as a strategic tool for identifying critical elements in a process, ensuring a clear understanding of how each component contributes to overall efficiency and effectiveness.

The cause-and-effect diagram facilitated the creation of a sampling sheet to pinpoint the root causes of inefficiency in the equipment. The preliminary step in identifying the reasons for downtime in the BOBST1, BOBST 3, BRAUSSE 145, and BRAUSSE 105 machines in the die-cutting department involved establishing a cause-and-effect diagram that mapped out the existing issues in the process. The strategy to enhance productivity centred on the gradual decrease of failure incidents, maintenance frequency, and, as a result, the minimisation of machine/tool downtime and the reduction of lost person-hours among machine/tool operators. Productivity was intrinsically linked to maximising the uptime of machines and tools, optimising the allocation of person-hours and machine hours, and affording the operational staff more opportunities to engage in high-value-added activities.

3.2. Measure phase

"Collect data and evaluate relevant indicators, diagnosing the initial state of the process using theoretical and technical tools and records. This phase includes evaluating OEE metrics in relation to sigma metrics."

The task here was to collect data and evaluate relevant indicators, diagnosing the initial state of the process using theoretical and technical tools and records. This phase includes evaluating OEE metrics in relation to sigma metrics.

In the 'measure phase', techniques for gathering data on the process's current performance were pinpointed, building upon the groundwork laid in the 'definition phase'. This phase was initiated by determining the nature of the data to be collected from a substantial sample size, which would bolster the subsequent project phase. The data amassed during this phase was instrumental in identifying variation sources and establishing a benchmark to corroborate the efficacy of the enhancements made.

To ascertain the causes of machinery stoppages and low speeds in the department, it was essential to gather information to understand production behaviour. This was achieved through the Gemba walk method (a process in which team members visit the workplace to observe and identify issues directly, helping to improve hands-on problem-solving). 'Gemba' is a Japanese term meaning "the actual place" where work is done. By visiting the Gemba, one could observe the process, ask questions, and learn how operations were conducted, which aided in proposing future solutions and supported data collection using tools such as photographs and interviews.

The process underwent analysis to identify failures and to understand the department's activities and the daily behaviour of personnel, and to confirm issues highlighted in surveys. Furthermore, discussions with production management were held to assess the status of deliveries and to determine whether there were problems in the production area. It was noted during these interviews that production targets and goals were not being met, leading to delays, overtime, and shift schedule alterations, all of which can result in substantial economic losses. For the work sampling, the following steps were taken:

- Prepare a sampling format: Develop a structured template systematically to collect information pertinent to the study.
- Select activities for sampling: Identify and define the specific activities to be observed. It was crucial to inform and engage workers in the process for effective execution and to ensure that the selected activities were representative of the study's focus.
- Calculate the activity or delay proportion (p): Establish the number of observations needed for the work sampling, based on the desired level of result accuracy. It was important to remember that a higher number of observations would yield greater confidence in the findings.
- Determine the number of observations: Use statistical tables or software to calculate the required number of observations for the desired accuracy, factoring in the value of the Z variable (normal distribution).
- Conduct data recording: Ensure that workers comprehend the significance of the study in order to guarantee that the data accurately reflected the activity's reality.
- Result analysis: Evaluate the collected data in alignment with the study's goals.

A structured sampling format was crafted to facilitate the collection of information and to delineate each procedural step. This format encompassed the start and end dates, sampling objectives, number of observations, names of the causes being sampled, sampling times, participants' names, and a designated area to tally occurrences of stoppages.

During an initial two-day period, 28 samplings were conducted, revealing that the most prominent causes of disruption were debris on the platen and material hauling. The data indicated that 20% of the issues were production-related, while 80% pertained to work stoppages. To ascertain the requisite number of samples with 90% confidence, ensuring that the actual proportion of delay time fell within a 1% to 10% range, the following formulae were applied. For a confidence level (CL) of 90%, the calculation of the alpha level (α) was derived using Eq. (1):

$$p = \frac{1+CL}{2} = \frac{1+0.90}{2} = 0.95 \qquad (1)$$

According to the confidence level used, the value of tables (or software) used in the sampling process was 1.645. Eq. (2) calculated the value of N = the number of observations that had to be sampled, where 8% of unavoidable delay times by personnel of the department under study determined the value *I*=0.08.

$$N = \frac{4\alpha^2 P_i(1-P_i)}{I^2} = \frac{4(1.645)^2 0.20(1-0.20)}{0.08^2} = 270.5\ samples \tag{2}$$

The result obtained was 270.5 samples. To improve the estimate, we collected 300 samples over 22 business days. This equated to almost 14 samples per day (300 samples ÷ 22 business days = 13.64 samples/day).

After completing the work sampling and compiling a list of causes with the involvement of supervisors and operators, the next step was to classify the stoppages and downtimes. This classification was crucial, as it provided a global perspective on the reasons behind the stoppages. It helped to determine whether a stoppage was the result of the quality of the material, maintenance needs, repairs, or product changes.

To streamline the process of monitoring and measuring productivity, record formats were established. These formats enabled operators to document each task performed during their shift, providing insights into time lost from machine stoppages or reduced speeds. The recorded data was then used to generate statistics and visual representations, such as graphs, via a productivity indicator. This allowed each operator's performance throughout their workday to be evaluated.

The stages of implementation for using these record formats were: a) instructing the operator on the measurement process; b) guiding the operator on how to complete the forms; c) clarifying the concept of productivity and its impact on the departmentl and d) demonstrating how results are visualised using graphs.

The concept of OEE served as a vital key performance indicator (KPI) within the TPM framework. OEE quantifies the efficiency of machinery and production lines by integrating three fundamental elements:

- Availability: This measures the actual production time of the machine, accounting for interruptions such as breakdowns, adjustments, and setups.
- Performance efficiency: This evaluates the actual production output within a specific timeframe, considering factors such as stoppages, idle time, and reduced speeds.
- Quality: This assesses the proportion of production that meets quality standards, factoring in the impact of defects and rework.

To calculate the current OEE for each machine in the process — Bobst 1, Bobst 3, Brausse 105, and Brausse 145 — the data derived from work sampling analysis, along with historical information from the engineering department, enabled a more precise determination of the die-cutting department's equipment efficiency.

The equipment's operational availability is 24 hours a day, six days a week. The die department operates on either two rotating 12-hour shifts or three eight-hour shifts, contingent upon client demand. The data reflected the two-shift model. The initial phase involved analysing the causes of time loss, based on predefined situations in the department. The subsequent calculations were performed using Eq. (3-5).

$$Availability = \frac{Operating\ Time}{Available\ time} \tag{3}$$

where available time = work hours – breaks and planned maintenance, and the operating time = net time – downtime because of breakdowns and adjustments.

$$Efficiency = \frac{Production/Std\ Production}{Operating\ Time} \tag{4}$$

Efficiency, in the context of OEE, reflects the actual level of production achieved during operational hours. It highlights areas where production may fall short of its potential owing to factors such as low processing speeds or frequent brief stoppages, known as micro-stoppages.

$$Quality = \frac{Total\ pieces\ produced - Total\ defective\ or\ reworked\ parts}{Total\ pieces\ produced} \tag{5}$$

The OEE calculation was measured by Eq. (6) and checked by Eq. (7).

$$OEE = Availability \times Efficiency \times Quality \quad (6)$$

$$OEE = \frac{Operating\ Value\ Time}{Available\ Time} \quad (7)$$

The relationship between OEE and yield is pivotal for evaluating the sigma metrics of a process. OEE is a composite metric that reflects the efficiency of a production process by combining three elements: availability, performance rate, and quality [12]. Yield, on the other hand, is a traditional measure of process performance at the end of the production line, calculated by dividing the number of defect-free units produced by the total number of units entered into the process, as in Eq. (8).

$$Yield = f(Availability \times Efficiency \times Quality) \quad (8)$$

For long-term sigma levels, 1.5 standard deviations would be added to account for the shift in the mean over time. This adjustment is known as the 1.5 sigma shift, which is a standard practice in Six Sigma to predict the performance of a process over the long term. The formula to calculate the defects per million opportunities (DPMO) is Eq. (9):

$$DPMO = (1 - Yield) \times 1{,}000{,}0000 \quad (9)$$

3.3. Analyse phase

“Use maintenance management tools to analyse the system and identify inefficiency causes related to stoppages.”

The company’s maintenance team plays a crucial role in ensuring the optimal functioning of equipment across various plant areas. The maintenance manager is at the helm, overseeing a diverse group of professionals:

- One maintenance planner: Responsible for scheduling and coordinating maintenance activities.
- Two electromechanical engineers: Specialised in both electrical and mechanical systems, they troubleshoot and improve equipment performance.
- Two maintenance supervisors: They oversee the maintenance technicians and ensure that all tasks are executed efficiently.
- Five mechanical/electrical technicians: These technicians carry out the hands-on work of repairing and maintaining machinery.
- Two engineering interns: They assist the team while gaining practical experience in the field.

This team is tasked with maintaining the production area’s machinery, which includes corrugated, cutting, printing, laminating, die-cutting, and glueing equipment. In addition, they are responsible for the upkeep of other essential machines such as compressors, boilers, and wiring systems, which are vital for the plant’s continuous operation. The types of maintenance carried out in the plant are as follows:

- Preventive maintenance (PM): These activities involve reviewing the condition of equipment to ensure that all elements and parts function correctly and remain in good condition.
- Corrective maintenance (CM): These tasks focus on correcting anomalies in machine parts that could cause them to stop. These activities are planned in coordination with the production area.
- Unplanned corrective maintenance (UCM): These activities aim to address any failure or breakdown that has halted a machine during the production process.

In 2023, the plant had the following percentages of maintenance orders: 33% for PM activities, 25% for UCM activities, and 42% for CM activities. For the die-cutting area specifically, the percentages were as follows: 20% for PM activities, 15% for UCM activities, 25% for CM activities, and 40% for activities not carried out. Maintenance orders are generated through a company programme and managed by the maintenance planner. However, sometimes these orders are not completed because of the following factors:

- Lack of department availability: Scheduled stops for preventive maintenance are not carried out to meet the demands of the subsequent process and the client.

- Unplanned damage: Issues that are not assigned to maintenance activities.
- High workloads: Excessive work demands.
- Lack of assistants: Insufficient support for maintenance technicians.

These factors contribute to equipment breakdowns in the production process and decrease departmental efficiency. Reports indicated an average of 100 preventive work orders per month, none of which were fully completed in any month of the year. During months with significant non-compliance, the volume of production orders does not allow time for maintenance activities in the die-cutting area.

For the analysis of data from 2023, in the die-cutting area the following results were obtained during the first quarter: The machines that generated the most downtime were Bobst#3 and Brausse#145, with 36 and 20 stoppages respectively, while the Bobst#1 and Brausse#105 die cutters had 15 and 12 stoppages respectively.

In total, only six preventive maintenance activities were carried out in the die-cutting area, indicating that not even one preventive maintenance was performed per week. During the problem identification process, a brainstorming session revealed the following issues: disorganised tools, lack of cleanliness in equipment, unclassified tools and spare parts, no tracking of spare parts and tools in the warehouse, failure to perform required preventive maintenance, lack of training, and poor communication.

Based on this information, autonomous maintenance was implemented, applying theoretical and technical records for proper monitoring and essential activities to optimise the time of the maintenance technicians. This approach showed visible results when adapted to the company's needs. The objective was to reduce the burden on the maintenance department through TPM and autonomous maintenance, involving die department workers in activities that could improve equipment performance.

3.4. Improve phase:

"Apply TPM tools and maintenance management strategies to enhance the process."

Lean manufacturing is a set of tools that are designed to eliminate operations that do not add value to products, services, or processes. It aims to remove unnecessary elements and to optimise resources by minimising unnecessary expenses. The focus is on reducing the seven types of waste and improving operation times. In this research phase, improvements were implemented through lean manufacturing principles to ensure an efficient level of operation. This was achieved using the autonomous maintenance methodology based on TPM. At this stage, the improvement changes were implemented and integrated into the responsibilities and action plan.

One of the pillars of TPM is to teach operators how to maintain their equipment in an acceptable condition by autonomously carrying out the following activities: daily checks, lubrication, replacement of parts that do not require technical expertise, minor repairs, checking accuracy, and detecting abnormal equipment conditions.

A fundamental part of ensuring the proper functioning of machinery is having a manual of standards and procedures that outlines the steps that technicians should follow when performing maintenance services. For its integration, the following factors should be considered:

- Periodic checks of equipment, structures, and units of the plant.
- Following maintenance recommendations from equipment suppliers.
- Applying experience gained during the operation of the plant.
- Developing tests to establish the frequency of failures.
- Constituting maintenance groups by area.

Cleaning is an educational process that often encounters resistance to change. This resistance arises because people are not accustomed to working in an orderly and clean manner, often believing that cleaning activities are solely the responsibility of the cleaning staff. They may ask, "Why clean if garbage accumulates quickly?" Understanding the need for cleanliness is crucial. The most difficult aspect for individuals is the initial cleaning. It requires personal commitment to keep the equipment clean, thereby reducing the overall cleaning time. Once the machine operator agrees to clean, they must propose measures to combat the causes of disorder, dirt, imbalances, and other issues.

Deep cleaning of equipment and other elements in the work area involves removing all types of dirt, including dust, product residues, oil, and grease. It also involves identifying the sources of dirt and restoring the equipment to its original condition. To implement cleaning and conservation routines in the die area, standards and procedures would have to be developed to maintain the integrity of the equipment and machinery. A Saturday shift could be assigned to perform these activities

A conservation routine involves all the preservation and maintenance tasks that are necessary to ensure the good duration and operation of resources. These tasks can be carried out over a few months, over more than a year, or permanently in the company. It was proposed to implement cleaning and conservation routines on a daily, weekly, and monthly basis using a checklist or verification list.

TPM outlines five measures for eliminating losses: knowledge of the primary conditions of the equipment; ensuring that equipment and its parts function under specific circumstances and tolerances; rebuilding or replacing damaged parts; correcting equipment design deficiencies; and improving operator skills.

The manuals for the die-cutting machines were reviewed and shared with supervisors to ensure compliance. These manuals describe the machine parts, the materials used for lubrication and cleaning, and the intervals at which actions are necessary to maintain the equipment. Before designing cleaning and maintenance routines, a deep cleaning was scheduled to establish a baseline.

A list of all necessary activities was created to ensure that the machines and equipment functioned correctly and to prevent stoppages caused by failures. Once the list of essential activities for optimal machine function was obtained, the tasks were divided into time intervals based on their importance to the equipment's functionality. Consequently, daily, weekly, or monthly cleaning and conservation routines were determined according to the requirements.

The seven steps of autonomous maintenance were implemented as follows:

- First phase: Initial cleaning and inspection
- Second phase: Eliminate contamination sources and inaccessible areas; alternatively, institute autonomous inspection standards
- Third phase: Cleaning and lubrication standards
- Fourth phase: General inspection
- Fifth phase: Autonomous inspection
- Sixth phase: Order and cleanliness of the workplace / standardisation
- Seventh phase: Full implementation of the work area / Full autonomous control

The TPM cards reported all anomalies found during the initial stage. They were made known at this stage and used throughout the implementation process. As people achieved autonomy, the cards continued to show the corrected anomalies along with improvement proposals throughout the plant.

We created yellow, red, and blue cards to indicate when anomalies occurred in the die cutters. The colour indicated who had to take charge and repair the irregularities during the shifts. The colours were as follows: red for failures that had to be addressed by maintenance; yellow for failures that only required cleaning or non-exhaustive maintenance that the machine operator had to attend to; and blue for machines and failures with more maintenance requirements that required an investment greater than had been budgeted.

The cards contained the following elements: machine, number, date of detection, detected by, and anomaly description.

3.5. Control

"Monitor OEE indicators and use additional control tools, such as those indicated in the process's failure modes and effects analysis (FMEA)."

The final phase of the DMAIC methodology is control. Its objective is to maintain the improvements achieved in the previous phases, ensuring the stability of processes, their capacity with a good sigma level, and the OEE. A process is considered stable when the KPIs remain consistent over time, making the process predictable. This phase requires the participation and adaptation of everyone involved in the process.

When implementing improvements, it is necessary to design a system to monitor these improvements until the continuous improvement cycle begins. Control actions must be agreed upon at three levels: process, documentation, and monitoring. Standardisation can have various meanings, depending on the process and the usual practices of each organisation. In any case, it involves implementing improvements through changes in systems and structures.

FMEA is a tool designed to reduce the probability of potential failures. It addresses the question: What can go wrong when implementing or executing a new or existing process? Based on this analysis, actions are prioritised to mitigate failures.

For this type of analysis, process FMEA is the most appropriate, as it can be applied while the process is operating. It identifies potential failures, and assesses the ability to detect these failures based on their occurrence. For a detailed review of the FMEA methodology, readers are encouraged to consult the AIAG & VDA FMEA manual [29]. In this study, OEE and sigma metrics were jointly applied to provide a comprehensive assessment of equipment efficiency and process quality. While OEE measures the availability, performance, and quality rates of machinery, sigma metrics offer a statistical perspective on process variability and defect rates. This dual approach is critical in identifying and addressing inefficiencies that affect both productivity and quality. To ensure sustained improvement, the control phase incorporates continuous monitoring tools, including control charts and periodic tracking of OEE and sigma levels. This structured approach enables the timely identification of deviations and supports long-term process stability, thereby validating the improvements achieved through the TPM and LSS methodologies.

While this study applied TPM and OEE within a LSS framework for cardboard box manufacturing, it acknowledges the potential for Industry 4.0 technologies to enhance maintenance practices and equipment efficiency. As an enhancement of TPM, integrating AI-driven predictive maintenance and IoT-based monitoring could provide real-time insights, reduce unexpected stoppages, and increase overall process reliability. Future studies could develop a novel framework that combines these Industry 4.0 tools with the TPM methodology, potentially achieving more robust outcomes in equipment efficiency and production flow.

4. RESULTS

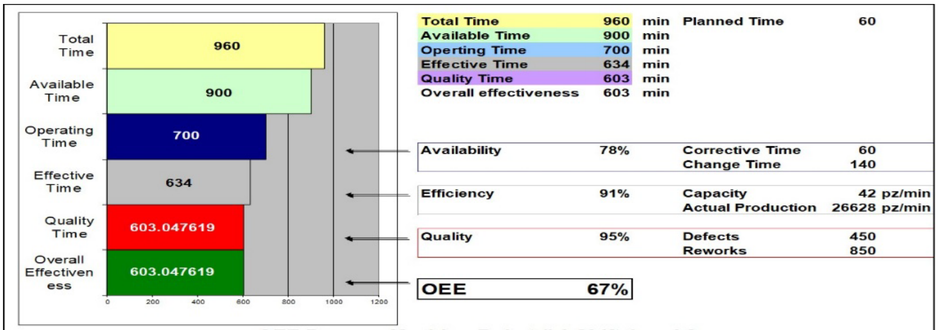
4.1. Initial and final improvement evaluation of the OEE metrics

Based on the information obtained from the process, work sampling, quality reports, and historical data provided by the engineering department, the initial OEE calculation was carried out. Figure 2 shows the breakdown of the elements involved in the calculations for the four machines. The classification criteria for OEE are shown in Table 2.

Table 2: Classification criteria for OEE

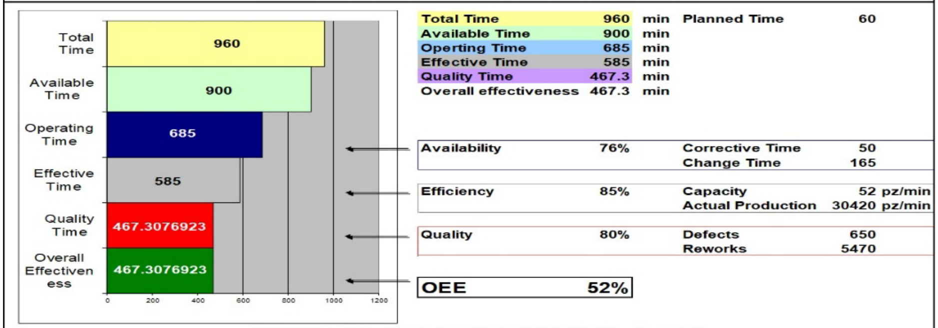
OEE	Criteria	Consequences
OEE < 65%	Unacceptable	Significant economic losses. Low competitiveness.
65% < OEE < 75%	Regular	Economic losses. Acceptable only if it is in the process of improvement.
75% < OEE < 85%	Acceptable	Slight economic losses. Slightly high competitiveness.
85% < OEE < 95%	Good	Indicators at world-class levels. Good competitiveness.
OEE > 95%	Excellence	Excellent competitiveness.

As shown in Figure 3, the estimated OEE in nearly all cases was below 68%. This indicated significant economic losses from inefficiency, which in turn resulted in low competitiveness. In addition, this data allowed for the analysis of the sigma metrics. After implementing the proposed methodology in the department, which included sampling, log reports, training plans, maintenance plans, equipment conservation manuals, reduction of machinery stoppages, and reduction of slow speeds, we re-evaluated the OEE and sigma metrics of the process after five months. Improvements were observed in all the indicators that constituted the OEE for the four machines, as shown in Figure 4, with the OEE metrics increasing to an average of around 80%.



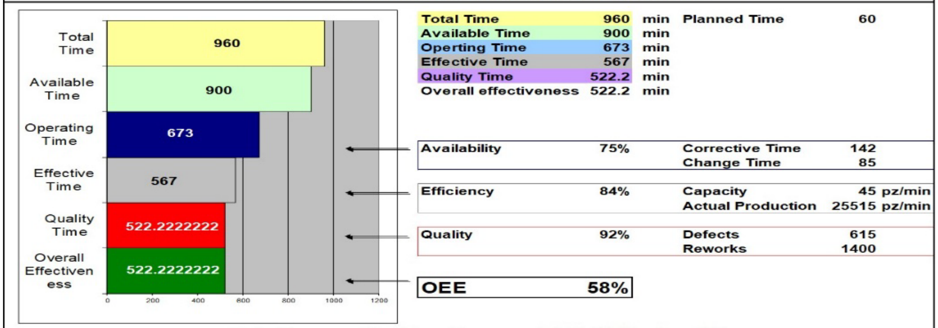
Total Time	960	min	Planned Time	60
Available Time	900	min		
Opering Time	700	min		
Effective Time	634	min		
Quality Time	603	min		
Overall effectiveness	603	min		
Availability	78%		Corrective Time Change Time	60 140
Efficiency	91%		Capacity Actual Production	42 pz/min 26628 pz/min
Quality	95%		Defects Reworks	450 850
OEE	67%			

OEE Process Machine Bobst # 1 Shift 1 and 2



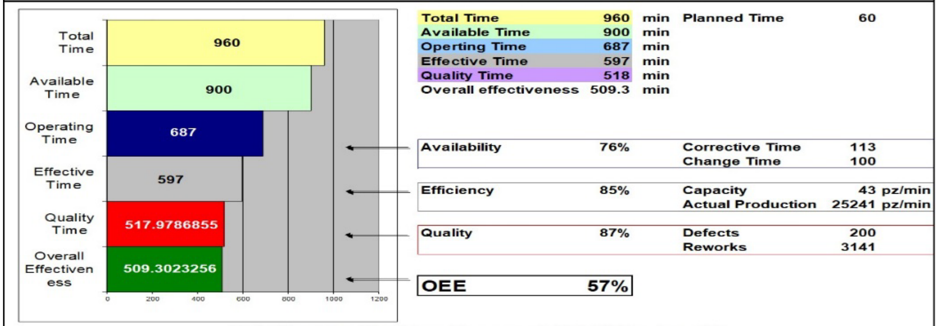
Total Time	960	min	Planned Time	60
Available Time	900	min		
Opering Time	685	min		
Effective Time	585	min		
Quality Time	467.3	min		
Overall effectiveness	467.3	min		
Availability	76%		Corrective Time Change Time	50 165
Efficiency	85%		Capacity Actual Production	52 pz/min 30420 pz/min
Quality	80%		Defects Reworks	650 5470
OEE	52%			

OEE Process Machine Bobst # 3 Shifts 1 and 2



Total Time	960	min	Planned Time	60
Available Time	900	min		
Operting Time	673	min		
Effective Time	567	min		
Quality Time	522.2	min		
Overall effectiveness	522.2	min		
Availability	75%		Corrective Time Change Time	142 85
Efficiency	84%		Capacity Actual Production	45 pz/min 25515 pz/min
Quality	92%		Defects Reworks	615 1400
OEE	58%			

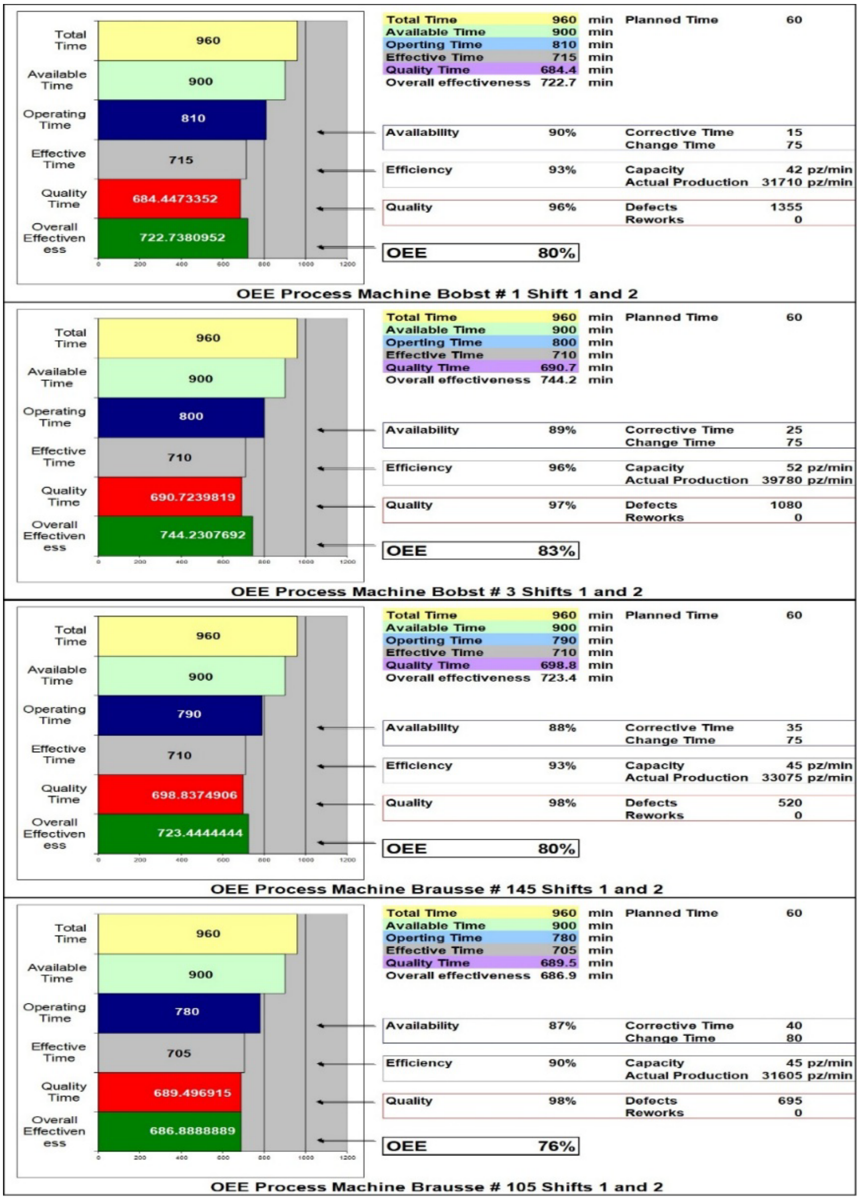
OEE Process Machine Brausse # 145 Shifts 1 and 2



Total Time	960	min	Planned Time	60
Available Time	900	min		
Operting Time	687	min		
Effective Time	597	min		
Quality Time	518	min		
Overall effectiveness	509.3	min		
Availability	76%		Corrective Time Change Time	113 100
Efficiency	85%		Capacity Actual Production	43 pz/min 25241 pz/min
Quality	87%		Defects Reworks	200 3141
OEE	57%			

OEE Process Machine Brausse # 105 Shifts 1 and 2

Figure 2: Calculation of the initial OEE in each of the machines for two shifts



Total Time	960	min	Planned Time	60
Available Time	900	min		
Operting Time	810	min		
Effective Time	715	min		
Quality Time	684.4	min		
Overall effectiveness	722.7	min		
Availability	90%		Corrective Time Change Time	15 75
Efficiency	93%		Capacity Actual Production	42 pz/min 31710 pz/min
Quality	96%		Defects Reworks	1355 0
OEE	80%			

OEE Process Machine Bobst # 1 Shift 1 and 2

Total Time	960	min	Planned Time	60
Available Time	900	min		
Operting Time	800	min		
Effective Time	710	min		
Quality Time	690.7	min		
Overall effectiveness	744.2	min		
Availability	89%		Corrective Time Change Time	25 75
Efficiency	96%		Capacity Actual Production	52 pz/min 39780 pz/min
Quality	97%		Defects Reworks	1080 0
OEE	83%			

OEE Process Machine Bobst # 3 Shifts 1 and 2

Total Time	960	min	Planned Time	60
Available Time	900	min		
Operting Time	790	min		
Effective Time	710	min		
Quality Time	698.8	min		
Overall effectiveness	723.4	min		
Availability	88%		Corrective Time Change Time	35 75
Efficiency	93%		Capacity Actual Production	45 pz/min 33075 pz/min
Quality	98%		Defects Reworks	520 0
OEE	80%			

OEE Process Machine Brausse # 145 Shifts 1 and 2

Total Time	960	min	Planned Time	60
Available Time	900	min		
Operting Time	780	min		
Effective Time	705	min		
Quality Time	689.5	min		
Overall effectiveness	686.9	min		
Availability	87%		Corrective Time Change Time	40 80
Efficiency	90%		Capacity Actual Production	45 pz/min 31605 pz/min
Quality	98%		Defects Reworks	695 0
OEE	76%			

OEE Process Machine Brausse # 105 Shifts 1 and 2

Figure 3: Calculation of the final OEE in each of the machines in two shifts

A comparison summary before and after the improvements can be found in Table 3.

Table 3: Comparison Summary before and after implementation

Machine	Bobst # 1		Bobst # 3		Brausse # 145		Brausse # 105	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final
Availability	78%	90%	76%	89%	75%	88%	76%	87%
Efficiency	91%	93%	85%	96%	84%	93%	85%	90%
Quality	95%	96%	80%	97%	92%	98%	87%	98%
OEE	67.00%	80.00%	52.00%	83.00%	58%	80%	57%	76%
Average OEE initial	58.50%		Average OEE final		79.75%	Improvement		21.25%

Table 4 presents the sigma metrics based on performance. According to the performance criteria for sigma metrics, it was observed that the sigma level for all machines was greater than 2, placing them in an intermediate range between poor and good performance. This indicated a regular performance level with room for improvement.

Table 4: Sigma metrics from performance after implementation of improvements

Machine	Long-term sigma level	Short-term sigma level	DPM	Cpk
BOBST # 1	0.84184	2.34184	200,000	0.28061
BOBST # 3	0.95431	2.45431	170,000	0.31811
BRAUSSE 145	0.84184	2.34184	200,000	0.28061
BRAUSSE 105	0.70664	2.20664	240,000	0.23555

We compared the OEE metrics and sigma levels for the four die-cutting machines before and after implementing improvements using the TPM methodology with a DMAIC approach. In all cases there was an improvement, which was more noticeable with the OEE metric. In contrast, although the sigma metric values increased, they were still classified as ‘regular performance’. Therefore, a more rigorous and demanding approach could be considered to help the organisation to raise its performance standards and achieve more thorough improvements in equipment use.

The FMEA was prepared after defining the cause-and-effect diagrams, Pareto diagrams, and department failures. It was crucial to consider the process operations diagram in order to follow the sequence of activities where problems were located. For each activity, potential failures and their impacts on the process were analysed. The risk priority number (RPN) was evaluated, based on the criteria of severity, occurrence, and detection by comparing the collected data with the tables established in the AMEF manual [26]. The RPN identified the process activities that required immediate actions to prevent and correct detected faults, assigning a date and a person responsible for monitoring compliance with these activities.

5. DISCUSSION

Low productivity in production processes often occurs because of constant stoppages for repairs and underuse of equipment, which reduces available working time and system efficiency. Maintenance costs are estimated to represent between 15% and 40% of total operating costs, with emergency repairs costing at least three times more than planned repairs. Poor operations account for 58% of maintenance costs, while poor lubrication causes 17% [23]. In traditional manufacturing, personnel often notice minor issues with equipment, such as dust and dirt, lack of lubrication, missing screws and parts, and loose components. These issues are typically considered the responsibility of the maintenance department and are often neglected, leading to more significant failures and unproductive downtime.

TPM is an improvement methodology that aims to eliminate stoppages, prevent failures and accidents, improve process flow, and involve production personnel in preventive maintenance and equipment conservation through autonomy. The effectiveness of TPM is enhanced by incorporating maintenance management and other Lean tools, such as the 9Ss, SMED, standard work, plant layout, cellular work, and visual tools such as VSM, Andon, Jidoka, and visual boards. These tools, combined with Industry 4.0 strategies, enable more efficient real-time monitoring.

Using a continuous improvement methodology such as DMAIC, which focuses on measurement and a continuous cycle of seeking excellence, is beneficial for effectively applying TPM. This approach integrates LSS principles, combining statistical tools and Lean techniques to address waste (Mura), process inefficiencies, overloads (Muri), and waste (Muda). OEE is a key indicator in TPM, integrating three critical aspects: equipment availability, performance, and quality. It provides an objective metric of efficiency for the improvement actions implemented by the work team. Integrating OEE with sigma metrics allows for the evaluation of the six significant losses with a rigorous statistical approach, enabling better control and the generation of improvement projects with a more substantial impact on companies.

To provide a more comprehensive view of the practical implications of the proposed TPM strategy, it would be important to consider the obstacles encountered during its implementation. While the application of the DMAIC cycle led to significant improvements in OEE and sigma metrics, several obstacles were identified. Resistance to change among staff, variations in skill levels and training, and limitations in the existing equipment presented difficulties that affected the pace and consistency of implementation. In addition, the initial lack of detailed process documentation made it difficult to assess baseline performance accurately. These factors should be considered when applying the TPM methodology in different organisational contexts, as they can influence the success and sustainability of improvements. Addressing these issues proactively through targeted training, better resource allocation, and clear communication would be crucial for overcoming barriers and achieving long-term operational efficiency.

6. CONCLUSION

In this study, the application of TPM through an LSS framework demonstrated meaningful initial improvements in OEE and sigma metrics, affirming the methodology's impact on operational efficiency and productivity. However, for sustained progress, it would be essential to reapply the DMAIC cycle iteratively to monitor and refine processes. Future cycles should incorporate advanced statistical analysis and Lean techniques within TPM to drive continuous improvement and to increase flow efficiency.

For further enhancement, specific actions are recommended to elevate sigma and OEE levels from 'regular' to 'good' or 'excellent' performance. These steps could include optimising maintenance schedules, refining equipment calibration, and offering targeted training for operators on TPM tasks that have a direct impact on sigma performance.

To address the limitations of this study, such as the relatively small sample size and the unique setup of the die-cutting machinery, future research should consider larger and more diverse operational contexts to validate the results. Exploring additional interventions, such as real-time monitoring using Industry 4.0 technologies, could also strengthen the methodology. AI-based predictive maintenance and IoT-enabled monitoring systems could allow for real-time feedback on OEE and sigma metrics, improving response times and decision-making accuracy. Such advancements would align well with the principles of the circular economy, promoting a resource-efficient and self-sustaining operational model.

The supply chain, as seen in this study, plays an essential role in overall productivity. Given that up to 80% of a business's revenue can be affected by supply chain activities, improving processes in logistics, materials management, and physical distribution would remain a priority. Ensuring seamless coordination across these areas could further bolster the impact of TPM and Lean initiatives, offering a competitive edge in high-demand environments. In conclusion, this study's findings suggest that integrating TPM with Industry 4.0 and supply chain strategies could significantly advance manufacturing performance. Future research could explore cross-industry applications and monitor the long-term performance of OEE and sigma metrics, providing a robust basis for sustained operational improvements in similar manufacturing contexts. To strengthen the methodology, the paper proposes an advanced TPM model incorporating Industry 4.0 solutions. Predictive maintenance leveraging AI could anticipate failure points, while IoT-enabled monitoring would support continuous data collection and analysis. This approach should make a novel contribution by extending TPM's capabilities in LSS applications, providing a framework that merges traditional maintenance with smart technology for greater process efficiency and reduced downtime.

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