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Original Article

Improvement Model of OEE in the Production Process of Cardboard Boxes Through SMED, TPM, Automation, and IoT

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Abstract *- As processes become more complex, measuring them using key KPI indicators, such as Overall Equipment Effectiveness (OEE), is essential. This study analyses the OEE of the cardboard box production process-the product with the highest annual revenue in a Peruvian printing company. The current OEE is 64.27%, which falls short of the graphic industry standard (72.5%). Increasing the OEE would provide several benefits, such as higher availability, improved product quality, reduced setup times, and lower machine wear. Therefore, an innovative solution model is proposed that will use SMED and TPM tools, as well as Automation and IoT technologies. These Lean tools will be enhanced through the mentioned technologies. The solution model will follow the PMBOK approach due to its significant contributions to project management and will consist of three phases: initial, implementation, and closure. Improvements will be projected for key SMART indicators that are identified. Subsequently, these improvements will be validated through simulation in Arena software across three scenarios: moderate, optimistic, and pessimistic. All three scenarios will show improvements over the current OEE, approaching the industry standard. Setup time in die-cutting was reduced to 836.69 minutes, die-cutter wear decreased to 24.58%, and lubricant usage in guillotines and offset machines increased to 255.04 ml and 569.21 ml, respectively.*

Keywords *- OEE, TPM, SMED, Automation, IoT, Graphic Sector*.

1. Introduction

It is essential at a global level to evaluate the performance of various organizational processes through relevant indicators, such as KPIs. A key KPI indicator that helps determine whether established process objectives are being met is Overall Equipment Effectiveness (OEE). However, many companies worldwide lack the means to monitor productivity and OEE objectives in real time. Graphic printing is also among the affected sectors, and it has shown considerably high production rates in Latin America, averaging over 80%. Nationally, the graphic printing sector's Gross Domestic Product (GDP) has been declining over the last decade due to the decline in the consumption of physical publications. This study analyzes the OEE level of the cardboard box production process (the product that generated the most annual sales) in a Peruvian graphic printing company. In the diagnostic study conducted in this paper, machine wear, poor lubrication, and setup issues were identified and measured using quality tools such as histograms, scatter plots, Pareto charts, Ishikawa diagrams, and Failure Mode and Effects Analysis (FMEA), among others. This led to the determination that a Peruvian graphic printing company's production process of cardboard boxes (the product that generated the highest annual sales) achieves an OEE of 64.27%. It is worth mentioning that this OEE level is mainly due to the impact of two factors on this indicator: quality and availability.

An adequate OEE level provides several benefits for a company in general. Studies have reduced machining setup time within an oil and gas company, achieving significant improvements such as a 91.6% reduction in setup time and a 44.6% increase in OEE [1]. A conceptual model reflects improvements in equipment availability by 13%, in efficiency, in product quality and an increase in OEE by 62.2% [2]. Implementing an automated system in the therapeutic drug monitoring laboratory reduced the cycle time by 1.5 hours and the cost per sample to 6.60 euros, increasing the OEE by improving availability by 25% and maintaining a quality above 94% [3]. Applying an IoT-based automatic diagnostic system in a mold company reduced downtime by 5% and increased OEE thanks to a detection accuracy of up to 96% in operating states, microstops and configurations [4]. The increase in process OEE offers other great benefits, as mentioned by the authors. Comparing the current OEE of the process under study (64.27%) with the standard value of the graphic sector (72.50%), a technical gap of 8.23% is found. Furthermore, this current OEE value generates economic losses for the company, representing 2.55% of annual sales.

Aiming to optimize the company's current OEE represents the desire to demonstrate how useful this can be by offering various benefits, such as increased machine availability, reduced setup times and machine wear, increased production volumes, which generate additional revenue, among other benefits. Therefore, this study proposes a solution model based on three stages: initial phase, implementation, and closure. This model suggests using Lean tools such as SMED and TPM (the pillars of Autonomous Maintenance and Planned Maintenance) and technologies such as Automation and the Internet of Things (IoT). The proposed model is embodied in a guide based on the Project Management Body of Knowledge (PMBOK), an internationally recognized standard by the Project Management Institute (PMI), as it allows for a clear and systematic structure of the planning, execution, and control of improvement projects in industrial environments. In the initial phase of the model, the project scope is defined, and SMART objectives focused on improving the root causes of poor OEE are identified. Regarding implementation, the proposed tools and technologies are implemented step by step so that, in the closing phase, improvements to the root causes of the main problem are evaluated and the project is finalized with a closure report.

2. Literature Review

It is essential to present a comprehensive analysis of the reviewed literature that pursues the common goal of optimizing OEE through implementing Lean tools, such as SMED and TPM, and technologies such as Automation and IoT. The achievements of various authors are presented chronologically.

2.1. SMED for OEE Improvement

The SMED method has demonstrated its significant capacity to reduce changeover times and optimize equipment availability. Integrating SMED with complementary Lean tools was proposed to reduce internal activities and achieve greater process standardization significantly [1]. In a food plant, there were reports of efficiency improvements of up to 36% thanks to the reorganization and outsourcing of tasks during changeovers [2]. These studies conclude that proper implementation of SMED allows for the recovery of productive time, especially in processes with high changeover frequency.

SMED was implemented with an operational focus, prioritizing staff training and workstation redesign [5]. It reduced tire calibration times by more than 50% by applying SMED, while emphasizing task sequencing [3]. In the hygiene products industry, changeover times were reduced without compromising process stability [6]. As can be seen, these results reinforce the effectiveness of SMED in various industrial sectors.

SMED was integrated with production scheduling, enabling simultaneous improvement in operational efficiency and alignment with demand [4]. Furthermore, it was demonstrated that SMED reduces time losses and serves as a basis for increasing OEE by facilitating more consistent production cycles [7]. They highlighted its importance for small and medium-sized manufacturing companies, where operational flexibility is critical for competitiveness [8].

While the potential of SMED is well documented, it is worth mentioning that most studies focus on its isolated application. Few studies have explored its integration with emerging technologies, such as automation or IoT sensors, which is limited in the short term. This research proposes a solution that integrates SMED with technological tools and, consequently, influences a cumulative improvement of OEE.

2.2. TPM for OEE Improvement

Total Productive Maintenance (TPM) maximizes equipment efficiency by eliminating failures, downtime, and micro-stops. It was stated that the pillars of autonomous and planned maintenance have a greater impact on availability, especially in equipment operating at high capacity [9]. It was proposed to adapt TPM to digitalized environments to incorporate sensors for predictive actions [10].

They applied TPM with IoT on a conveyor line, which increased availability by more than 90% through data-driven decisions [11]. Indicators were implemented to evaluate TPM and more accurately monitor its impact on OEE [12].Haga clic o pulse aquí para escribir texto.. A sequential TPM implementation framework that enabled sustained improvements in industrial production plants [13]. Consequently, it is demonstrated that its effectiveness depends on both the technique and organizational commitment. TPM was analyzed in the cork industry and identified the most adaptable tools for addressing critical failures, where the need for trained personnel and well-defined procedures was essential [14]. They showed that a well-implemented TPM strategy can increase productivity in the pharmaceutical industry by more than 20% and improve operational reliability [15].

Despite its great conceptual importance, TPM continues to present challenges in environments with low levels of digitalization. Integration with technologies such as IoT allows for anticipating failures and optimizing maintenance plans, but requires minimal infrastructure. This model addresses this need through progressive integration, where

TPM is supported by sensors for wear and lubrication monitoring, maximizing its effectiveness under controlled conditions.

2.3. Automation for OEE Improvement

Industrial automation has been recognized as a key tool for reducing manual intervention, minimizing operational errors, and improving process stability. A productivity framework was developed for the semiconductor industry, demonstrating that structured automation can improve OEE in high-precision settings [16]. They highlighted its contribution to the circular economic approach, as it allows for extending the product lifecycle through more consistent and controlled processes [17].

Automation was studied in a packaging company, achieving effective integration with food safety standards such as BRC certification, facilitating better process control without increasing operational complexity [18]. They proposed an intelligent VSM model, integrating automation with Industry 4.0 technologies, facilitating bottleneck visualization and faster decision-making [19]. These studies agree that automation directly affects performance, especially in highly variable processes.

A hybrid model was designed for performance monitoring in injection molding, using digital architecture that allowed for improved monitoring of process efficiency [20]. They presented a methodology for converting graphical models into automatic control languages, facilitating the integration of legacy systems with new technologies [21].

Similarly, an interoperable system was developed to extract control data from old machinery, opening a path to digitizing operations without total replacement [22].

Although the benefits of automation are widely recognized, much of the literature focuses on high-tech industries, ignoring sectors where processes are still partially manual. In these contexts, the key is to identify repetitive and error-prone subprocesses. In this model, automation focused on the setup, cutting, and die-cutting subprocesses, which reduced operational variability, improved accuracy, and generated more predictable conditions to achieve a higher OEE.

2.4. IoT for OEE Improvement

The Internet of Things (IoT) has transformed industrial monitoring systems by enabling real-time analysis of variables and facilitating predictive maintenance. An IoT-based automatic diagnostic system was implemented, reducing downtime and anticipated production line failures [23]. They demonstrated that integrating IoT into a conveyor line enabled faster maintenance decisions and increased asset availability by over 90% [24].

IoT dashboards were used to monitor key variables such as pressure, temperature, and speed, which helped keep the process within defined parameters [20]. A multi-theoretical conceptual model was developed to explain IoT adoption in manufacturing, highlighting that success depends on the technology and organizational preparedness [25]. It was identified that IoT improves visibility into the production process, enabling more accurate diagnostics and resource savings [26].

They developed an intelligent monitoring system that enabled automated decision-making based on sensor data at each process stage [27]. TPM, IoT, and Lean Six Sigma were combined in a pharmaceutical plant, improving maintenance planning and reducing unforeseen failures [28]. They reinforced the importance of IoT by pointing out that its implementation, along with SMED and TPM, directly contributes to a sustained increase in OEE [7].

The reviewed studies conclude that the impact of IoT is significant, provided critical operating variables are identified and an organized response is generated to the captured data. This work’s proposal considered sensors to monitor die-cutting machine wear and lubricant use in offset and guillotine presses. This integration facilitated maintenance planning, reduced corrective interventions, and contributed to a quantifiable improvement in OEE, validated through simulation.

3. Innovative Proposal

3.1. Rationale

The design of this proposal to increase Overall Equipment Effectiveness (OEE) in the carton production process is based on key research studies addressing the use of tools and technologies such as SMED, TPM, automation, and IoT. These studies highlight industrial approaches that optimize operational efficiency and reduce downtime.

One-Minute Die Change (SMED) is a technique used to minimize tool changeover times and, therefore, increase equipment availability. This implementation in machining processes achieved a 44.6% increase in OEE, a 30% reduction in changeover times and a 9% increase in OEE was reported [2]. These results emphasize the importance of SMED in optimizing downtime and increasing efficiency.

Regarding Total Productive Maintenance (TPM), its perspective on autonomous and planned maintenance is crucial to avoiding unexpected failures and improving machine availability. OEE increased from 60.7% to 65.3% thanks to this implementation [29], while preventive maintenance improved by 88% and repair time was reduced by 53% [10]. These facts confirm that TPM is essential for preventing unplanned downtime and maintaining efficient machine operation.

Automation is another fundamental tool. Robots and PLCs have helped companies to reduce human errors and accelerate production processes [17]. Efficiency was also improved by 15% and costs reduced by 20% through automation [30].

Finally, IoT allows real-time monitoring and anticipation of failures, improving connectivity and enabling faster decision-making, optimizing production processes [25]. Furthermore, it increases the accuracy of OEE measurements by 25% and reduces operating costs by 18% [20]. This demonstrates the value of IoT in improving machine efficiency and connectivity, providing a solid foundation for implementing SMED, TPM, automation, and IoT to improve OEE and operational efficiency, enabling the effective integration of these tools into the carton production process.

3.2. Proposed Model

The objective is to increase the OEE of the cardboard box production process by 64.27% through the use of SMED and TPM tools, optimized with automation and IoT, respectively. The solution is developed in a three-phase conceptual model, guided by the PMBOK approach. The first phase includes defining the scope and SMART objectives related to the causes of low OEE. The second phase focuses on implementing SMED, TPM, automation, and IoT. Finally, the third phase involves evaluating improvements and closing the project to achieve an increase in OEE and other additional benefits.

This solution model (summarized in Figure 1) is distinguished by its innovative approach in the graphic sector, combining Lean tools such as SMED and TPM with advanced technologies like Automation and the Internet of Things (IoT). Rather than applying these techniques and technologies separately, it proposes a sequential integration: first SMED, then automation, followed by TPM, and finally, its integration with IoT. This combination seeks to maximize the effectiveness of Lean tools and significantly improve OEE, highlighting the value of technologies in process optimization.

3.3. Model Details

A flowchart was created to present the implemented procedures and improvement approach to outline the specific steps taken, as shown in Figure 2.

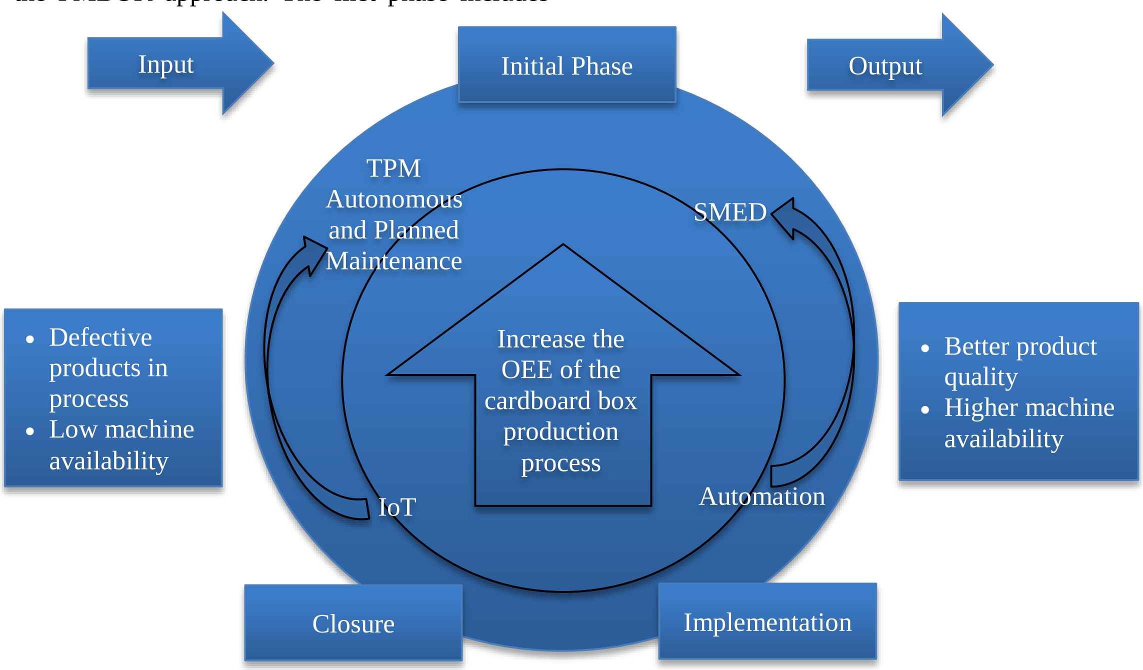

Fig. 1 Proposed conceptual solution model

3.3.1. Initial Phase

In this first phase, the first step is determining the project scope. This is achieved using a project charter. The project committee will consist of the general manager, operations manager, press supervisor, maintenance supervisor, and the Quality Management System leader. The project scope is also defined by assigning roles to the project members through a RACI matrix (Responsible, Accountable, Consulted, and Informed).

The second step in this initial phase involves identifying the SMART objectives closely related to the root causes contributing to the current low OEE. The identified root causes focus on machine wear, lubrication, and setup configuration. The conducted diagnosis reveals that within the overall carton box production process, the cutting, printing, and die-cutting subprocesses are the most critical as they have the lowest OEE compared to other subprocesses. Therefore, the SMART objectives are:

Reduce setup time in the die-cutting process by 33.33% within six months by implementing SMED and integrating Automation with SMED.

Reduce wear on die-cutting machines due to improper pressure by 30% within six months through implementing TPM and integrating IoT with TPM.

Improve machine lubrication in the cutting process by 43.50% within four months by implementing standardized procedures and specific training.

Improve machine lubrication in printing by 23.81% within four months through standardized procedures and specific training.

3.3.2. Implementation

SMED

Implementing SMED (Single-Minute Exchange of Die) in carton box production focuses on reducing setup times for the cutting, printing, and die-cutting subprocesses. The six steps of the implementation process are as follows (summarized in Figure 3):

Breakdown of the changeover into operations: Identify each operation involved in the setup process.

Separation of internal and external activities: Classify each operation as internal (requires stopping the machine) or external (can be performed while the machine is running).

Conversion of internal activities to external: Restructure the process to move as many internal activities as possible to external ones, allowing the machine to operate for longer without interruptions.

Reduction of internal activities: Minimize internal activities that cannot be converted to external through the standardization of procedures.

Reduction of external activities: Optimize them so they are performed quickly.

Standardization of the changeover: Document and formalize the new process to ensure the changes are maintained and consistently applied.

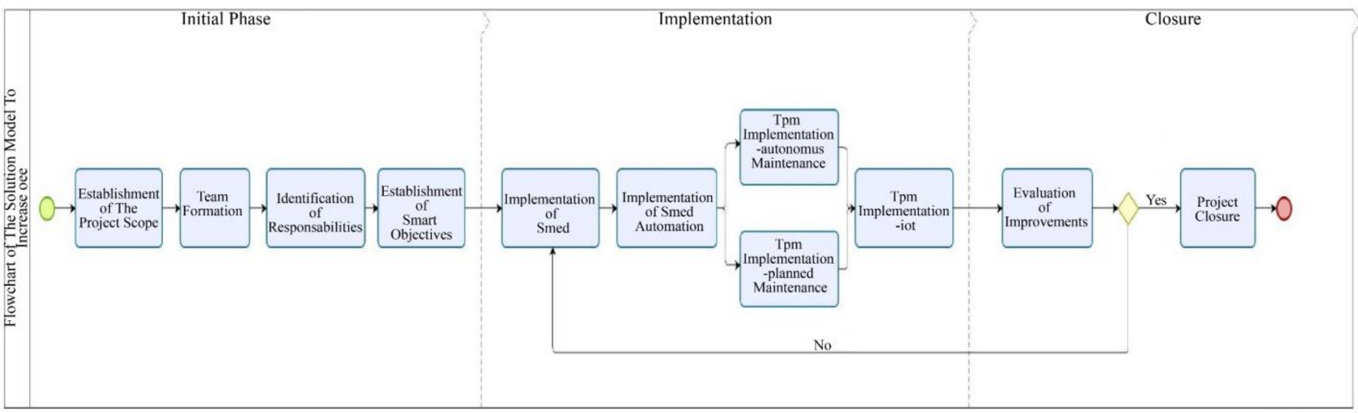

Fig. 2 Procedure for the solution model

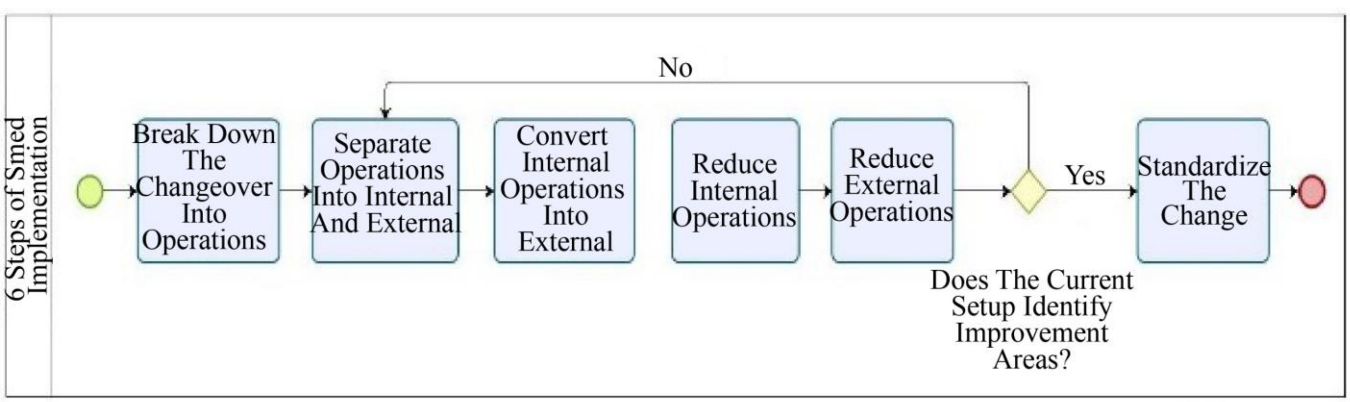

Fig. 3 Flowchart for SMED implementation

The setup verification sheet is fundamental for recording and controlling the activities performed during setup changes. After every setup, each operator must complete it, ensuring all activities are carried out according to the expected standards and times.

This instrument allows for detailed monitoring of each task, offering a tangible way to evaluate the process's efficiency. Centralizing information makes identifying problem areas or unexpected downtime easier, allowing for quick adjustments. It also guarantees operational responsibility since each operator signs and commits to following the steps.

SMED with Automation

Automation complements the implementation of SMED, focusing on critical tasks such as configuration adjustments and tool changes using cobots (collaborative robots). The key steps for automating SMED are (summarized in Figure 4):

- Automation plan for configuration adjustments: Identify the tasks that can be automated, such as roller changes, cutting pressure adjustments, and component alignment.
- Use of cobots in the setup process: Cobots carry out setup activities automatically, reducing the time previously taken for manual tasks.
- Automatic sequencing and setup optimization: Cobots are programmed to perform configuration adjustments in an optimal sequential order, minimizing downtime.

The Configuration Adjustment Automation Plan details the automated tasks, the cobots assigned, current times, and the reductions achieved, allowing for continuous monitoring of the process and ensuring effective time reductions.This instrument acts as a structured guide that allows for the evaluation of automation effectiveness. Documenting the adjustments made by cobots enables an objective comparison of the impact of automation versus manual methods. It also provides a clear basis for continuous improvement since each automated process is recorded and can be reviewed for further optimization.

TPM

Autonomous Maintenance

Autonomous Maintenance within TPM aims to have operators take responsibility for the basic maintenance of machines. This process follows five key steps (summarized in Figure 5):

- Initial cleaning: Operators thoroughly clean the machines to remove dust and debris.
- Eliminating contaminant sources: Areas prone to contaminant buildup are identified, and preventive measures are taken.
- Establish cleaning and lubrication standards: Create clear procedures to perform these tasks efficiently.
- Inspection and standardization: Operators check machines to identify any signs of wear.
- Implement systematic Autonomous Maintenance: Operators regularly perform established tasks, creating a discipline of continuous and repetitive maintenance.

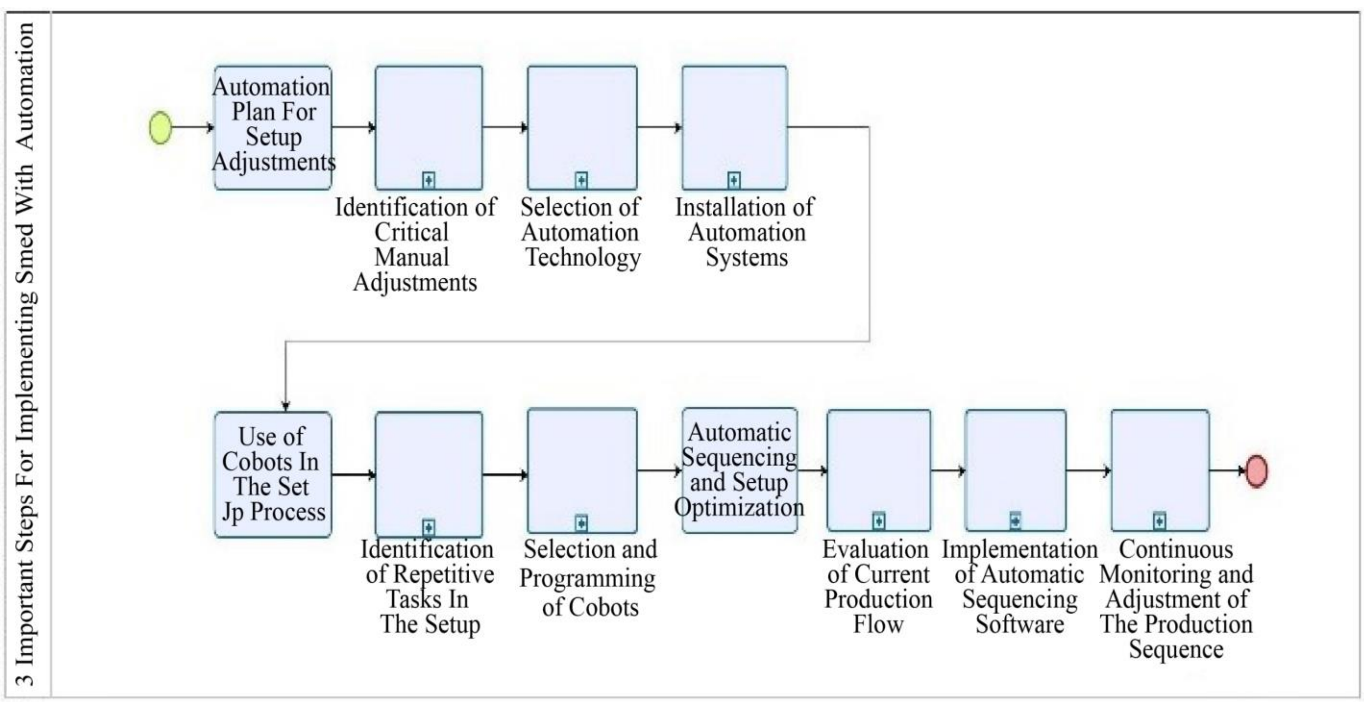

Fig. 4 Flowchart for SMED implementation with automation

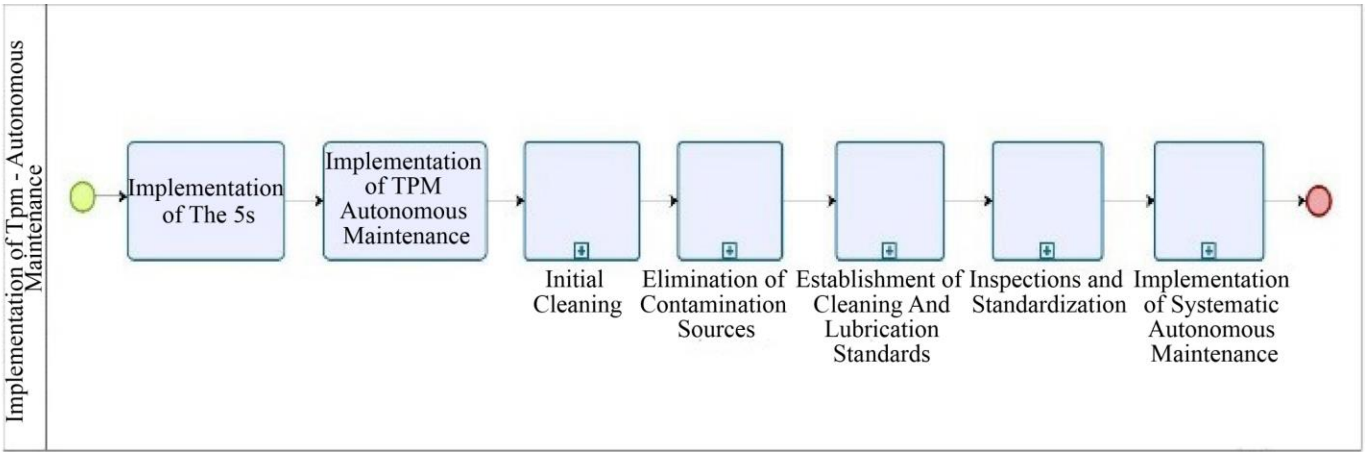

Fig. 5 Flowchart for TPM – autonomous maintenance implementation

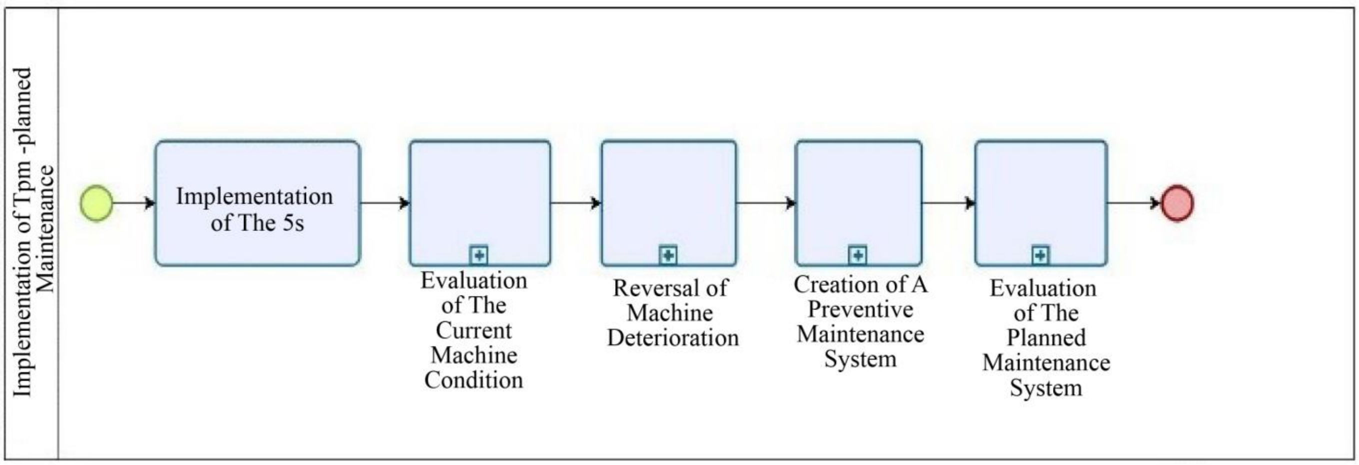

Fig. 6 Flowchart for TPM – planned maintenance implementation

Planned Maintenance

Planned maintenance is essential for preventing failures and reducing unplanned downtime. It involves the following steps (summarized in Figure 6):

- Assessment of the current machine condition: Perform diagnostics to identify signs of wear or potential failures.
- Restoration of machine condition: Perform repairs to restore optimal operating conditions.
- Creation of a preventive maintenance system: Schedule regular maintenance based on machine usage and condition.
- Evaluation of the Planned Maintenance system: Periodic reviews of maintenance results are conducted to ensure effectiveness and adjust if necessary.

The One-Point Lesson guides operators through planned maintenance procedures, detailing each step with clear instructions to ensure all tasks are performed consistently and efficiently.

This format is a simple yet effective tool that can standardize technical knowledge quickly and clearly. Following this document ensures that all operators follow the same procedure, reducing variability and improving the quality of maintenance work.

TPM with Internet of Things (IoT)

Integrating IoT sensors enables real-time monitoring of machine status, which facilitates predictive maintenance. Some key steps for this implementation are (summarized in Figure 7):

- Implementation of IoT sensors: Installation of sensors at critical points of the machines, monitoring variables such as pressure, vibration, and temperature.
- Automatic alert generation and proactive response: When sensors detect values outside normal parameters, alarms are generated, allowing immediate action.
- Data analysis for predictive maintenance: Stored data is analyzed to identify repetitive failures and anticipate potential anomalies.
- Action plan and monitoring: Based on the data and alarms generated, the necessary operational work is planned to avoid unplanned downtime.

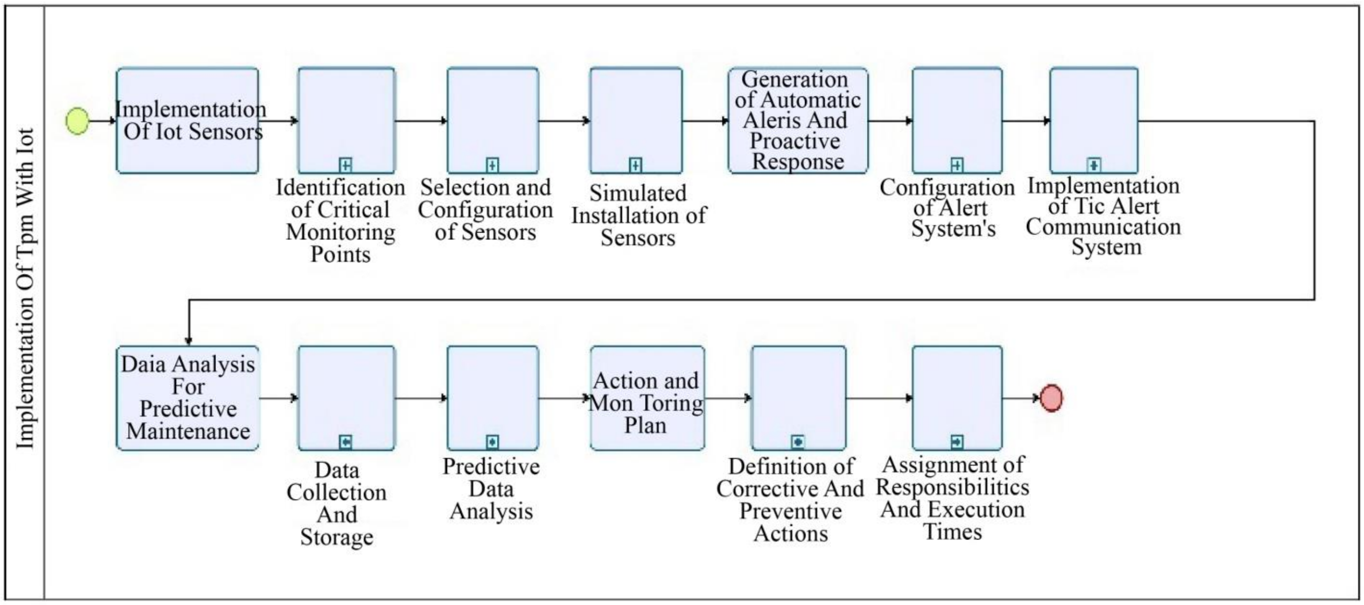

Fig. 7 Flowchart for TPM implementation with IoT

The IoT Sensor Implementation Plan shows the installed sensors' location, monitoring frequency, and the respective installed measurements that will trigger automatic alarms and enable efficient predictive maintenance management.

This document is crucial because it provides a structured and detailed overview of the technology used for machine monitoring. With this document, sensors can be managed, and their effectiveness in data collection can be evaluated, ensuring that predictive maintenance works proactively and not reactively.

3.3.3. Closure Phase

In this final phase, the improvements are evaluated using quality tools such as histograms (for setup times), scatter plots (for lubrication), and the Process Capability Index (Cpk) (for die-cutting machine wear).

Regarding the setup times for die-cutting, the histogram shown in Figure 8 reveals a notable improvement in efficiency and consistency following the implementation of improvements. The reduction in mean and standard deviation reflects an optimized process, resulting in shorter and more stable times.

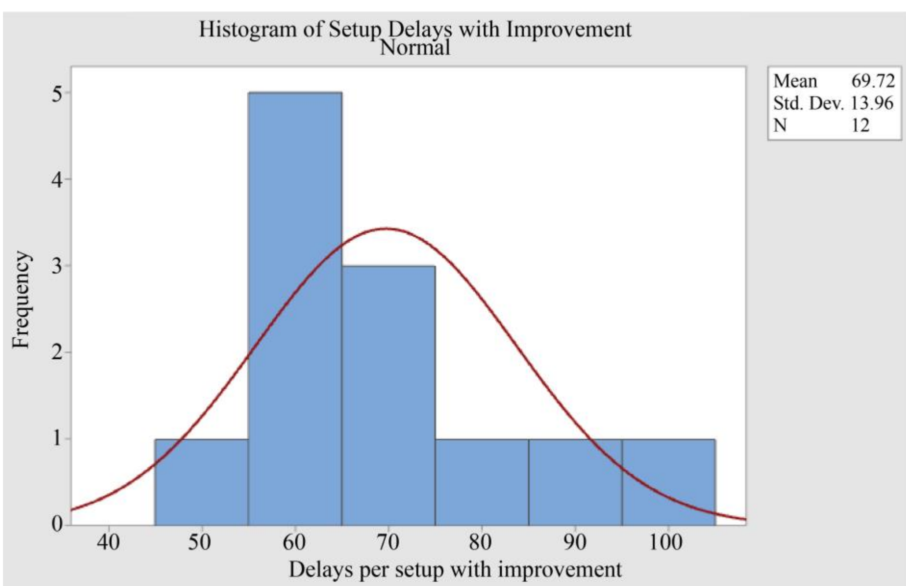

Fig. 8 Histogram for setup delays in die-cutting

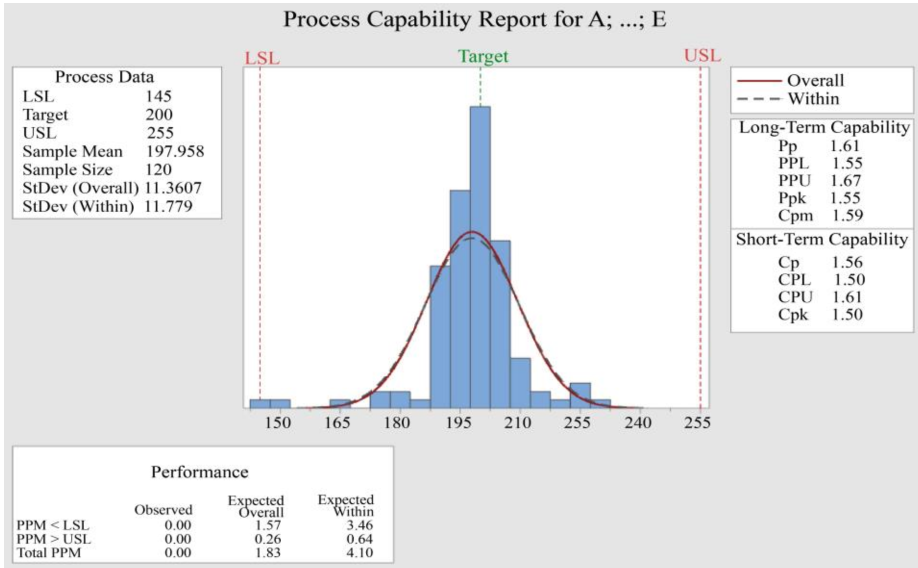

Fig. 9 Cpk for die-cutting after improvement

Table 1. Global project indicator

Indicator	Unit	Calculation Formula	As-Is
Setup time in die-cutting	Min	$Setup\ time = End\ Time\ of\ Setup - Start\ Time\ of\ Setup$	1255
Wear of die-cutting machines	%	$\frac{Actual\ production\ time}{Total\ expected\ production\ time} \times 100$	36.87%
Lubrication of guillotines	mL	$\sum (Number\ of\ lubricated\ points\ \times Amount\ of\ lubricant\ per\ point)$	177.73
Lubrication of offset printers	mL	$\sum (Number\ of\ lubricated\ points\ \times Amount\ of\ lubricant\ per\ point)$	437.85
OEE	%	$Availability\ \times Performance\ \times Quality$	64.27%

Concerning the wear of die-cutting machines, after the improvement, the Cpk (shown in Figure 9) increases from 0.57 to 1.50, falling within the "good capacity" range. This value of 1.50 exceeds the minimum parameter of 1.25, indicating that the subprocess can now meet requirements.

For lubrication of the cutting machines, it is observed (see Figure 10) that the coefficient of determination (R2) is 0.7131. Although the goal was to reach an R2 of 0.72 according to the SMART objective, the obtained value of 0.7227 means that the goal was surpassed.

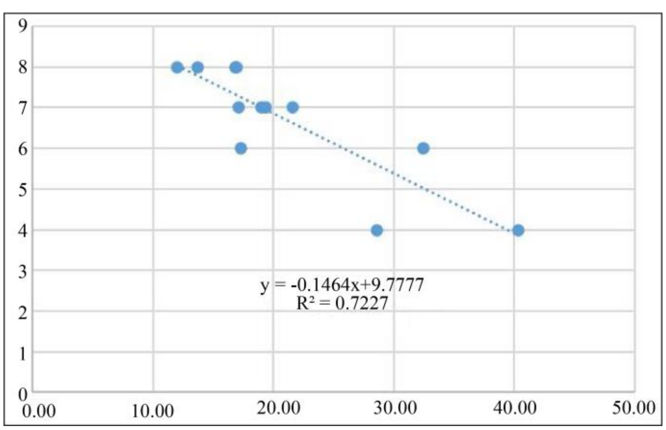

Fig. 10 Scatter plot after improvements in cutting machine lubrication

Regarding the lubrication of offset printers (see Figure 11), the coefficient of determination (R2) is 0.6426. The goal was to achieve an R2 of 0.65 according to the SMART objective, but an R2 of 0.6523 was reached, which also exceeds the set goal.

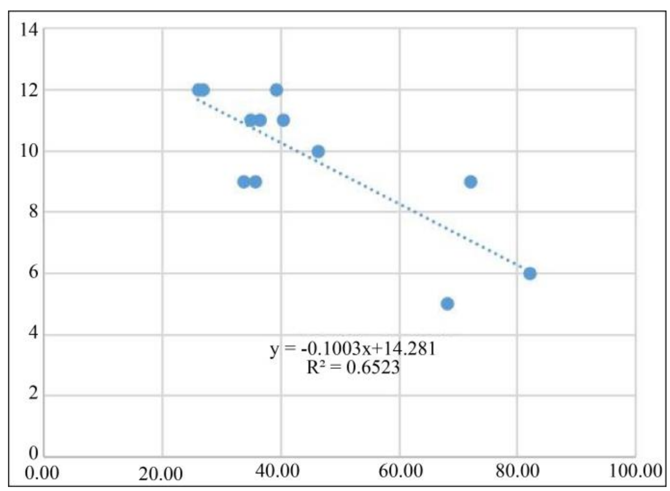

Fig. 11 Scatter plot after improvements in offset printing lubrication

After evaluating the improvements, a project closure document is used to finalize the proposed solution model guide.

3.4. Model Indicators

Based on the previously identified SMART objectives, the relevant SMART indicators for this study are detailed, including OEE, which is the primary objective:

Table 1 analyzes key aspects of the production process, focusing on critical performance variables in the operation of die-cutters, guillotines, and offset printers, as well as evaluating the overall equipment efficiency through the Overall Equipment Effectiveness (OEE) indicator. These indicators are essential for understanding current performance and identifying improvement areas in each process.

Setup Time in Die-Cutting: This indicator is recorded in minutes and measures the duration of setup time in the die-cutting process. This time is obtained by subtracting the start time of the setup from the end time, revealing the total time spent preparing the equipment before starting production. Currently, the recorded setup time is 1255 minutes, indicating a significant opportunity for optimization, as prolonged setup times directly impact overall productivity.

Die-Cutter Wear: This percentage-based indicator evaluates the level of wear on machines by comparing actual production time with the total expected production time. This calculation provides insight into machine effectiveness and suggests the need for preventive maintenance or even replacement in some cases to avoid downtime. Currently, wear is at 36.87%, which can be interpreted as a considerable level of use, suggesting a potential intervention in terms of maintenance.

Lubrication of Guillotines: This indicator is measured in milliliters and calculates the amount of lubricant used for the optimal operation of guillotines. The formula considers the number of lubrication points and the specific amount of lubricant to be applied at each point. The recorded consumption is 177.73 mL, which allows programming lubrication frequency and anticipating wear, ensuring consistent guillotine performance.

Lubrication of Offset Printers: This indicator follows a similar approach, accounting for lubricant consumption by the number of points and the volume applied to each. In this case, the total lubricant used is 437.85 mL. This data is relevant to ensure printer efficiency and avoid potential issues related to friction or overheating.

Finally, Overall Equipment Effectiveness (OEE) is expressed as a percentage. OEE evaluates operational efficiency by considering availability, performance, and quality. Currently, OEE is at 64.27%, providing an integrated view of equipment effectiveness in production. This value allows identifying improvement areas in each contributing factor of OEE, thus enabling greater overall productivity and a more optimized operation.

4. Methodology

4.1. Problem Analysis

4.1.1. Technical-Operational Diagnosis

The diagnosis was done through a process audit, on-site data collection, and statistical analysis of key indicators. Three levels were addressed:

- Machine Level: Analysis of individual performance of die-cutters, guillotines, and offset printers, identifying failure patterns and non-productive times.
- Process Level: Study workflow, identify bottlenecks, and calculate average cycle time.
- Organizational Level: Evaluation of maintenance culture, personnel technical skills, and technological adoption level.

4.1.2. Main Findings

- Prolonged Setup: The die-cutting subprocess had setup times of 1,200 minutes per month, with redundant and non-standardized activities.
- Accelerated Wear: Die-cutters exhibited 36.87% wear, which was associated with incorrect pressure settings and a lack of predictive maintenance.
- Reactive Maintenance: A failure-response culture prevailed, with no planning or preventive inspections.
- Deficient Lubrication: Guillotines and offset printers had low lubrication levels (177.73 ml and 437.85 ml, respectively), reducing their lifespan.
- Limited Digitalization: There were no real-time monitoring systems or centralized maintenance databases.

4.1.3. ROOT Cause Analysis

Quality tools such as the Ishikawa Diagram and the 5 Whys were applied, establishing that equipment's low availability and performance stemmed from the absence of standardization, limited technical training, and lack of technology for informed decision-making.

4.2. Innovative Proposal

The proposal's design to improve Overall Equipment Effectiveness (OEE) in the cardboard box production process is based on key studies addressing the use of tools, and Single-Minute Exchange of Die (SMED) is a technique used to minimize tool changeover times and thus increase equipment availability.

A 44.6% OEE increase was achieved through SMED implementation in machining processes [1], while another study reported a 30% reduction in changeover times, with a 9% OEE increase [5]. These studies highlight SMED's importance in optimizing downtime and boosting efficiency. These studies highlight industrial approaches that optimize operational efficiency and reduce non-productive time.

Total Productive Maintenance (TPM) focuses on autonomous and planned maintenance, essential to avoid unexpected failures and increase machine availability. The OEE improved from 60.7% to 65.3% thanks to the implementation of TPM [29], while preventive maintenance increased by 88% and repair time decreased by 53% [13].

It can be seen that these studies reinforce the idea that TPM is crucial for preventing unplanned downtime and maintaining optimal equipment operation. Automation is also a fundamental technology. Human errors were reduced, and byobots and PLCs accelerated production processe [28]. Efficiency also increased by 15% and costs decreased by 20%, all thanks to automation [22].

Furthermore, it is worth highlighting that IoT enables and supports real-time monitoring and failure anticipation. It is reported that IoT improves connectivity and enables decision-making based on real-time data, leading to optimized production processes [25]. Furthermore, IoT has increased OEE by 25% and reduced operating costs by 18% [20]. Machine efficiency and connectivity can be improved through the implementation of IoT.

It should be noted that the aforementioned studies symbolize a solid foundation for the implementation of SMED, TPM, automation, and IoT, the objective of which is to optimize OEE and, therefore, integrate tools and technologies into the cardboard box production process.

The improvement proposal was also developed based on the PMBOK (Project Management Body of Knowledge) project management approach, following three main phases in this study: initiation, implementation, and closure. These phases allowed the model to be structured sequentially and aligned with the strategic OEE improvement objectives.

In the Initiation phase, the project scope and SMART objectives associated with the identified root causes were defined, and finally, the involvement of those responsible was assigned through the charter and the RACI (Responsibility Assignment Matrix).

In the implementation phase, SMED and TPM tools, automation and IoT technologies were used following a strategic sequence. Technical tools such as checklists, single-point lessons, maintenance plans, and sensor schematics were also used.

Finally, in the Closing phase, the improvements were evaluated using statistical tools and simulation in Arena, in addition to preparing validation reports and the project closure document.

4.2.1. Application of SMED

A thorough analysis of setup times on critical process machines was carried out to identify and separate internal from external operations. Procedures were then redesigned to outsource as many operations as possible, significantly reducing setup times and increasing equipment availability.

4.2.2. Implementation of TPM

Total Productive Maintenance (TPM) was applied based on two fundamental pillars:

- Autonomous Maintenance: Personnel had to be trained to perform inspections and maintenance to prevent failures early.
- Planned Maintenance: It was essential to develop a structured schedule for preventive maintenance, the objective of which was to minimize unplanned downtime and extend the life of the machines.

4.2.3. Use of Automation

Automation was implemented to optimize repetitive and high-precision tasks, such as automatically adjusting machine operational parameters. This technology reduced human error and improved consistency in the final product's quality.

4.2.4. Integration of IoT

IoT sensors were installed at strategic points to monitor real-time critical variables such as operating times, temperatures, and machine vibrations. The collected data was integrated into a centralized platform that enabled predictive analysis and informed real-time decision-making.

4.2.5. Closure Phase: Evaluation and Validation of Results

In the final phase, the implemented improvements were evaluated through Arena software simulations. The simulation projected the impact of interventions in three scenarios:

- Moderate Scenario: Assumes gradual improvement by partially implementing the proposed tools and technologies.
- Optimistic Scenario: Considers complete and efficient implementation of all solutions, achieving proximity to the graphic industry's OEE standard.
- Pessimistic Scenario: Envisions limited implementation due to operational or budgetary constraints.

Comparisons were made between the current OEE and the projected values in each scenario. Key metrics such as setup time reduction, machine wear, and resource consumption (e.g., lubricants) were also analyzed.

4.3. Validation

The proposed model was validated through computer simulation using Arena software, a tool widely recognized for its ability to represent complex industrial processes through discrete event logic. The simulation enabled the projection of the impact of SMED, TPM, Automation, and IoT in a controlled environment, without affecting real plant operations, and facilitated comparisons across different implementation levels.

4.3.1. Simulation Structure

The model included the eight subprocesses of the production flow, with cutting, printing, and die-cutting being the most detailed as they were the focus of the improvements. Each subprocess included:

- Queues and processing times based on real data.
- Scheduled events such as maintenance or setup stoppages.
- Random events such as technical failures and human errors (reduced through automation).
- IoT sensors monitor Variables in real time (temperature, vibration, lubrication).

Considering three daily shifts, a simulation horizon of one operational month was defined. Results were averaged after multiple replications to ensure reliability.

4.3.2. Validation Scenarios

Three scenarios, summarized in Table 2, were evaluated to measure the effect of progressive model implementation:

Table 2. Validation scenarios

Scenario	Implementation	Main Objective
Moderate	Partial implementation of SMED, TPM, Automation, and IoT	Analyze progressive improvements
Optimistic	Full implementation of SMED, TPM, Automation, and IoT	Evaluate the maximum possible impact
Pessimistic	Limited implementation of SMED, TPM, Automation, and IoT due to operational restrictions	Verify minimum viability

4.3.3. Results Obtained

- Moderate Scenario: OEE of 71.90%, setup time reduced to 950 minutes, die-cutter wear at 27.80%. Partial but relevant improvements.
- Optimistic Scenario: OEE of 82.70%, setup time reduced to 836.69 minutes, die-cutter wear reduced to 24.58%, practical IoT monitoring.
- Pessimistic Scenario: OEE of 66.22%, an improvement over the baseline (64.27%), confirming model effectiveness even under restrictive conditions.

4.3.4. Validation Indicators

- Key KPI: Reduction in setup time, wear, and lubricant consumption.
- Internal Benchmarking: Comparison with previous periods and SMART goals.
- Validation Report: Technical documentation of achieved performance and standardization recommendations.

The simulation demonstrated that the model is technically feasible and scalable, generating tangible operational efficiency and resource use improvements. Arena allowed accurate projection of the benefits of the implemented tools, supporting informed decision-making for real-world application. The model outperformed the initial state in all scenarios, validating its robustness and adaptability to various operational conditions.

4.3.5. Sensitivity Analysis of OEE Indicators

As part of the model validation process, a sensitivity analysis was conducted based on the three simulated scenarios: optimistic, moderate, and pessimistic. The purpose was to identify which factors most strongly impact OEE variations and which should be prioritized in future practical implementation.

One of the most influential elements was the implementation of technologies such as IoT and automation. In the optimistic scenario, where both were fully integrated, the OEE reached 82.70%. In contrast, limited adoption, as simulated in the pessimistic scenario, resulted in a reduced OEE (66.22%), demonstrating a strong performance dependence on the degree of technological transformation.

Maintenance management, both preventive and predictive, also had a significant impact. Proper planning of these activities and the active participation of personnel in autonomous routines generated notable improvements in machine availability and wear. In scenarios where management was poor, considerably lower results were observed. Another key factor was the efficiency of format changeovers, optimized using the SMED methodology. Reducing setup times and eliminating unnecessary activities improved machine availability, particularly in processes such as die-cutting, where setup time represented a significant bottleneck. The technical training of staff also played an important role. A team trained in autonomous maintenance, Lean tool management, and digital technologies can accelerate the adoption of improvements and reduce operational errors. On the other hand, a lack of technical knowledge tends to limit the effectiveness of any intervention.

5. Results

Implementing the improvement model generated substantial transformations in the company’s operational efficiency. Results are presented in three phases: analysis before the model (before), development of the innovative proposal, and evaluation after implementation (after). The results focus on quantitative indicators, impacts per subprocess, and technical and economic validation of the improvements.

5.1. Problem Analysis (Before)

5.1.1. Comprehensive Process Diagnosis

During the initial stage, critical issues affecting the productivity and quality of the cardboard box production process were identified. Low equipment availability, variability in final products, and accelerated machine wear created constant inefficiencies.

5.1.2. Baseline Indicators

The following indicators, summarized in Table 3, reflect the initial operational situation, obtained after a three-month data collection period:

Table 3. Global Indicators of the AS-IS Project

Indicator	Unit	Initial Result
Setup time (die-cutting)	Minutes	1,200.00
Die-cutter wear	Percentage	36.87%
Lubricant consumption (guillotines)	ml/month	177.73
Lubricant consumption (offset)	ml/month	437.85
Total process OEE	Percentage	64.27%

5.1.3. Subprocess Analysis

- Die-Cutting: Represented the largest bottleneck, with excessive setup times and frequent unplanned stoppages.
- Guillotine: Lack of proper lubrication caused micro-stoppages due to manual adjustments, affecting performance.
- Offset Printing: Variability in print quality due to calibration errors and lack of automatic control.
- Maintenance: Reactive approach with low planning and limited involvement from operational staff.

5.1.4. Technical and Economic Implications

Low OEE caused a negative financial impact, leading to increased downtime, rework, and material waste costs—Additionally, low OEE limited production capacity in response to urgent orders, affecting the company's competitiveness.

5.2. Innovative Proposal

5.2.1. Scope of the Implemented Model

The proposal consisted of a structured conceptual model in phases that directly addressed the root causes of inefficiencies. The model is integrated:

- SMED: Redesign of die-cutting setup.
- TPM: Autonomous and planned maintenance.
- Automation: Automatic control of parameters in guillotines and offset printers.
- IoT: Smart monitoring of critical variables.

5.2.2. Specific Actions by Tool

Table 4 summarizes the implemented action and expected result for each tool.

Table 4. Actions Implemented by Tool

Tool	Implemented Action	Expected Result
SMED	Standardization and externalization of activities	Reduction in setup time
TPM	Daily autonomous inspection, monthly planning	Reduction in machine wear
Automation	Installation of automatic controllers	Higher precision, reduced errors
IoT	Vibration, temperature, and lubrication sensors	Predictive and real-time monitoring

5.2.3. Projected Impact of the Model

The model was simulated before real implementation, allowing results and parameter adjustments to be projected. It was estimated that, in an optimal scenario, OEE would exceed 80%, while setup times would be reduced by more than 30%.

5.3. Validation (After)

5.3.1. Post-Implementation Results

Validation included comparison of indicators before and after model implementation, using three scenarios projected in Arena software: moderate, optimistic, and pessimistic. Table 5 shows the results of the project.

Table 5. Global indicators of the TO-BE project

Indicator	Initial	Moderate	Optimistic	Pessimistic
OEE (%)	64.27	71.90	82.70	66.22
Setup time (die-cutting) (min)	1,200.00	950.00	836.69	1,050.00
Die-cutter wear (%)	36.87	27.80	24.58	30.50
Lubricant (guillotines) (ml)	177.73	230.00	255.04	220.00
Lubricant (offset) (ml)	437.85	530.00	569.21	515.00

The Improvement Model is Structured into Three Main Phases:

- Setup Time Reduction via SMED: This phase optimized setup times in key subprocesses, from 1,255 to 836.69 minutes. Rapid changeover was achieved through procedure standardization and operator training.
- Autonomous and Planned Maintenance with TPM: TPM implementation reduced die-cutter wear from 36.87% to 24.58%, improving machine availability and reducing corrective interventions. Staff were trained to perform autonomous maintenance.
- Automation and IoT: Integration of IoT sensors in guillotines and offset printers enabled real-time monitoring of operating conditions, enhancing fault detection accuracy and ensuring optimal lubricant use. Lubricant usage was expected to increase to 255.04 ml in guillotines and 569.21 ml in offset printers.

The implementation of the model will follow a plan structured in phases, allowing the results to be continuously validated:

- SMED Phase: Setup times were reduced by standardizing internal and external activities, improving operational efficiency.
- TPM Phase: Preventive maintenance programs were established to minimize die-cutter wear and ensure optimal operation.
- Automation and IoT Phase: IoT sensors were integrated to capture and analyze real-time data, optimizing resources and anticipating potential failures.

The projected results after the implementation of the SMED, TPM, Automation and IoT tools are analyzed in three scenarios:

- Moderate Scenario: Expected OEE: 73.27%, due to the 9% increase in the current OEE (64.27%) according to [2].
- Optimistic Scenario: Expected OEE: 81.27%, due to the 17% increase in the current OEE (64.27%) according to [5].
- Pessimistic Scenario: Expected OEE: 67.53%, due to the 3.26% increase in the current OEE (64.27%) according to [31].

After the implementation of the model, a significant improvement is expected in the key indicators:

- Setup Time: Reduced from 1,200 minutes to 950 minutes in the moderate scenario.
- Die-cutter Wear: Reduced from 36.87% to 27.80% in the moderate scenario.
- Lubrication: Increased to 230.00 ml in guillotines and 530.00 ml in offset printers.

These results demonstrate significant improvements in operational efficiency, aligning with previous studies.

The simulation has been key in implementing SMED, TPM, IoT, and Automation to optimize production processes and improve OEE. In the case of SMED, they developed a methodological approach assisted by Lean tools that allowed for a more efficient reorganization of internal and external changeover activities [1]. They implemented this same methodology in tire calibration procedures, achieving a reduction of over 50% in changeover times [3].

In a food plant, they documented a 36% improvement in changeover efficiency after introducing Lean principles [2]. It was demonstrated that combining SMED with production scheduling reduces bottlenecks in processes with high product turnover [4].

Regarding TPM, it was concluded that autonomous and planned maintenance pillars are the most influential in increasing equipment availability [9]. The methodology was adapted to a digital environment with sensors, proposing a preventive maintenance scheme capable of anticipating failures before they affect operational continuity [10]. They presented a case where the integration between TPM and IoT significantly improved the availability of a conveyor line through maintenance actions based on real data [11]. The results reported in these studies reflect a clear trend towards convergence between Lean tools and digital technologies to achieve more reliable, stable, and efficient processes.

In Automation and IoT, simulations demonstrated how automated lines can be optimized and failures prevented [23, 30]. It was validated that IoT in simulations improves operational efficiency [20, 25]. Significant improvements in availability were shown using simulations in the maintenance context [7, 13].

In another case, the experience of an industrial plant that integrated torque sensors and continuous monitoring systems into its packaging lines is presented [32]. Thanks to this technology, automatic adjustments were made during operation, improving process stability and extending the life of the blades used in final cuts.

For their part, they analyze automation in adjusting registers and parameters of offset presses [33]. The study shows a 40% reduction in setup times by eliminating manual errors during paper setup. This automation also made it possible to standardize positioning and minimize waste in the first meters of printing.

From a more quality-focused perspective, automation is documented through optical systems in the binding process [18]. The integration of cameras and detection algorithms reduced the rate of defective products by 18% through early detection of finishing covers and cuts errors.

Interoperable system simulations were employed to reduce downtime by 18% [22], while IoT-based simulations demonstrated a 20% reduction in failure response time [19]. IoT simulations were used to enhance flexibility in Industry 4.0, with improvements in operational efficiency [34].

In conclusion, simulation is an essential tool for predicting the impact of SMED, TPM, IoT, and Automation improvements, enabling significant increases in operational efficiency and OEE across various industrial sectors.

6. Discussion

6.1. Scenarios Vs Results

The analysis of the three proposed scenarios (moderate, optimistic, and pessimistic) demonstrates the model's capacity to significantly improve OEE in the cardboard box production process by integrating SMED, TPM, Automation, and IoT. The quantitative results reflect the impact of these technologies and methodologies on the efficiency and availability of the production process.

- Moderate scenario: This scenario increases OEE from 64.27% to 71.90% (shown in Table 6), which is significant and brings the index closer to the graphic sector standard of 72.5%. This increase is mainly achieved by reducing die-cutting setup time from 1,200 to 950 minutes and printing from 1,875 to 1,450 minutes. Machine availability improves, reducing unexpected stoppages and increasing effective production time.

Table 6. Comparison of current OEE Vs. moderate scenario

OEE (As–Is)	OEE (To-Be Moderate)
64.27%	71.90%

Optimistic Scenario: With a more ambitious improvement, OEE reaches 82.70% (shown in Table 7), surpassing industry standards. This is achieved by reducing die-cutting setup time to 836.69 minutes and printing setup time to 1,200 minutes. Additionally, equipment availability increases due to combining TPM and predictive maintenance with IoT, enabling real-time machine status monitoring. This optimization reduces equipment wear, particularly for die-cutters, whose wear rate decreases from 36.87% to 24.58%.

Table 7. Comparison of current OEE VS. optimistic scenario

OEE (As–Is)	OEE (To – Be Moderate)
64.27%	82.70%

- Pessimistic Scenario: Even under less favorable conditions, the proposed model increases OEE from 64.27% to 66.22% (Table 8). In this case, improvements in setup times and equipment availability are moderate but still show an increase that helps maintain stable production and reduce process losses. This scenario demonstrates that the applied improvement tools and technologies can enhance process efficiency even with resource limitations.

Table 8. Comparison of current OEE Vs pessimistic scenario

OEE (As–Is)	OEE (To – Be Pessimistic)
64.27%	66.22%

The results highlight the model's ability to adapt to different conditions and investment scales, supporting its flexibility and scalability. The improvement in OEE across all scenarios underscores the importance of integrating Lean tools and Industry 4.0 technologies in production processes to achieve competitive efficiency levels.

6.2. Results Analysis

The analysis considered economic, operational, and maintenance criteria, providing a comprehensive view of the model's impact.

Table 9. Financial indicators

Scenario	Moderate	Optimistic	Pessimistic
COC	19.16%	19.16%	19.16%
NPV	53,567.50	177555.74	10023.76
IRR	36.77%	72.60%	32.34%
B/C	1.4363	2.4463	1.3266
PBP	3.07	1.70	3.54
Years	3	1	3
Months	1	8	6

- Economic criterion: The financial results summarized in Table 9 demonstrate that the model is profitable in all evaluated scenarios. In the moderate scenario, the Net Present Value (NPV) is $ 53,567.50, and the Internal Rate of Return (IRR) reaches 36.77%, significantly exceeding the Cost of Capital (COC) of 19.16%. In the optimistic scenario, these values increase due to improvements in OEE and reduced operating costs, optimizing resource usage. Additional revenues from increased production and reduced downtime enable an investment payback period of approximately three years, supporting the economic feasibility of the proposal.
- Operational criterion: The improvements in the operational efficiency of the production process are remarkable. In the die-cutting subprocess, reducing setup times from 1,200 to 836.69 minutes in the optimistic scenario allows for greater production flexibility, optimizing workflow and reducing waiting times. In printing, reducing setup times from 1,875 to 1,200 minutes in the same scenario increases production capacity. These optimizations improve equipment availability and enhance responsiveness to fluctuating market demands.
- Maintenance criterion: The implementation of TPM, along with predictive maintenance through IoT, provides

more efficient asset management for the company. In the optimistic scenario, die-cutter wear is reduced from 36.87% to 24.58%, minimizing failure stoppages and extending equipment lifespan. Additionally, increased lubricant usage in guillotines and printing (255.04 ml and 569.21 ml, respectively) helps maintain equipment in optimal operating conditions. These changes reflect decreased corrective maintenance costs and greater equipment reliability, ensuring continuous and uninterrupted operation.

7. Conclusion

- The implementation of the model based on SMED, TPM, Automation, and IoT increases the OEE of the cardboard box production process from an initial 64.27% to 82.70% in the optimistic scenario. This improvement allows the company to reach and surpass the industry standard of 72.5%, positioning it at a competitive level in the market. This increase in efficiency optimizes resource usage and reduces operating costs by minimizing downtime, resulting in a key competitive advantage for the company.
- The financial results validate the viability of the proposed model in all evaluated scenarios. In the moderate scenario, with an NPV of $ 53,567.50 and an IRR of 36.77%, the project's profitability significantly exceeds the Cost of Capital (19.16%), indicating a payback period of approximately three years. This demonstrates that the model is financially sustainable and contributes to the company's long-term economic stability, enabling increased revenue derived from greater operational efficiency.
- The reduction in die-cutter wear (from 36.87% to 24.58% in the optimistic scenario) and the optimization of lubricant usage are indicators of efficient maintenance management. TPM implementation, together with real-time monitoring via IoT, reduces unplanned stoppages, ensuring the availability and continuity of the production process. These results confirm that the proposed model increases efficiency and ensures operational sustainability by optimizing the use and maintenance of assets.
- The model improves efficiency, reduces costs, and contributes to more sustainable production. Reduced downtime and lower equipment wear decrease the need for frequent repairs and material use, which reduces the company's carbon footprint and promotes responsible manufacturing practices. This approach, aligned with sustainability trends, provides an additional advantage regarding corporate social responsibility.
- The model establishes a solid foundation for digital transformation in the graphic sector by integrating IoT and Automation into production processes. This allows for smarter and more adaptive operations that can efficiently respond to changes in demand and market fluctuations. This model represents a significant step toward smart manufacturing, strengthening the company's position as an innovative and resilient player in a constantly evolving sector.

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