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An Integrated Preventive Maintenance Transformation Framework Combining Lean Practices, Autonomous Maintenance and Digital Traceability

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Abstract: Despite the widespread adoption of Lean and Total Productive Maintenance (TPM) methodologies, many manufacturing companies still struggle to operationally integrate preventive maintenance, workplace organization, autonomous maintenance, and digital traceability into a coherent and measurable maintenance-improvement system. This Action Research study presents an integrated Lean-based preventive maintenance transformation framework implemented in a production unit of a major corrugated cardboard packaging manufacturer. The project focused on the DRO 1628 NT rotary die-cutter, identified as the most critical asset in the converting section through a structured multi-criteria criticality assessment. The proposed framework combined autonomous maintenance routines, standardized inspection procedures, 5S workplace organization, KPI-driven monitoring, and maintenance communication digitalization through a custom Microsoft Power Apps (Microsoft Corporation, Redmond, Washington, DC, USA) solution. The novelty of the study lies in the operational integration of these organizational, technical, and digital elements within a unified preventive maintenance transformation strategy specifically adapted to a high-pressure industrial environment characterized by limited traceability, reactive maintenance practices, and strong dependence on informal operator knowledge. Between the September 2024 baseline and the May 2025 post-intervention assessment, productivity increased by 14.0%, monthly production output increased by 16.8%, Mean Time between Failures (MTBF) increased by 18.0%, and Mean Time to Repair (MTTR) decreased by 43.3%. Beyond these quantitative gains, qualitative observations indicated improvements in operator engagement, routine discipline, workplace organization, anomaly traceability, and production-maintenance communication. The findings further suggest that substantial maintenance-performance improvements can be achieved through the structured integration of Lean routines, operator-centered maintenance practices, and accessible digital support systems, even in industrial environments that do not yet rely on advanced predictive maintenance architectures. The study therefore contributes a preventive maintenance transformation framework empirically evaluated through an industrial Action Research study and provides new insights into how organizational routines, operator involvement, standardized work, and digital traceability interact to strengthen preventive maintenance capability, with potential transferability to other manufacturing environments.

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1. Introduction

In modern industrial environments, maintenance has evolved into a strategic function with a direct impact on equipment reliability, operational efficiency, and production continuity. Within this context, preventive maintenance is essential for reducing unplanned downtime, extending equipment lifespan, and stabilizing production performance.

A persistent challenge in manufacturing systems is the high dependence on specialized maintenance teams for routine tasks that could be partially delegated to operators. This limitation reduces responsiveness to emerging issues and increases the likelihood of equipment failures. To address this problem, autonomous maintenance has been widely promoted within the frameworks of Total Productive Maintenance (TPM) and Lean Manufacturing.

Autonomous maintenance engages operators in basic activities such as cleaning, inspection, tightening, and lubrication, supported by standardized procedures and checklists. This approach contributes to improved maintenance execution, enhanced equipment awareness, and increased operator responsibility for process reliability.

This study focuses on improving the preventive maintenance system through the implementation of autonomous maintenance practices supported by standardized documentation. The research was conducted in a corrugated cardboard manufacturing environment, where high production pressure and frequent operational changes make equipment reliability a critical factor.

Although numerous studies have demonstrated the benefits of Lean Manufacturing, TPM, autonomous maintenance, and maintenance digitalization individually, considerably less attention has been given to understanding how these elements interact as an integrated maintenance-transformation process. Consequently, the scientific relevance of this study lies not only in evaluating an industrial intervention but also in explaining the mechanisms through which organizational practices, operator involvement, process standardization, and digital traceability jointly contribute to preventive maintenance transformation.

The objectives of this study are:

- To assess the current state of preventive maintenance;
- To identify improvement opportunities in existing practices;
- To develop equipment-specific autonomous maintenance standards;
- To design standardized checklists to support operator activities;
- To implement and validate the proposed approach in an industrial setting;
- To evaluate its impact on maintenance performance and the reduction of unplanned downtime.

This research contributes to the development of structured and operator-centered maintenance systems, with practical implications for improving reliability and operational performance in manufacturing environments. Beyond its practical implications, this study also contributes theoretically to the maintenance management literature by demonstrating how autonomous maintenance, workplace organization, asset criticality assessment, and low-code digitalization may be operationally integrated into a unified preventive maintenance transformation framework. The study therefore reinforces the perspective that maintenance effectiveness emerges not only from isolated technical interventions, but from the systemic interaction between organizational discipline, standardized routines, operator involvement, and digital support mechanisms.

2. Literature Review

In modern industrial environments, maintenance is no longer viewed as a secondary support activity but as a strategic function with direct influence on reliability, productivity, quality, cost, and operational continuity [1,2]. This evolution has been driven by the increasing complexity of production systems and by the need to ensure higher asset availability in highly competitive markets [3]. As a result, companies have progressively moved from reactive maintenance logic toward more structured and preventive approaches, supported by planning, standardization, and performance control [4,5].

Preventive maintenance has therefore become a key pillar of industrial performance because it contributes to reducing unplanned stoppages, extending equipment life, and stabilizing production flows [1,6]. Its relevance is particularly evident in manufacturing settings where equipment failures generate not only repair costs, but also losses in throughput, quality deviations, delivery delays, and inefficient resource utilization [2,7]. For this reason,

the literature has consistently highlighted the importance of organizing maintenance activities around preventive routines, structured planning, and continuous monitoring of execution and results [3,8].

A central dimension of this evolution concerns maintenance performance measurement. The use of key performance indicators such as Mean Time between Failures (MTBF), Mean Time to Repair (MTTR), availability, compliance with preventive plans, and maintenance productivity has become essential for transforming maintenance into a measurable and manageable function [6,8]. Empirical studies have shown that maintenance indicators support decision-making, reveal hidden operational losses, and improve alignment between maintenance and production objectives [9,10]. In the same line, benchmarking practices and comparative analyses of maintenance systems have been identified as important mechanisms for increasing managerial maturity and promoting the adoption of best practices [4,11].

Another relevant research stream emphasizes that maintenance effectiveness depends not only on technical interventions but also on how assets and resources are prioritized. Asset criticality assessment has been widely used to define differentiated maintenance strategies according to the impact of equipment on safety, production, quality, and operational continuity [12]. Similarly, risk-based approaches applied to maintenance-related decisions, such as supplier evaluation and support-process reliability, reinforce the idea that maintenance performance is deeply affected by structured prioritization criteria [13]. In industrial reality, where time, labor, and budget are limited, maintenance management must therefore combine technical knowledge with clear prioritization logic.

Among the most influential approaches in this field, Total Productive Maintenance (TPM) has received particular attention due to its ability to integrate maintenance, production, and continuous improvement within a common operational philosophy [14,15]. One of its most important pillars is autonomous maintenance, through which operators become responsible for routine activities such as cleaning, inspection, lubrication, tightening, and early detection of abnormalities [16]. This shift increases equipment ownership at the shop-floor level and helps create more disciplined and stable operating conditions [14]. Case-study evidence shows that autonomous maintenance implementation can significantly improve equipment availability and operational performance; for example, in an automotive components manufacturer, the implementation of autonomous maintenance contributed to a 10% increase in availability and an 8% increase in OEE [16].

The benefits of TPM-oriented strategies have also been reported in broader maintenance improvement initiatives. Continuous improvement projects in industrial maintenance have demonstrated that combining Lean tools with maintenance analysis can enhance process control and reduce inefficiencies [17]. Likewise, the implementation of strategic maintenance plans structured around TPM principles has been associated with measurable gains in maintenance responsiveness, preventive execution, and asset performance [18,19]. In one case of the energy solutions sector, improvements in preventive maintenance management led to a 66% reduction in failures, a 12% increase in compliance with preventive plans, and significant savings in maintenance-related costs [20]. These results reinforce the view that maintenance improvement depends on a combination of technical planning, operator involvement, and process discipline.

This perspective is also consistent with research on process improvement in corrugated cardboard production. Studies in this industrial sector have shown that operational performance can be improved through process analysis, elimination of non-value-adding activities, standardization, and structured improvement methodologies [21]. At the same time, novel approaches to maintenance operations have proposed integrated frameworks combining diagnosis, KPI monitoring, intervention planning, and follow-up verification to improve maintenance effectiveness [22]. Taken together, these contributions suggest that maintenance management should not be treated as an isolated technical domain, but rather as part of a broader production-improvement system.

In parallel with managerial and organizational approaches, preventive maintenance has also been studied through analytical and optimization-based models. Research on distributed systems has shown that preventive maintenance planning may involve trade-offs between cost minimization and operational effectiveness, especially when routing and scheduling constraints are considered [23]. Similar optimization concerns are found in the aircraft maintenance literature, where mathematical models and heuristics have been proposed to support routing decisions under operational restrictions [24,25]. Other studies have further highlighted the importance of skill allocation and training schedules in maintaining maintenance-system feasibility and efficiency over time [26]. Although such models are often developed in high-complexity sectors, they confirm a broader principle: effective preventive maintenance depends on structured planning, adequate resource allocation, and support for decision-making.

The ongoing digital transformation of manufacturing has added a new layer to this discussion. Maintenance in digitalized environments increasingly relies on real-time information, traceability, monitoring systems, and intelligent decision-support architectures [27,28]. Work-progress monitoring models show that maintenance planning can be significantly improved when managers have visibility over execution status, delays, and task interdependencies [27]. In addition, smart maintenance decision support systems based on large-scale data analysis

have been proposed to improve planning, diagnosis, and responsiveness [29]. Strategic frameworks for maintenance decision support have further reinforced the importance of integrating data, structure, and decision logic in maintenance environments [30].

Industry 4.0 technologies also contribute to maintenance improvement by enhancing communication, visualization, and execution support. Augmented reality solutions for remote maintenance have shown potential to facilitate technical assistance, accelerate intervention, and improve access to critical information in real time [31]. Similarly, the conversion of maintenance actions into standardized visual symbols has been proposed as a way to support more consistent execution and knowledge transfer in digital industrial environments [32]. These developments indicate that digitalization can strengthen maintenance not only through better data collection, but also through greater operational standardization and more effective support to technicians and operators.

Besides operational efficiency, recent literature has also linked maintenance to sustainability and long-term value creation. Studies on human factors in aircraft maintenance highlight that deviations in execution may arise from organizational and behavioral causes, stressing the importance of robust systems and disciplined work practices [33]. More broadly, advanced maintenance services have been proposed as a means of promoting sustainability by improving asset lifecycle performance and resource efficiency [34]. The prioritization of sustainable maintenance drivers has likewise shown that maintenance decisions increasingly need to incorporate economic, technical, and environmental dimensions [35]. Thus, maintenance is now recognized not only as a reliability function, but also as a contributor to competitive and sustainable industrial performance.

Despite the extensive literature on Lean tools, TPM, autonomous maintenance, 5S, and maintenance digitalization, these approaches are predominantly examined either as individual improvement practices or as components of broader industrial initiatives, with limited attention given to their coordinated role in preventive maintenance transformation. Although previous studies have demonstrated the operational benefits of these practices and highlighted their contribution to maintenance performance, reliability, and production efficiency [11,16,19], the literature still provides only limited theoretical understanding of how these organizational, technical, and digital elements interact to produce a coherent maintenance-transformation process. This limitation is particularly relevant in manufacturing sectors such as corrugated cardboard production, where equipment reliability depends not only on the adoption of maintenance tools but also on the systematic integration of operator involvement, standardized routines, workplace organization, digital traceability, and maintenance prioritization within a unified operational framework [21]. Consequently, the existing gap concerns not simply the availability of Lean or digital maintenance practices, but the absence of a structured conceptual perspective explaining how their coordinated implementation transforms preventive maintenance from a predominantly reactive activity into a standardized, operator-supported, digitally traceable, and performance-driven organizational capability. Such a perspective is especially valuable for manufacturing companies seeking scalable maintenance transformation strategies without relying, as a first step, on advanced predictive maintenance technologies.

The principal scientific contribution of this study is the development and empirical evaluation of an integrated preventive maintenance transformation framework that conceptualizes preventive maintenance improvement as the coordinated interaction of organizational, technical, and digital capabilities rather than as the implementation of isolated maintenance initiatives. The framework combines four complementary elements within a unified transformation process: a multi-criteria asset criticality assessment to identify the pilot equipment; autonomous maintenance routines supported by technical manuals and standardized inspection sheets; 5S workplace organization as an enabler of disciplined routine execution; and a low-code Power Apps solution for maintenance request management and digital traceability. By applying this framework to the DRO 1628 NT rotary die-cutter and evaluating its impact through productivity, production, MTBF, MTTR, and maintenance request data, the study provides empirical evidence that preventive maintenance transformation emerges from the systematic integration of these organizational, technical, and digital practices. Beyond the specific industrial case, the proposed framework offers a transferable conceptual perspective for understanding how coordinated maintenance practices can strengthen preventive maintenance capability in manufacturing environments.

To provide a structured overview of the proposed intervention logic, Figure 1 summarizes the integrated Lean-based preventive maintenance framework developed and implemented in this study. The framework consolidates the main stages of the improvement process, from the initial diagnosis and asset criticality assessment to the implementation of autonomous maintenance routines, workplace organization practices, digital support systems, and continuous performance monitoring. The objective of this integrated structure is to demonstrate how organizational, technical, and digital elements were systematically combined to support preventive maintenance transformation within the corrugated cardboard manufacturing environment.

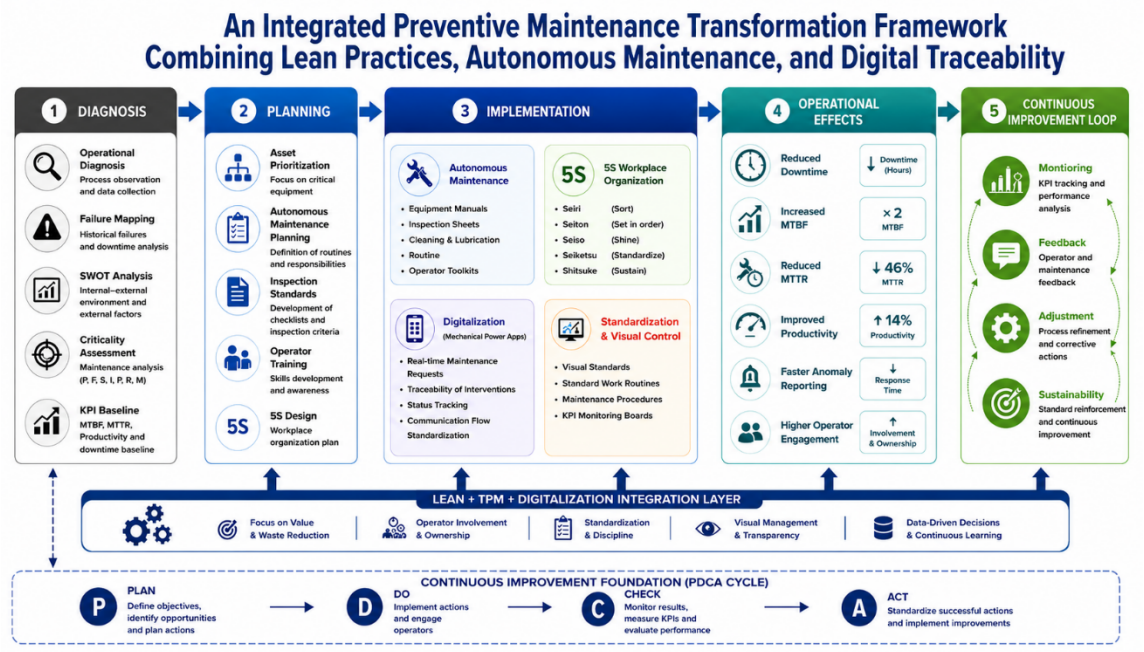


Figure 1. Conceptual architecture of the integrated preventive maintenance transformation framework for corrugated cardboard manufacturing, illustrating the structured integration of diagnosis, asset criticality assessment, autonomous maintenance, 5S workplace organization, digitalization, standardization, KPI monitoring, and continuous improvement mechanisms implemented in the DRO 1628 NT maintenance-transformation project.

Unlike conventional TPM implementations, which primarily emphasize the deployment of autonomous maintenance routines within the TPM pillar structure, the proposed framework conceptualizes preventive maintenance transformation as the coordinated integration of organizational, technical, and digital capabilities. Rather than treating asset prioritization, workplace organization, autonomous maintenance, and digital traceability as sequential or independent initiatives, the framework explicitly links these complementary elements within a unified maintenance-transformation architecture.

The framework highlights that the effectiveness of the proposed maintenance transformation did not result from isolated technical actions, but rather from the coordinated interaction between Lean principles, operator involvement, standardized execution routines, and digital traceability mechanisms. Within this architecture, digital traceability is not introduced merely to replace paper-based records or improve communication efficiency. Instead, it functions as the integrating mechanism that connects operator observations, maintenance execution, standardized routines, asset prioritization, and performance monitoring into a continuous information flow supporting organizational learning and decision-making. In this sense, the proposed approach should be interpreted as a systemic maintenance-improvement architecture designed to stabilize operational routines, reduce variability, strengthen communication flows, and improve maintenance responsiveness within a high-pressure manufacturing environment.

The effectiveness of the framework therefore emerges from the synergistic interaction between its four complementary components. Asset prioritization ensures that improvement efforts are concentrated on equipment with the greatest operational impact; autonomous maintenance promotes early anomaly detection and operator ownership; workplace organization stabilizes routine execution and reduces process variability; and digital traceability captures, shares, and structures maintenance knowledge. Acting together, these elements reinforce one another and generate maintenance capabilities that cannot be achieved through the isolated implementation of each practice.

While Figure 1 presents the conceptual architecture of the proposed maintenance transformation framework, Figure 2 summarizes its recommended implementation workflow. It illustrates the practical sequence adopted during the industrial intervention, providing practitioners with a structured roadmap from the initial diagnosis to continuous performance improvement.

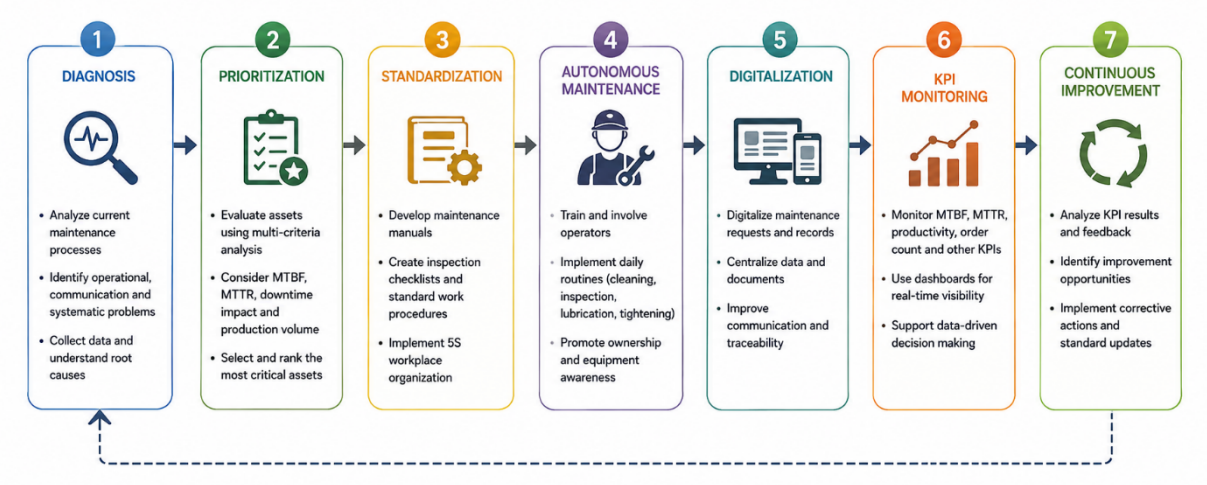


Figure 2. Industrial application workflow of the integrated preventive maintenance transformation framework.

It is within this context that the present study is developed. Focusing on a corrugated cardboard industrial environment, this work aims to improve and optimize preventive maintenance management through the combined application of autonomous maintenance principles, asset criticality analysis, standardized inspection and support documents, workplace organization based on 5S, and maintenance process digitalization. The study intends to demonstrate that the structured integration of these practices can strengthen operator involvement, improve maintenance traceability, support better prioritization, and increase the overall effectiveness of preventive maintenance in a real industrial setting.

This study contributes to maintenance management research in three complementary ways. First, it proposes an integrated preventive maintenance transformation framework that conceptualizes maintenance improvement as the coordinated interaction between organizational routines, operator involvement, standardized work, asset prioritization, and digital traceability. Second, it extends existing maintenance management literature by demonstrating that the effectiveness of Lean and TPM practices depends not only on the adoption of individual improvement tools but also on their systemic integration within a structured transformation process. Third, it provides empirical evidence that accessible low-code digital technologies can strengthen preventive maintenance capability when embedded in standardized organizational routines, offering a transferable perspective for manufacturing environments beyond the specific industrial case investigated.

3. Methodology

This study adopts an Action Research methodology because the research was conducted in a real industrial environment with the dual purpose of solving a practical operational problem and generating context-based knowledge. Action Research is particularly suitable for organizational and industrial improvement projects, as it combines intervention, collaboration between researchers and practitioners, systematic data collection, and reflection on the effects of implemented actions [36–38]. In the field of operations management, Action Research has been recognized as an appropriate methodology for studying and improving operational systems through direct engagement with real-world processes [38].

3.1. Research Design

Classical Action Research models describe the research process as a cyclical sequence of phases. Susman and Evered [36] proposed a five-phase cycle composed of diagnosing, action planning, action taking, evaluating, and specifying learning. A similar five-phase structure has also been adopted in applied organizational and information systems research [37]. However, Action Research is also commonly operationalized through four interconnected stages—planning, acting, observing, and reflecting—allowing the research cycle to be adapted to the specific context and scope of the intervention [39].

The choice of Action Research was particularly appropriate because the study required simultaneous intervention and observation within a real industrial environment characterized by dynamic operational constraints, continuous production pressure, and direct interaction between researchers, operators, supervisors, and maintenance technicians. This methodological approach allowed iterative refinement of the implemented actions throughout the project, increasing both practical relevance and contextual validity.

Therefore, this study operationalized the Action Research cycle into four main stages: diagnosis, planning, action, and evaluation/reflection. The fifth phase of the classical model, specifying learning, was not omitted; rather, it was incorporated into the evaluation/reflection stage, where the results were interpreted, lessons learned were consolidated, and the potential replication of the improvement framework to other equipment was assessed.

The four stages adopted in this study were defined as follows:

1. Diagnosis: Assessment of the current maintenance system through direct observation, informal interviews with operators and technicians, document analysis, SWOT analysis, and review of operational data.
2. Planning: Definition of improvement actions based on Lean and TPM principles, including the selection of the pilot asset through criticality analysis and the design of autonomous maintenance routines, inspection standards, 5S actions, and digital reporting requirements.
3. Action: Implementation of the improvement program on the DRO 1628 NT machine (BOBST SA, Mex, Vaud, Switzerland), including technical manuals, standardized inspection sheets, operator training, workplace organization, and a Power Apps-based maintenance request system.
4. Evaluation: Comparison of operational indicators before and after implementation, including productivity, MTBF, MTTR, failure records, and maintenance requests, complemented by qualitative assessment of operator involvement, communication, traceability, and workplace organization.

3.2. Case Study Context

The company where this study was conducted produces corrugated cardboard sheets and packaging. After the production of corrugated board sheets in the corrugator, they are sent to the converting section, where they are processed in industrial machines dedicated to operations such as cutting, creasing, printing, and gluing. This section includes six industrial machines divided into three categories, as shown in Table 1.

Table 1. Converting machines at the company.

Type	Acronym	Definition	Machines
Rotary Die Cutter	RDC	Rotary die-cutting machine with printing units, which uses cylinders fitted with fixed dies/cutting tools to cut, crease, and perforate corrugated board continuously. It is widely used in high-volume production, especially for complex cutting shapes and where high operating speed is required.	DRO 1628 NT
Flexo Folder Gluer	FFG	Complex machine that performs flexographic printing, slotting and creasing, folding, and box gluing in a single line. It is especially suited for the mass production of standard boxes with high efficiency and repeatability.	Martin 924-1 (MARTIN S.A., Lyon, France) Martin 924-2 Bobst 618 Miniline
Flat Bed Die Cutter	FBC	Flatbed die-cutter that uses a vertical press system to cut the board with high precision. It is ideal for jobs that require detailed or complex cuts, although it operates at a lower speed compared to rotary machines.	Bobst 160-S Bobst 1600 (BOBST SA, Mex, Vaud, Switzerland)

The performance of these machines has a direct impact on the factory's efficiency. The analysis carried out revealed a series of limitations in preventive maintenance, recurring failures, and communication problems between operators and the technical team. The traceability of information was practically nonexistent, which prevented the development of a reliable history of failures and interventions carried out. Without this information base, the planning of corrective or preventive actions relied solely on individual memory and accumulated experience, which, although useful, severely limited the ability to make decisions based on objective data. From an operational point of view, this reality was reflected in several recurring problems, namely:

- Increased frequency of repeated failures at the same points of the machines;
- Delays in resolving simple anomalies;
- Lack of reliable indicators to assess maintenance performance.

Based on the evidence collected throughout the diagnostic phase, a SWOT analysis was carried out, as shown in Figure 3, to summarize the main internal and external factors influencing the maintenance system. This matrix helped clarify the strengths that could be leveraged, the weaknesses that needed to be addressed, as well as the opportunities and threats to be considered in the improvement proposal. This analysis supported the definition of priorities in the intervention planning. The existing technical capability and the involvement of the teams proved to be important assets to be explored. On the other hand, the urgent need to transform outdated processes and the possibility of scaling digital solutions were seen as major opportunities that should not be overlooked.

This diagnosis highlighted the urgent need to modernize processes, both at the technical level (through the digitalization and standardization of tasks) and at the organizational level (through the training and active

involvement of operators). These findings motivated the development of the present improvement project, focused on implementing a structured autonomous maintenance approach and the digitalization of processes. To prioritize intervention, the machines with the greatest impact on overall productivity and the highest number of breakdowns were identified. The selection of the target equipment for the pilot phase was based on objective criteria such as production volume (m^2 produced), number of technical stoppages, and the availability of the operator team to collaborate in the implementation of the new routines.

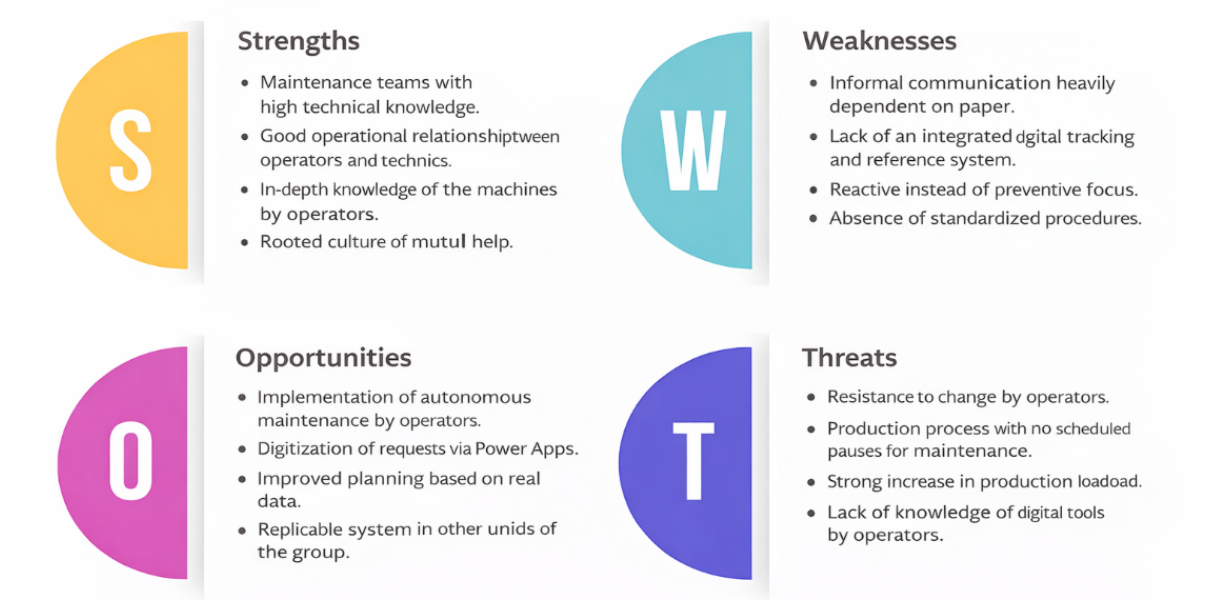


Figure 3. SWOT analysis of the current maintenance state at the company.

The identification of the critical problems resulted from an integrated analysis combining direct on-site observation, the analysis of historical data, and the testimonies collected from operators and technicians. The problems identified were distributed across three fundamental levels: operational, communication, and systematic.

3.2.1. Operational Problems

- Absence of formal inspection routines carried out by operators. Basic tasks such as cleaning, inspection, and lubrication were performed randomly, without any record or defined frequency.
- Strong dependence on corrective maintenance, with intervention only after a failure occurred, often with a direct impact on product quality or productivity.

3.2.2. Communication Problems

- Use of paper observation sheets, often subject to completion errors, loss, or delivery delays.
- Lack of feedback to the operator after the submission of an intervention request, which led to demotivation and the gradual abandonment of the recording practice.
- Communication difficulties between shifts resulting in the loss of relevant information between teams operating the same machine.

3.2.3. Systematic Problems

- Lack of a digital system to support maintenance and data recording, making it difficult to centralize and monitor interventions.
- Absence of performance indicators (KPIs) that would allow failures, completed interventions, and compliance with inspections to be monitored.
- Constant production pressure, which led to the postponement of basic maintenance tasks, such as cleaning and adjustments, due to the lack of available time.

These weaknesses made it clear that simply intensifying the existing routines would not be enough to ensure the reliability of the system. A profound reformulation was required in the way maintenance was understood and integrated into the daily operation of production, based on a culture of shared responsibility, supported by reliable data and practical tools that would make the process more efficient, intuitive, and sustainable.

A multi-criteria criticality analysis, considering MTBF, MTTR, production volume, order count, and average order size, identified the DRO 1628 NT rotary die-cutter as the most critical asset.

3.3. Data Collection

Data was extracted from the OMP production management system and covered:

- Productivity (m^2/h)
- Total monthly production (m^2)
- MTBF (h)
- MTTR (min)
- Number and type of failures
- Maintenance requests (pre/post digitalization)

Data covered the period from September 2024 to May 2025. September 2024 was adopted as the baseline reference, while the main implementation activities were conducted during November and December 2024. The subsequent January–May 2025 period was used to assess the post-implementation evolution of the operational and maintenance indicators, with May 2025 representing the final post-intervention assessment point for direct comparison with the baseline.

3.4. Improvement Program Components

In this section, a roadmap of the actions needed to take on the shop floor is depicted, describing the different actions taken under each of the three tools considered in this work: autonomous maintenance, 5S workplace organization, and digitalization.

Autonomous Maintenance

- Creation of technical manuals
- Standardized inspection sheets
- Unique inspection codes
- Operator training
- Fundamentals toolkit installation

5S Workplace Organization

- Seiri: removal of unnecessary items
- Seiton: tool shadow boards, die storage layout
- Seiso: cleaning standards
- Seiketsu: visual standards and documentation
- Shitsuke: sustained discipline with weekly checks

Digitalization (Power Apps)

- Digital maintenance request submission
- Standardized forms
- Real-time status tracking
- Technician assignment
- Full traceability
- Central database integration

4. Results

This chapter presents the action and evaluation stages of the Action Research process. Based on the diagnosis carried out and the weaknesses identified in the maintenance management of the company's unit, an improvement proposal was designed, focused on the structured implementation of the Fundamentals program.

This program aims to promote operational excellence through the systematization of autonomous maintenance activities, the organization of workstations, and the effective recording of failures and anomalies. The proposal was based on adapting the Fundamentals methodology to the specific reality of the unit, following a practical approach that included the following lines of action:

- Asset criticality assessment, to define the pilot equipment;
- Adaptation of technical manuals and standardized inspection sheets, specific to each machine and adjusted to operational routines;
- Training of operators and teams, through training sessions and follow-up in the real work context;
- Organization of workstations according to 5S principles, promoting clean, functional, and safe environments;
- Digitalization of inspection and recording processes, through the development of a dedicated Power Apps application, enabling real-time data entry and information traceability.

4.1. Asset Criticality

Defining priorities within autonomous maintenance requires an objective diagnosis of the production reality, in order to ensure that the first improvement actions focus on the equipment with the greatest impact on operational performance. For this purpose, a critical analysis was carried out of the main assets in the converting area, with the aim of selecting the most suitable equipment to begin the implementation of the project. This analysis was based on the evaluation of six essential pieces of equipment in the converting process: DRO 1628 NT, MARTIN 924-1, MARTIN 924-2, BOBST 160-S, BOBST 1600, and BOBST 618 MINILINE. These assets were assessed according to a set of previously defined technical and operational criteria, with the aim of measuring not only the reliability of the equipment, but also the impact that its potential unavailability could have on the overall production performance. The following criteria were initially established for the criticality assessment:

- Number of work orders;
- Produced area (m^2);
- Average order size (m^2);
- Productivity (m^2/hour);
- MTBF (Mean Time between Failures);
- MTTR (Mean Time to Repair).

Based on the operational data extracted from the factory's internal system, OMP, a theoretical criticality classification matrix was developed, as presented in Table 2. This matrix makes it possible to classify each piece of equipment into classes A, B, or C, according to the degree of impact that each indicator represents in the production context. The definition of the criteria and their respective classification ranges was based on the accumulated experience of the planning teams and was adjusted to the specific reality of the converting unit under study. For aggregation purposes, classes A, B, and C were assigned scores of 3, 2, and 1, respectively, and the overall equipment criticality score was calculated as the sum of the six criterion scores.

Factors R (Reliability) and M (Maintainability) correspond to quantitative variables associated with the performance of corrective maintenance and were determined based on the MTBF and MTTR indicators. These two indicators make it possible to assess, respectively, the average time between failures and the average time required to restore the functionality of a piece of equipment after a breakdown occurs. In general terms, higher MTBF values and lower MTTR values reflect better asset performance, both in terms of reliability and response efficiency.

MTBF was used as a metric to assess the reliability of the assets in the converting area. Its calculation was based on the total operating hours during the period under analysis, divided by the total number of recorded failures. The observation period considered corresponded to the monthly average for the year 2024, excluding scheduled shutdown days and public holidays. Based on the unit's shift records, considering 8-h production cycles, it was possible to determine the total operating hours available.

Table 2. Equipment criticality classification matrix.

Factor	Indicator	Class A (High Criticality)	Class B (Medium Criticality)	Class C (Low Criticality)
P	Number of Work Orders	Above 200 orders/month.	Between 150 and 200 orders/month.	Below 150 orders/month.
S	Produced Area	Above 2 million m^2/month.	Between 1.5 and 2 million m^2/month.	Below 1.5 million m^2/month.
T	Average Order Size	Below 5000 m^2.	Between 5000 and 10,000 m^2.	Above 10,000 m^2.
PT	Productivity	Above 3500 m^2/h.	Between 3500 and 3000 m^2/h.	Below 3000 m^2/h.
R	Reliability	Less than 5 h.	Between 5 and 10 h.	Above 10 h.
M	Maintainability	Above 15 min.	Between 15 and 10 min.	Below 10 min.

In a complementary manner, MTTR was calculated based on the records of the corrective interventions carried out by the maintenance teams. This indicator represents the average time elapsed between the detection of a failure and the restoration of the equipment's normal operation. For its calculation, the total sum of repair times was used, divided by the number of recorded breakdowns. The main purpose of monitoring this indicator is to progressively reduce its value, promoting a faster and more effective response to occurrences. In addition to the

reliability and maintainability indicators, other factors were also considered within the scope of the criticality analysis, namely the number of maintenance requests, monthly production volume, average order size, and productivity in square meters per hour. These parameters, of a qualitative and operational nature, make it possible to assess the degree of demand and complexity to which each asset is subject. The criticality classification was carried out based on specific ranges for each indicator, as presented in the theoretical matrix previously illustrated (Table 2). The equipment was classified into distinct levels: Level A, associated with situations of high demand and impact; and Level C, corresponding to contexts of lower operational load or influence on production.

The integration of maintenance indicators with operational data made it possible to carry out a comprehensive assessment of the assets in the converting area, providing the basis for prioritizing improvement actions and for selecting the pilot equipment in the context of the implementation of autonomous maintenance. Thus, the MTBF and MTTR of all machines were computed, resulting in the values depicted in Table 3.

Table 3. 2024 monthly average MTBF and MTTR by machine.

Machine	MTBF [h]	MTTR [min]
MARTIN 924-1	8.43	24.84
MARTIN 924-2	7.41	25.40
BOBST 618 MINILINE	4.95	17.72
DRO 1628 NT	7.64	15.95
BOBST 160-S	17.33	16.4
BOBST 1600	20.54	10.2

Based on the values of the MTBF and MTTR indicators presented in Table 3, it is possible to identify significant variations in the performance of the equipment in the converting area, particularly with regard to failure frequency and average repair time. The BOBST 618 MINILINE machine shows the lowest MTBF value, with only 4.95 h between failures, which positions it as the equipment with the highest tendency for breakdowns during the period under analysis. In contrast, the BOBST 160-S and BOBST 1600 equipment show high levels of reliability, with MTBF values of 17.33 h and 20.54 h, respectively, reflecting substantially longer intervals between successive failures. With regard to average repair time, the highest MTTR values were recorded for the MARTIN 924-1 and MARTIN 924-2, with 24.84 and 25.40 min per intervention, respectively. These extended times may be associated with the internal configuration of the equipment or with the technical complexity of certain maintenance operations. However, it is important to highlight that these two machines show MTBF values above the sample average—8.43 h for the MARTIN 924-1 and 7.41 h for the MARTIN 924-2—which indicates a relatively moderate failure frequency. This behavior may be partially explained by the type of orders usually processed on the MARTIN 924 machines, which are characterized by large volumes and low technical complexity. This production profile favors more stable and repetitive operations, which contributes to reducing the probability of failures and is positively reflected in the reliability indicators. However, when breakdowns do occur, they tend to require longer interventions, which justifies the higher MTTR values. The DRO 1628 NT machine presents intermediate values for both indicators, with an MTBF of 7.64 h and an MTTR of 15.95 min, suggesting a balance between failure frequency and the time required for repair. Meanwhile, the BOBST 1600 stands out by simultaneously showing the longest interval between failures and the lowest average repair time (10.2 min), demonstrating robust performance in terms of both reliability and maintainability.

Table 4 presents the values corresponding to the number of processed work orders and the average order size for each of the six machines analyzed in the converting section. These indicators make it possible to assess the degree of demand and operational pressure to which each piece of equipment is subjected and are therefore considered determining factors in defining its criticality.

Table 4. 2024 monthly average of the number of work orders and order size per machine.

Machine	Number of Orders	Average Order Size [m^2]
MARTIN 924-1	219	5667
MARTIN 924-2	108	12,279
BOBST 618 MINILINE	197	6413
DRO 1628 NT	209	8659
BOBST 160-S	182	2625
BOBST 1600	62	3639

About the average number of monthly orders, MARTIN 924-1 stands out with a total of 219 orders, followed by DRO 1628 NT with 209 orders and BOBST 618 MINILINE with 197 orders. These three machines fall into Class A of the theoretical criticality matrix, showing a high volume of production orders. This operational intensity

translates into greater logistical complexity, increased setup frequency, and, consequently, a higher risk of wear or failure. BOBST 160-S also records a significant value (182 orders), placing it at the upper limit of Class B, which reinforces its classification as a highly utilized piece of equipment.

In contrast, MARTIN 924-2 and BOBST 1600 present significantly lower values, with 108 and 62 orders, respectively. These figures suggest less intensive use, corresponding to lower operational demand, and are therefore classified as having low criticality in this specific criterion.

Regarding average order size, an indicator considered to be inversely proportional to operational complexity (that is, smaller orders imply greater variability and higher demand), BOBST 160-S shows the lowest value (2625 m^2), followed by BOBST 1600 (3639 m^2) and MARTIN 924-1 (5667 m^2). These three machines handle, on average, smaller-sized orders, which implies a greater number of product changeovers, higher setup frequency, and greater variability in the production process. In particular, the value recorded by BOBST 160-S clearly places it in Class A of the criticality matrix for this factor.

On the other hand, MARTIN 924-2 presents the highest average order size (12,279 m^2), which, together with its low number of orders, reinforces its profile of low operational complexity, leading to its classification in Class C. DRO 1628 NT and BOBST 618 MINILINE present intermediate values, 8659 m^2 and 6413 m^2, respectively, placing them in Class B according to this criterion.

Table 5 presents the values relating to cumulative production (m^2) and average productivity (m^2/hour) of the main equipment in the converting section. These two indicators make it possible to evaluate, simultaneously, the degree of contribution of each machine to the unit's overall production volume and its operational efficiency per unit of time. From a critical perspective, equipment with high levels of production and productivity is particularly sensitive to unexpected stoppages, since its downtime represents a significant potential loss to the operation. Regarding total production volume, the DRO 1628 NT machine clearly stands out, with a cumulative total of 2,022,773 m^2, positioning it as the asset with the greatest weight in the factory's output. It is followed by MARTIN 924-2, BOBST 618 MINILINE, and MARTIN 924-1, with similar values (ranging between 1,333,000 m^2 and 1,391,000 m^2), which places them in Classes B or A of the theoretical criticality matrix, depending on the defined thresholds. Therefore, these assets represent a significant share of the unit's total production, which highlights the importance of ensuring high levels of reliability and availability.

In contrast, BOBST 160-S and BOBST 1600 record significantly lower production volumes, with 558,562 m^2 and 265,344 m^2, respectively. These values place them in Class C of the matrix, showing a lower contribution to the factory's overall volume and, consequently, lower criticality in this specific parameter.

As for average hourly productivity, the superiority of DRO 1628 NT is once again evident, with 4284 m^2/h, followed by MARTIN 924-2 (4046 m^2/h) and BOBST 618 MINILINE (3051 m^2/h). These values demonstrate high instantaneous production efficiency, which implies that any interruption in their operation may have a considerable impact on daily output. These machines should therefore be the focus of robust preventive and autonomous maintenance strategies, capable of minimizing the risk of unexpected failures.

Table 5. 2024 monthly average of productivity and production per machine.

Machine	Production [m^2]	Productivity [m^2/h]
MARTIN 924-1	1,333,357	2897
MARTIN 924-2	1,390,897	4046
BOBST 618 MINILINE	1,335,186	3051
DRO 1628 NT	2,022,773	4284
BOBST 160-S	558,562	1194
BOBST 1600	265,344	1267

On the other hand, BOBST 160-S and BOBST 1600 show low productivity levels (1194 m^2/h and 1267 m^2/h, respectively), which, combined with the low production volumes recorded, reinforce their classification as assets of reduced criticality in the criteria of volume and performance. This analysis makes it possible to consolidate the perception that the most demanding equipment from the point of view of production and productivity are DRO 1628 NT, MARTIN 924-2, and, to a lesser extent, BOBST 618 MINILINE. These machines are therefore particularly sensitive to breakdowns and operational failures, justifying increased attention in the context of maintenance.

Based on the individual classification of each piece of equipment according to the different criteria considered, namely number of orders, downtime, productivity, MTBF, among others, an ABC matrix analysis was then applied, as shown in Table 6, with the aim of ranking the assets according to their cumulative level of criticality. This methodology makes it possible to identify the equipment that, together, concentrates most of the operational risk of the converting unit, following the Pareto principle, according to which a small proportion of assets tends to

represent most of the productive impact. For this purpose, each piece of equipment was assigned a total criticality score, calculated based on the sum of the classifications obtained in each of the criteria analyzed individually.

Table 6. ABC matrix analysis of equipment criticality.

Equipment	P	S	T	PT	R	M
MARTIN 924-1	A	C	B	C	B	A
MARTIN 924-2	C	C	C	A	B	A
BOBST 618 MINILINE	B	C	B	B	A	A
DRO 1628 NT	A	A	B	A	B	A
BOBST 160-S	B	C	A	C	C	A
BOBST 1600	C	C	A	C	C	C

The application of the ABC analysis made it possible to consolidate, in an objective and systematic way, the prioritization of the equipment in the converting section based on their overall level of criticality. The results obtained highlighted DRO 1628 NT, BOBST 618 MINILINE, and MARTIN 924-1 as the assets with the highest operational criticality. For this reason, these three machines were selected for a more in-depth analysis in the following section. This selection aims to identify, in greater detail, which equipment is the most suitable to begin the implementation of the autonomous maintenance plan, ensuring that the actions developed generate the highest possible return in terms of reliability, performance, and impact on production.

The comparison of the equipment total criticality in the converting section, presented in Table 7, clearly confirms the priority of DRO 1628 NT within the scope of the implementation of autonomous maintenance. With a total of 16 criticality points, this equipment shows the highest value in the analysis, standing out consistently in the most relevant criteria, namely number of orders, production volume, productivity, and technical demand. Although BOBST 618 MINILINE also shows a high level of criticality, its strategic impact is more limited. This equipment is not responsible for high-value-added products, nor does it have high-quality printing capability, which reduces its priority in the intervention hierarchy.

In turn, MARTIN 924-1, despite presenting a significant number of orders, is usually associated with the processing of less complex and technically simpler orders, which justifies its classification at a lower level of criticality. Based on the objective sum of the factors analyzed, and also taking into account the strategic value of DRO 1628 NT as the only equipment with high-quality printing capability and the one responsible for the highest production volume in the unit, it can be concluded that this machine represents the most suitable choice for launching the autonomous maintenance plan. Its selection ensures the greatest potential return from the actions to be developed, both in terms of reliability and operational performance.

Table 7. Critical equipment selection matrix.

Equipment	Criticality	Conclusion
DRO 1628 NT	16	Most critical in almost all criteria, only capable of producing high-quality print.
BOBST 618 MINILINE	13	High technical criticality (low reliability and high maintainability).
MARTIN 924-1	12	Heavily used, with simple orders and lower impact.
MARTIN 924-2	11	Heavily used, with simple orders and lower impact.
BOBST 160-S	11	Moderate criticality.
BOBST 1600	9	Low criticality.

4.2. Implementation of the Fundamentals Program

Once the critical equipment for the pilot test had been identified—DRO 1628 NT—the first stage of the process began: the implementation of the Fundamentals program. This program is based on a logic of progressive operator accountability, assigning them the execution of basic maintenance tasks without, however, replacing the functions assigned to the specialized technical team. The main objective of Fundamentals is to promote a culture of prevention by encouraging the direct involvement of operators in the functional condition of the equipment, thereby contributing to increased reliability and the reduction of avoidable failures.

4.2.1. Creation of Manuals, Inspection Checklists, and Tool Kit

The implementation of the Fundamentals application on the DRO 1628 NT machine required the development and integration of a set of technical and operational supports to ensure that maintenance tasks could be carried out autonomously, safely, and in a standardized manner by the operators. This set is composed of three main elements: the machine's technical manual, the periodic inspection checklists, and the tool kit.

The technical manual is the central support document for autonomous maintenance. It was prepared based on the corporate template of the manufacturer and subsequently adapted to the operational reality of the production unit. The document was subject to an internal validation process and includes the identification of the machine, the implementation version, as well as the persons responsible for its review and approval, thereby giving it formal documentary value. The technical manual (Figure 4) is organized by the machine's functional modules (for example: feeder, printing unit, die-cutting unit, among others), with one page dedicated to each technical inspection point. For each inspection, the following elements are presented:

- Real images of the component to be inspected;
- Detailed description of the task to be performed;
- Visual indication differentiating the acceptable condition from the non-conforming condition;
- Recommended corrective actions;
- The frequency with which the task should be carried out;
- A unique inspection code (e.g., RDC.FE.BC.01.VW).

These inspection codes play a central role in the autonomous maintenance system, as they allow a direct association between each practical task and its respective technical content. The manual's index itself reflects this logic: each code is linked to a machine module and to a specific page, facilitating structured navigation and quick consultation by both operators and supervisors.

Excelência Técnica e Operacional

Folha de verificação - Introdutor

Data: __/__/____

Unidade	Tipo	Documento	Etapa	Dimensão	Frequencia	Valor Atual	Valor do Display	Valor de referência	Tolerancia	Necessita Ajuste
Rodas de vácuo	Verificação dos componentes básicos do introdutor	RDC.FE.BC.01.VW (Pág 1)	1	Rodas de entrada	Semanal			Novo/Bom/Aceitável/Necessita substituição	Aceitável	
			2	Altura das rodas relativa ao prato Introdutório (alimentação interrompida)	Semanal			Pelo menos 1mm	NA	
			3	Altura das rodas relativa ao prato Introdutório (posição introdutória)	Semanal			Pelo menos -1mm	NA	
Prato de alimentação	Verificação dos componentes básicos do introdutor	RDC.FE.BC.01.VW (Pág 1)	1	Condição do prato de alimentação	Semanal			Novo/Bom/Aceitável/Necessita substituição	Aceitável	
Rolo Introdutor	Verificação dos componentes básicos do introdutor	RDC.FE.BC.01.VW (Pág 1)	1	Condição do rolo introdutor	Mensal			Novo/Bom/Aceitável/Necessita substituição	Bom	
Todas	Paralelismo do batente traseiro do introdutor	RDC.FE.CA.01 (Pág 3)	1	Distância	Mensal			A=B	1 mm	
Todas	Paralelismo dos rolos de alimentação no introdutor	RDC.FE.CA.02 (Pág 4)	1	Espaço entre os rolos	Mensal			Lado motor = Lado operador/Valor físico = Dial	0,20 mm	
Todas	Paralelismo dos batedores do introdutor	RDC.FE.CA.03 (Pág 6)	1	Altura dos batedores	Mensal			Lado motor = Lado operador/Valor físico = Dial	0,20 mm	
			2	Paralelismo dos batedores	Mensal			Lado motor = Lado operador	0,20 mm	
Todas	Paralelismo dos batedores laterais do introdutor	RDC.FE.CA.04 (Pág 8)	1	Distância entre os calibradores	Mensal			A ≤ B	A ≤ B	
Folha de verificação - Unidade de impressão										
Rolo de borracha	Sistema de doseamento, camera, rasqueta e goma	PRI.AR.BC.03.CB (Pág 9)	1	Limpeza e estado	Semanal			Novo/Bom/Aceitável/Necessita Substituição	Limpo/Bom	
Todas	Limpeza geral da unidade de impressão	PRI.PU.BC.06.CB (Pág 11)	1	Estado dos rolos impressores	Semanal			Limpo/Sujo	Limpo/Boas condições	
			2		Semanal					
			3	Estado do sistema de vácuo	Semanal					
Secadores	Limpeza dos secadores de halogénio	PRI.AR.BC.07.CB (Pág 13)	(1-5)	Limpeza e estado	Semanal			Limpo/Sujo	Limpo/Boas condições	
			6	Verificação das cassetes	Semanal			Novo/Bom/Aceitável/Necessita Substituição	Bom	
Todas	Verificação do paralelimo do anilox com o diché	PRI.PU.CA.08 (Pág 16)	(1-2)	Paralelismo do rolo de goma / anilox	Mensal			Lado operador = motor / Valor físico = Dial	0,20 mm	
Todas	Verificação do paralelismo do rolo impressor com o rolo de introdução	PRI.PU.CA.02 (Pág 15)	(1-2)	Paralelismo do rolo impressor / contrapressão	Mensal			Lado operador = motor / Valor físico = Dial	0,20 mm	

Figure 4. Overview of the DRO 1628 NT technical manual (in Portuguese, as the original).

The manual pages also include intuitive visual cues, consisting of explanatory images, dimensional criteria, technical tolerances, and real photographic examples. This visual and practical approach facilitates the operators' understanding and the correct execution of the tasks.

In addition, physical pads of periodic inspection sheets were developed to support the recording of routine tasks carried out by operators. Each sheet makes it possible to document the operator's signature, the inspection date, the observed condition, and whether an adjustment or intervention is required. These pads are organized according to the frequency of the tasks (weekly, monthly, etc.) and include a standardized cover page, which facilitates the identification and control of the frequency of the inspections carried out. This standardization allows the supervision teams to quickly and effectively verify compliance with the established routines (see Figure 5).

Each inspection sheet contains columns dedicated to the parameters to be inspected, the reference values, and the inspection codes, the latter being the same as those included in the technical manual. This structure ensures a direct and systematic link between the recording of field inspections and the previously established technical knowledge base. Figure 5 presents an example of this type of sheet, illustrating detailed inspections carried out in the feeder and printing unit modules, thereby demonstrating the practical application of the methodology.

To ensure that all tasks could be carried out with full autonomy by the operators, a Fundamentals tool kit was made available and placed next to DRO 1628 NT, duly identified for exclusive use in inspection activities. This toolkit includes a set of essential tools, such as feeler gauges, standard wrenches, a rubber mallet, measuring tape, and cleaning consumables, all organized in an accessible and safe manner. The physical presence of this resource reinforces the principles of equipment ownership and operational discipline, which are central elements of the autonomous maintenance model, by encouraging the operators' direct responsibility for the machine's basic conditions.

Taken together, these materials represent the practical embodiment of the Fundamentals application, ensuring that autonomous maintenance routines are carried out in a coherent, traceable, and sustainable way. The systematic use of technical codes makes it possible to establish a cross-reference between field records and the reference documentation, facilitating not only the execution of internal audits but also the training of new operators and the scalability of the model to other equipment in the unit.

This approach represents a significant evolution compared to the informal methods previously adopted, promoting greater technical rigor, strengthening the culture of reliability, and encouraging the active involvement of the operational teams in the preservation and continuous improvement of productive assets.

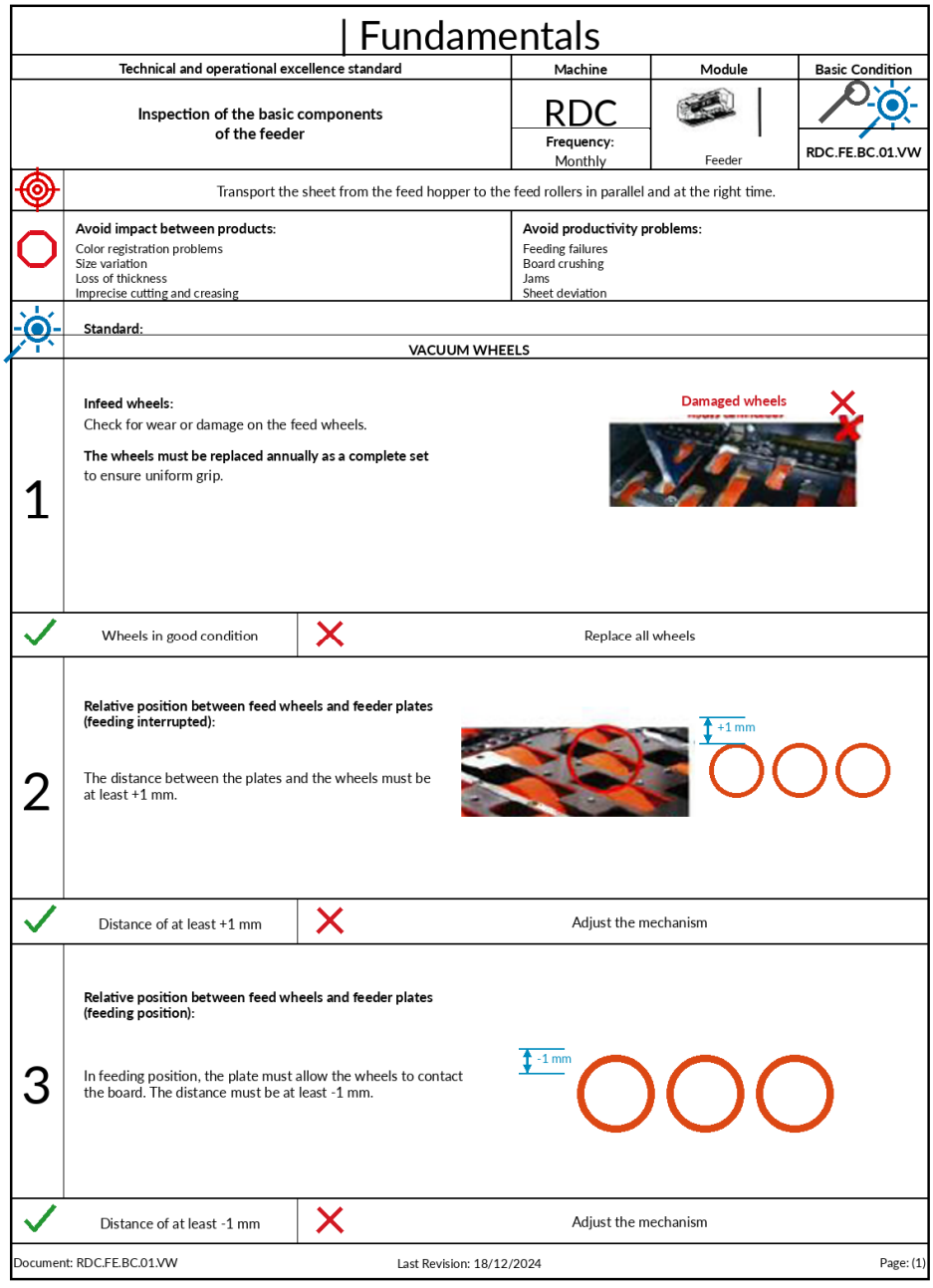


Figure 5. DRO 1628 NT inspection checklist sheet.

4.2.2. Preliminary Results

Despite the short duration of the pilot phase, the implementation of the Fundamentals program on the DRO 1628 NT machine revealed immediate and positive impacts on the production routine, both at technical and organizational levels. From a technical perspective, a significant increase was observed in the frequency of inspections carried out, as well as a clear improvement in the timely identification of anomalies and their communication to the maintenance team. This proactive action by the operators contributed to reducing recurring failures at critical points of the machine, resulting in greater operational stability.

At the same time, a stronger sense of operator responsibility was observed, associated with the practical ownership of the autonomous maintenance process. The presence of the technical manuals next to the machine, together with the inspection sheets and the tool kit, enabled the tasks to be carried out autonomously and in a structured manner. This infrastructure made it possible to eliminate previously identified constraints, such as the unavailability of resources or the absence of clear documentation, factors that had compromised the effectiveness of basic interventions.

Additionally, the sequential and standardized organization of the materials contributed to improving communication between shifts and reinforcing the standardization of operational routines. The existence of a physical record of the actions carried out, supported by technical coding and visual validation, encouraged knowledge transfer between teams and helped prevent the repetition of simple operational errors, an aspect that is particularly relevant in the context of continuous production. Overall, the preliminary results reinforced the importance of consolidating Autonomous Maintenance as a systematic and permanent practice within the unit. Furthermore, they confirmed the strategic value of effective communication between the production and maintenance areas. These early advances support the need to expand the program to other equipment, as well as its future integration with digital reporting systems, as will be explored in the following sections.

4.3. 5S in the Workplace

The implementation of the Fundamentals application required, in addition to the development of technical content and support materials, a parallel intervention in the physical and organizational conditions of the workstations. Within this context, the 5S methodology was applied, recognized as the foundation of the key pillars of the Total Productive Maintenance (TPM) model, whose function is to create organized, clean, and safe environments, thereby enhancing operational efficiency and team involvement.

5S is a methodology of Japanese origin composed of five sequential stages—Seiri, Seiton, Seiso, Seiketsu, and Shitsuke—which aim to transform the workplace into a functional, sustainable space oriented toward waste elimination, while ensuring standards of operational excellence. At the production unit, the application of this methodology was mainly focused on the support bench of the DRO 1628 NT machine, a central element in the execution of autonomous maintenance routines.

Before the intervention, the bench showed several operational and organizational problems: accumulation of obsolete equipment, improper storage of printing plates, lack of standardization in the arrangement of tools, absence of identification of work areas, and dispersion of materials due to the lack of defined storage locations. These conditions made the efficient execution of tasks more difficult and ran counter to the principles of discipline and organization promoted by autonomous maintenance.

The practical application of the 5S methodology was carried out in a planned and phased manner, based on a prior photographic survey and functional diagnosis, which made it possible to define an action plan aligned with the five pillars. Table 8 summarizes the main improvements implemented in each stage of the methodology, highlighting the gains achieved in the functionality and organization of the workstation.

As can be seen, each of the five pillars corresponds to a specific set of actions implemented with the aim of achieving a lasting transformation of the work environment. The improvements introduced were subsequently documented through comparative “before and after” images, making it possible to objectively highlight the visual and functional impacts of the intervention. The following topics describe in detail each of the stages of the 5S method applied to the DRO 1628 NT machine, highlighting the results achieved and their relevance in the context of autonomous maintenance.

While 5S is often presented as a qualitative workplace organization tool, its implementation in this study was also assessed in terms of its contribution to maintenance performance. To address this aspect and reduce the descriptive nature of the analysis, each 5S pillar was systematically linked to its operational impact and expected effects on key performance indicators. Table 8 presents this structured evaluation.

Table 8. 5S in the workplace.

5S Stage	Meaning	Objective	Actions	KPI Affected
Seiri	Sense of use	Eliminate what is unnecessary from each workstation.	Removal of obsolete or irrelevant tools, papers, and materials from the workstations.	MTTR ↓
Seiton	Sense of organization	Organize what is necessary in a logical and accessible way.	Definition of fixed and identified locations for each tool, using lables and supports.	MTTR ↓ / Productivity ↑
Seiso	Sense of cleaning	Ensure cleaning and regular inspection of the workplace.	Establishment of simple cleaning routines at the beginning and end of each shift, carried out by operators.	MTBF ↑
Seiketsu	Sense of standardization	Standardize working methods and conditions.	Common structure for all workbenches in terms of arrangement and visual signaling.	Reliability ↑
Shitsuke	Sense of discipline	Ensure continuity and systematic compliance with the previous 4S.	Placement of visual reminders, regular supervisor checks, and reinforcement of behavioral discipline.	All KPIs

4.3.1. Seiri—Sense of Use

The first stage of 5S focused on identifying and removing unnecessary materials from the support benches of the DRO 1628 NT machine, with the aim of eliminating elements that did not contribute to maintenance activities or that compromised workplace safety and efficiency.

A systematic assessment of the existing materials was conducted with operator involvement, leading to the removal of unused items such as empty boxes, obsolete equipment components, and non-functional structures. These elements occupied valuable space and hindered quick access to essential tools.

As part of this stage, a cabinet was installed to store work orders and operational documents (Figure 6), contributing to a cleaner, more organized, and functional workspace.



Figure 6. DRO 1628 NT workbench.

4.3.2. Seiton—Sense of Organization

After removing unnecessary materials, the Seiton stage focused on defining fixed locations for all required items to improve accessibility and consistency across shifts. A closed and organized tool board was installed next to the DRO 1628 NT machine (Figure 7), containing essential autonomous maintenance tools. Access was controlled through six keys assigned to shift supervisors, ensuring traceability and proper equipment management.

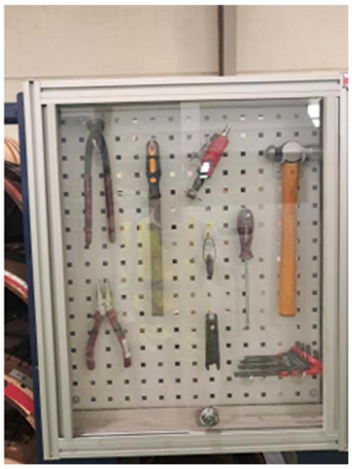


Figure 7. Organized toolbox.

Additionally, the storage system for cutting dies was reorganized by identifying and labeling the 20 most frequently used dies (Figure 8). These were relocated to a storage area next to the machine, replacing the previous distribution across multiple locations. This reorganization significantly reduced setup times and improved workplace efficiency.



Figure 8. Top 20 cutting dies for DRO 1628 NT.

4.3.3. Seiso—Sense of Cleaning

The third stage, Seiso, focused on standardizing cleaning practices for the workbenches and adjacent areas of the DRO 1628 NT to support operator well-being and enable early detection of anomalies. Cleaning routines, defined with operator involvement, were integrated into daily activities, reinforcing responsibility and workplace discipline. A key intervention was the reorganization of the printing plate cleaning area (Figure 9), which included deep cleaning, physical separation, and functional layout improvements, enhancing both safety and operational efficiency.



Figure 9. Organization and cleaning of the printing plate cleaning area.

4.3.4. Seiketsu—Sense of Standardization

This phase, corresponding to Seiketsu, aimed to ensure consistency and sustainability of the practices implemented in the previous stages. Short weekly meetings with shift supervisors were established to review progress, clarify doubts, and ensure alignment across shifts. Additionally, standardized storage (identified folders and covers) was introduced for cleaning documentation, ensuring easy access, proper organization, and compliance with traceability and quality requirements.

4.3.5. Shitsuke—Sense of Discipline

The final stage, Shitsuke, aimed to sustain the practices implemented by embedding them into daily routines and organizational culture. Weekly visual checks conducted by shift supervisors supported immediate feedback and correction of minor deviations. Operators were also encouraged to contribute improvement suggestions,

fostering continuous improvement and strengthening ownership and responsibility. This approach enabled the consistent maintenance of workplace standards without the need for formal corrective actions.

4.4. Process Digitalization

Following the improvements implemented in terms of autonomous maintenance and workstation organization, the need was identified to introduce a digital tool capable of structuring the reporting of technical failures, improving the traceability of interventions, and promoting more effective communication between operators and the maintenance team. In this context, a customized application was developed internally in Microsoft Power Apps, focused on the digital management of maintenance requests by machine and by shift, completely replacing the previous informal methods based on paper and verbal communication. This application is connected to a central database and was designed to be intuitive, accessible, and functional, even for users with limited familiarity with technology. The platform was structured into four main interfaces, which are detailed in the following subsections.

4.4.1. Request Overview—"My Requests" Page

This page, shown in Figure 10, represents the operator's individual consultation dashboard, where it is possible to view all maintenance requests submitted from the machine to which the user is assigned. The operator has direct access to the history and current status of each request and can therefore monitor its progress over time. Each request is displayed in a row, with fields organized by request title, equipment, level of urgency, submission date, request status, technical comments, and identification of the assigned electromechanical technician. To facilitate consultation and visual control, the requests are marked with a color code according to their status:

- Red: request not yet reviewed by the maintenance team:
- Yellow: request in progress, pending intervention, materials, or machine availability:
- Green: completed request, with technical comment recorded:

This functionality operates as a communication interface between departments, ensuring that operators have visibility over the progress of requests and preventing duplication or omissions.

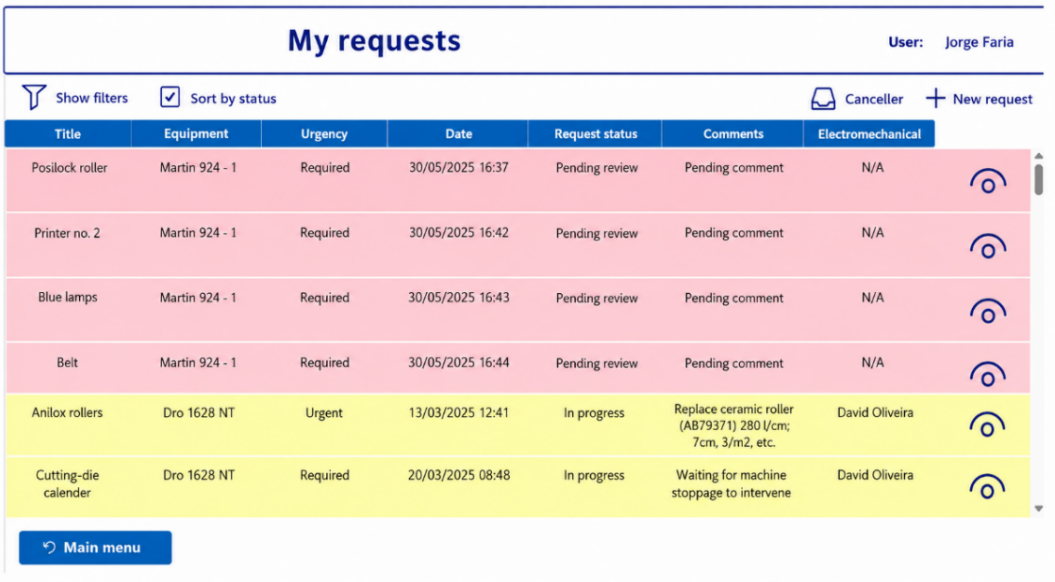


Figure 10. Request overview page.

4.4.2. Request Submission—"Submit a Request" Page

Requests are submitted through a page with a structured and interactive form, created to standardize the way anomalies are reported. The form contains the following mandatory fields:

- Request title: brief description of the problem (free-text field);
- Equipment: selected through a drop-down list, preloaded with the names of the factory machines;
- Location: selected through a drop-down list, preloaded with the machine compartments;
- Urgency: classification of the severity of the problem (e.g., required, urgent, as soon as possible);

- Detailed description: open field with guided completion instructions, suggesting examples of typical anomalies;
- Attachments: option to upload photos, documents, or screenshots (optional).

The use of drop-down fields makes submission faster, avoids spelling mistakes, and ensures uniformity in the database, making the application simple to use even for operators with limited experience with digital applications.

4.4.3. Request Management—"Request Management" Page

This page is accessible exclusively to the technical maintenance team. Here, the maintenance manager can view all active and completed requests, with the possibility of applying customized filters, such as:

- Date range;
- Current request status;
- Type of equipment;
- Level of urgency.

The interface allows requests to be sorted and segmented based on operational priorities, facilitating intervention planning and the allocation of technical resources. This functionality became particularly relevant in the management of critical machines, where there is a need to align production availability with the time required for maintenance. This interface introduced a level of control that previously did not exist, allowing management to have a consolidated and real-time view of the status of all reported anomalies.

4.4.4. Update and Feedback—"Request Management" Page

The final interface of the application allows the maintenance team to edit the requests received, updating their fields according to the progress of the intervention. This page displays the full request and allows users to:

- Change the status (pending review, in progress, completed);
- Insert technical comments explaining what was done or the reason for the delay;
- Record the response date;
- Assign the request to a specific electromechanical technician on the team.

This formalized feedback field to the user replaces the previous verbal communication, promoting transparency, historical recordkeeping, and improved trust between departments. Operators now receive clear and accessible information about the interventions, reducing doubts and facilitating accountability.

4.4.5. Overall Impact of Process Digitalization

The introduction of the application developed in Power Apps marked a turning point in the digital transformation of maintenance processes at the production unit, replacing the paper records and informal methods previously used. This solution, adapted to the reality of the factory, made it possible to eliminate traceability failures and reduce delays in resolving anomalies. One of the main impacts was the standardization of records through structured forms with mandatory fields and drop-down lists, ensuring consistency, legibility, and a lower likelihood of errors or information loss. The simple interface made the application accessible even to operators with limited digital experience.

The application also ensured full traceability by associating each submission with a user, date, and time, and by enabling real-time monitoring of request status, with visual signaling and updated technical comments, thereby promoting transparency and accountability. From the perspective of technical management, the filtering and sorting functionalities enabled supervisors to prioritize interventions based on objective criteria, optimizing planning and avoiding unnecessary downtime. This data-driven approach represents a significant improvement compared to the previous, more reactive model. In addition, the request editing page functioned as a formal communication channel between maintenance and production, making it possible to record comments and the status of interventions, which strengthened trust, follow-up, and cooperation between teams—factors that are fundamental to the success of autonomous maintenance within the scope of the Fundamentals program.

Finally, this digitalization contributed to the creation of a complete preventive and autonomous maintenance ecosystem, composed of:

- Standardized technical documentation (technical manuals);
- Routines with structured physical records (inspection sheets and checklist pads);
- And a centralized digital reporting and monitoring system (Power Apps).

4.5. Quantitative Analysis of Operational Indicators

Evaluating the effectiveness of the actions implemented by this work required a comparative analysis of the main operational indicators of the DRO 1628 NT machine, measured before and after the implementation of the Fundamentals application, the 5S methodology, and process digitalization through Power Apps.

For this analysis, monthly data collected between September 2024 and May 2025 were considered, extracted directly from the OMP platform, and validated by the technical team of the production unit. The selected indicators include productivity, reliability, and technical performance metrics, which are essential for assessing the impact of the actions on the overall functioning of the machine. The data are organized in Table 9, and their evolution will be analyzed in detail in the following paragraphs.

Table 9. Operational indicators by machine.

Indicators	09/24	10/24	11/24	12/24	01/25	02/25	03/25	04/25	05/25
[S]-Production [m^2]	2,003,149	2,066,130	1,868,537	1,654,111	2,018,037	2,150,263	2,201,456	2,314,831	2,340,321
[PT]-Productivity [m^2/h]	3974	4386	4077	4435	4279	4450	4369	4489	4529
[R]-MTBF [hours]	8.69	7.85	5.62	7.25	8.2	8.1	9.4	9.56	10.25
[M]-MTTR [min.]	20.0	22.0	25.0	26.0	30.0	19.58	12.54	14.33	11.35
[P]-no. of orders	198	208	182	155	180	193	167	177	219
[T]-Order size [m^2]	8998	9115	9391	9560	10,025	8684	10,001	8972	9872

Overall, the September 2024–May 2025 evolution demonstrates a clear improvement in both production and maintenance performance following the implementation phase conducted during November and December 2024, when production temporarily decreased as the new maintenance routines, standardized procedures, workplace organization practices, and digital support mechanisms were introduced. From the September 2024 baseline to May 2025, monthly production increased by 16.8% (2,003,149 to 2,340,321 m^2), productivity by 14.0% (3974 to 4529 m^2/h), and MTBF by 18.0% (8.69 to 10.25 h), while MTTR decreased by 43.3% (20.0 to 11.35 min). These improvements were achieved while the number of processed orders increased by 10.6% (198 to 219) and the average order size by 9.7% (8998 to 9872 m^2), indicating that the post-implementation gains were sustained under higher production demand rather than being associated with reduced operational load.

Before analyzing the individual indicators, it is important to clarify the distinction between productivity and production, as both metrics are complementary but represent different dimensions of operational performance. In this study, productivity refers to the output rate of the DRO 1628 NT machine, expressed in square meters per hour (m^2/h). It therefore measures how efficiently the machine converts available operating time into produced area. This indicator is directly influenced by factors such as machine speed, minor stoppages, setup stability, operator interventions, technical adjustments, and the reduction of avoidable losses.

By contrast, total production refers to the accumulated monthly output, expressed in square meters (m^2). This indicator reflects the final production volume achieved during each month and depends not only on productivity, but also on the number of effective operating hours, production planning, demand, order mix, and downtime. Therefore, an increase in productivity does not automatically lead to a proportional increase in monthly production if the available operating time is reduced. Conversely, production may increase even with stable productivity if the machine operates for more hours.

For this reason, the two indicators were analyzed together. Productivity was used to assess the efficiency of machine operation, while total production was used to evaluate whether the efficiency gains were effectively translated into higher monthly output. In simplified terms, monthly production can be understood as the result of the productivity rate multiplied by the effective operating time, although this relationship is also affected by stoppages, order characteristics, and planning conditions.

4.5.1. Productivity

Figure 11 presents the evolution of the monthly productivity of the DRO 1628 NT machine, measured in square meters per hour (m^2/h), over nine consecutive months. It can be seen that, after an initial phase marked by some instability, the productivity values show a sustained upward trend, clearly visible in the graph's trend line.

In September 2024, productivity was 3974 m^2/h. This value fluctuated in the following months, reaching a low point in November (4077 m^2/h). Following the implementation period conducted during November and December 2024, productivity showed an increasingly favorable trajectory, namely the introduction of the Fundamentals program and the reorganization of the workbenches according to the 5S methodology, the values became more consistent. In the months of 2025, greater stability and a gradual increase in efficiency can be

observed, with particular emphasis on April (4489 m^2/h) and May (4529 m^2/h), the latter recording the highest productivity peak of the period analyzed.

This growth can be explained by the progressive elimination of unplanned interruptions, the systematic execution of basic inspection tasks, and greater fluidity in the operation, resulting from the improved physical organization of the workstations and the reduction of unproductive time in preparation and minor adjustments.

The implementation of the Power Apps application, in turn, contributed to a faster maintenance response and greater predictability in the execution of corrective interventions, minimizing the impact of occasional failures on the production pace.

Thus, the analysis of this indicator confirms that the measures implemented produced consistent and measurable results in terms of productivity, providing a solid basis for the future consolidation of the autonomous maintenance methodology within the organization.

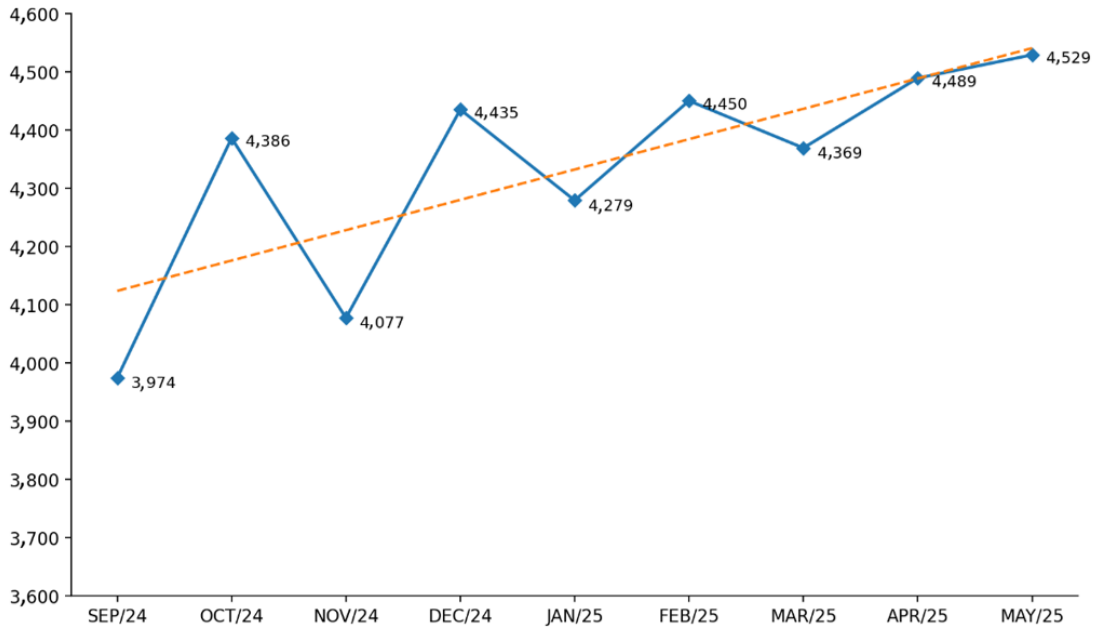


Figure 11. Productivity analysis (m^2/h).

The increase in productivity indicates that DRO 1628 NT became more efficient in transforming operating time into output. This improvement is particularly relevant because productivity is normalized by time and therefore reflects gains in operational efficiency rather than merely an increase in scheduled production hours. The observed improvement suggests that the implemented actions—autonomous maintenance routines, better workplace organization, standardized inspections, and faster anomaly reporting—contributed to reducing small stoppages, improving machine stability, and making production time more effective. However, productivity alone does not show the total volume produced. For this reason, its interpretation must be complemented by the analysis of monthly production, presented in the following section.

4.5.2. Production

Figure 12 presents the evolution of the total monthly production of the DRO 1628 NT machine, expressed in square meters (m^2), between September 2024 and May 2025. While productivity measures the output rate per hour, production represents the total volume effectively produced during each month. Therefore, this indicator makes it possible to assess whether the efficiency gains identified in Section 3.5.1 were translated into a higher accumulated output under real operating conditions.

As observed with productivity, total production also reveals an overall upward trend, particularly evident after the formal implementation of the improvement actions. This relationship suggests that the increase in productivity was not an isolated efficiency gain but was accompanied by a greater ability to generate production volume. In other words, the machine not only produced more efficiently per hour, but this improved efficiency also contributed to a higher monthly output when combined with better reliability, fewer unplanned stoppages, and more stable operating conditions.

As observed with productivity, this indicator also reveals an overall upward trend, particularly evident after the formal implementation of the improvement actions.

In the last months of 2024, marked fluctuations were recorded, with particular emphasis on the minimum value of 1,654,111 m^2 in December, immediately before the full implementation of the Fundamentals program and the 5S methodology. This period was characterized by recurring stoppages, the absence of systematized inspection routines, and operational disorganization. From January 2025 onward, a path of recovery and continuous growth can be observed, culminating in May 2025 with a total production of 2,340,321 m^2, the highest value of the period analyzed. This increase represents a gain of more than 40% compared to the most critical point (December), reflecting significant improvements in equipment reliability and in the management of productive time.

This performance is interpreted as the result of the combination of three main factors:

- Reduction of unplanned stoppages, thanks to the early identification of failures through autonomous maintenance;
- Improvement of the physical organization of the workstation, with easier access to tools and a functional and clean environment;
- More efficient planning of interventions, ensured by the introduction of the Power Apps application and the systematization of maintenance requests.

In addition to the increase in production volume, it is also important to note the stabilization of the process, with monthly values becoming more consistent and closer to the upward trend line, reinforcing the sustainability of the improvements implemented.

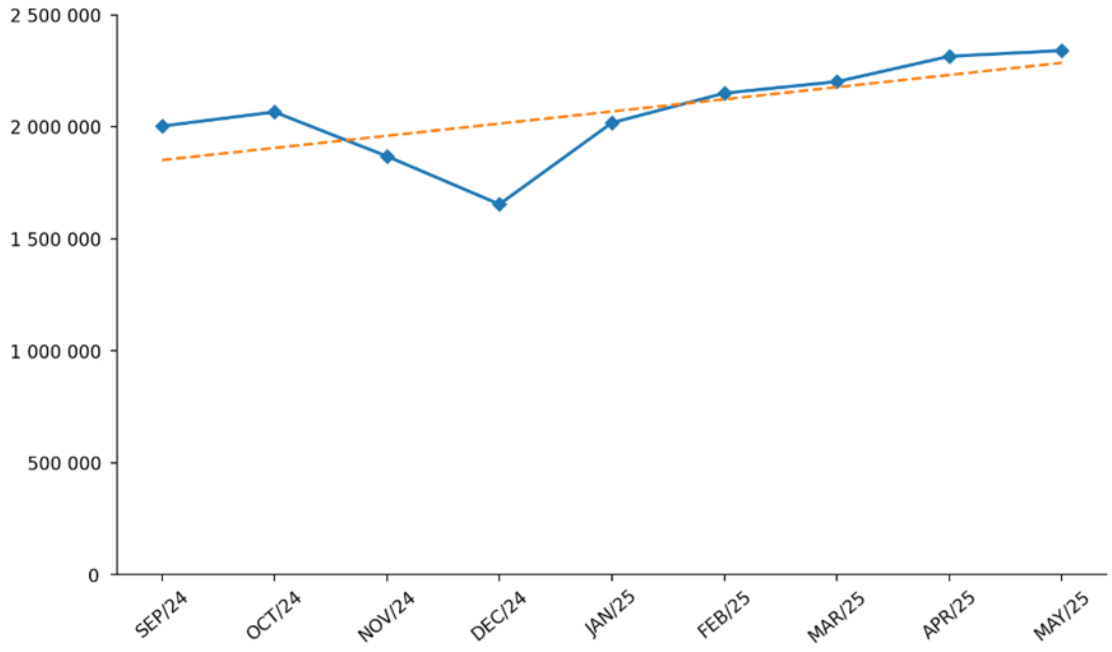


Figure 12. Production evolution (m^2).

Taken together, the evolution of productivity and production strengthens the evidence that the improvement program had a dual effect: it increased the efficiency of the machine during operating time and also supported a higher monthly production volume. This connection is particularly important because it shows that the maintenance improvements were not limited to technical reliability indicators, but also generated measurable operational benefits for the production system.

4.5.3. MTBF (Mean Time between Failures)

Figure 13 illustrates the evolution of the MTBF indicator, expressed in hours, which represents the average operating time of the machine between two consecutive failures. This indicator is fundamental for analyzing the operational reliability of the DRO 1628 NT machine, as it is directly influenced by preventive maintenance practices and autonomous inspection routines. Between September and December 2024, MTBF showed unstable behavior, reaching its lowest value of 5.62 h in November. This interval encompassed the baseline and implementation period, during which the structured maintenance practices were progressively introduced and had not yet reached operational stabilization.

From January 2025 onward, a reversal of the previous trend was observed, with MTBF progressively increasing to 10.25 h in May 2025, the highest value recorded during the analyzed period. Compared with the September 2024 baseline of 8.69 h, this corresponds to an 18.0% increase in MTBF, indicating improved operational reliability during the post-implementation period. This improvement is attributed to the adoption of the Fundamentals program, which established daily basic inspection routines carried out by operators, allowing the early detection and correction of minor deviations. At the same time, the organization of the workbenches according to the 5S methodology facilitated access to tools and eliminated sources of disorder that could lead to mechanical failures.

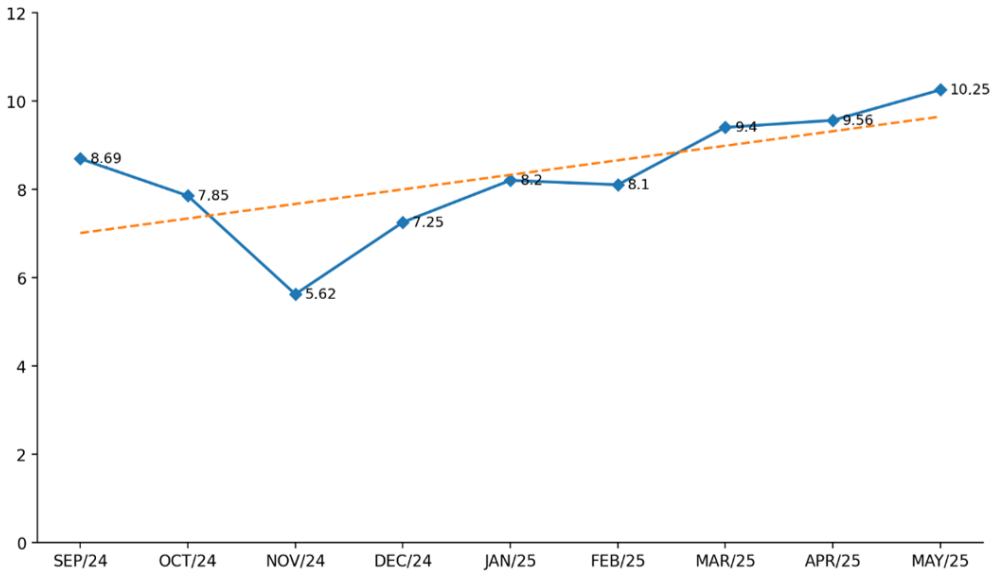


Figure 13. MTBF evolution (h) (mean time between failures).

The contribution of the Power Apps application should also be highlighted, as it enabled fast and structured communication of anomalies, allowing quicker and more effective intervention, while preventing the recurrence of failures that had previously been neglected.

The analysis of this indicator confirms that the implemented actions had a direct impact on the machine's reliability, contributing to greater production continuity and a reduction in unplanned technical interventions.

4.5.4. MTTR (Mean Time to Repair)

Figure 14 presents the evolution of the MTTR indicator, expressed in minutes, which represents the average time required to restore the functionality of the DRO 1628 NT machine after a failure occurs. This indicator directly reflects the effectiveness of the maintenance team and the organization's ability to respond quickly to unexpected events. During the last quarter of 2024, a gradual upward trend in MTTR was observed, culminating in a maximum value of 30 min in January 2025. This peak is associated with the accumulation of failures in equipment with insufficient preventive maintenance, poor communication between operators and the technical team, as well as the absence of structured intervention planning. From February 2025 onward, following the implementation and consolidation of the autonomous maintenance routines and digital maintenance-request system, MTTR showed a pronounced downward trajectory, reaching 11.35 min in May 2025, the lowest value of the analyzed period. Compared with the September 2024 baseline of 20.0 min, this corresponds to a 43.3% reduction in average repair time, indicating a substantial improvement in maintenance responsiveness during the post-implementation period.

This progress results from the combination of several factors:

- Structured and immediate submission of requests through Power Apps, with detailed description of the anomaly, urgency level, and visual attachments, allowing better prior preparation by the maintenance team;
- Clear assignment of responsibilities, with identification of the technician responsible for each intervention;
- Reduction of diagnosis time, facilitated by the standardization of operator reports and access to the digital request history;
- Immediate availability of tools and components, ensured by physical organization according to the 5S principles.

It is important to emphasize that this improvement did not compromise production volume, which confirms the real operational effectiveness of the interventions implemented. The positive evolution of MTTR, together with the MTBF results discussed in the previous subsection, demonstrates that maintenance began to operate in a more preventive, faster, and data-driven way, consolidating an effective response model that minimizes the impact of failures on production and maximizes equipment availability.

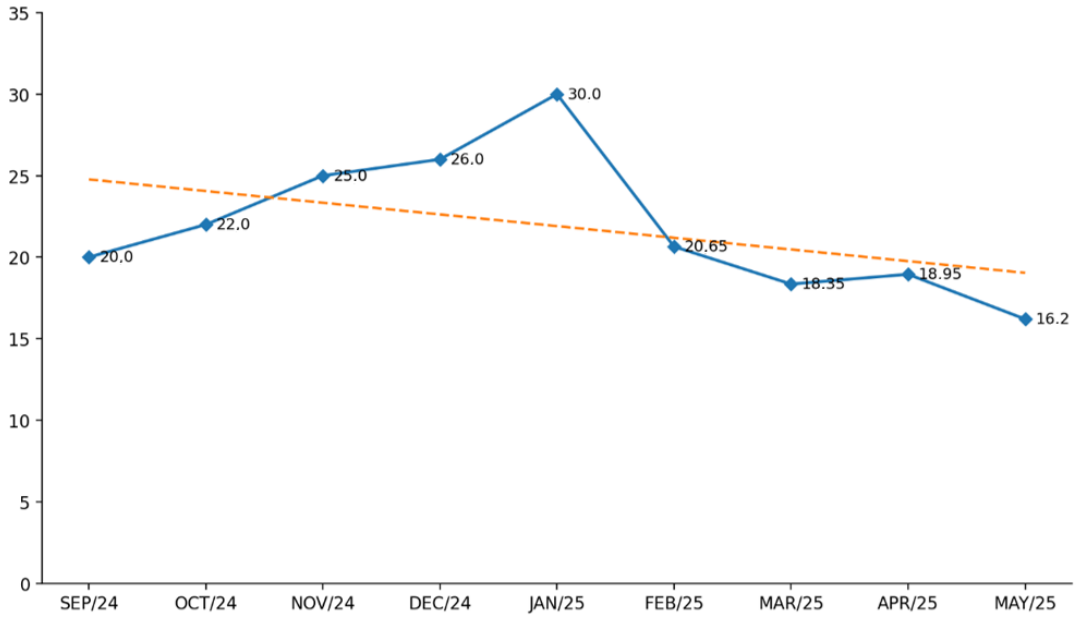


Figure 14. MTTR evolution (min) (mean time to repair).

5. Discussion

The case study results provide consistent evidence that the proposed concept for improving preventive maintenance management is valid in a real industrial environment. Rather than producing isolated improvements, the intervention was associated with measurable improvements in productivity, equipment reliability, and repair responsiveness, while qualitative observations indicated improvements in operator involvement, workplace organization, and production–maintenance communication. These results support the argument developed in the introduction that preventive maintenance becomes significantly more effective when it is structured through standardization, operator participation, prioritization logic, and digital support tools.

One of the clearest findings of the case study is that preventive maintenance performance improved when operators were more actively involved in routine maintenance-related activities. The implementation of autonomous maintenance principles through manuals, verification sheets, and basic inspection routines increased operator responsibility and contributed to more disciplined equipment monitoring. This result is strongly aligned with the literature on TPM and autonomous maintenance. Guariente et al. [16] showed that assigning operators a greater role in basic maintenance tasks improved equipment availability and OEE in an automotive context. The present case confirms the same underlying logic in a corrugated cardboard industrial environment: when operators are provided with clear instructions, simple control tools, and defined responsibilities, preventive maintenance becomes more stable and more effective. In this sense, the case study supports the practical relevance of autonomous maintenance not only as a theoretical TPM pillar but as a practical mechanism for strengthening equipment care and reducing maintenance vulnerability in day-to-day operations.

The observed increase in MTBF is consistent with the preventive nature of the proposed framework. The introduction of standardized inspection routines, operator involvement in autonomous maintenance, and systematic workplace organization increased the early detection of equipment deterioration before failures could develop into functional breakdowns. Rather than reducing failures through corrective interventions alone, the framework shifted maintenance toward proactive anomaly identification and routine stabilization, thereby extending the operating time between successive failures. This interpretation provides a plausible mechanism for interpreting the observed reliability improvements observed in the case study and complements the empirical MTBF results presented in the Results section.

The improvements observed in reliability indicators further reinforce this interpretation. The increase in MTBF and the reduction in MTTR suggest that the intervention did not merely improve documentation or internal

organization but actually enhanced the operational condition of the maintenance system. These results are particularly important because they indicate that the implemented changes contributed both to preventing failures and to improving the speed and effectiveness of response when breakdowns occurred. This is consistent with the findings of Pinto et al. [17], who showed that maintenance improvement initiatives supported by structured analysis and Lean tools can reduce inefficiencies and improve maintenance outcomes. It is also aligned with the results reported by Martins et al. [20], who found that a more structured preventive maintenance approach led to a substantial reduction in failures and better compliance with preventive plans. Therefore, the present case study supports the view that preventive maintenance improvement should be evaluated not only through qualitative perceptions of better organization, but also through measurable effects on reliability and maintainability.

The reduction in MTTR can also be interpreted as the consequence of improved organizational coordination rather than only faster technical repairs. Standardized maintenance documentation reduced diagnosis time, 5S workplace organization improved access to tools and spare parts, and digital maintenance requests accelerated communication between operators and maintenance technicians. Consequently, maintenance interventions became faster because delays associated with information transfer, task allocation, and preparation were substantially reduced.

Another important aspect of the case study concerns the role of standardization. The creation of maintenance manuals, support documents, and verification sheets was not merely an administrative exercise but a fundamental condition for improving execution consistency and operator autonomy. In practice, standardization reduced ambiguity, clarified responsibilities, and facilitated more systematic preventive routines. This is a highly relevant result because many maintenance inefficiencies in industrial settings arise not from a lack of technical competence, but from weak process discipline and inconsistent task execution. Pinto et al. [18,19] emphasized that TPM implementation requires more than maintenance planning alone; it depends on creating basic conditions of discipline, cleanliness, clarity of procedures, and operational control. The findings of the present study strongly support this perspective. The case demonstrates that standardization is not an accessory element of preventive maintenance management, but one of its structural enablers.

The workplace organization improvements introduced through 5S also played an important role in validating the concept. In the case study, 5S contributed to better organization of maintenance-related materials and work areas, helping create a more controlled and visually structured environment. Although 5S is often discussed as a general Lean tool, in this case, it functioned as a direct support mechanism for preventive maintenance, because it improved accessibility, reduced disorder, and reinforced routine discipline. This is consistent with TPM-oriented literature, particularly the work of Guariente et al. [16] and Pinto et al. [18,19], where organization and visual control were presented as essential preconditions for autonomous maintenance and process stabilization. The present case confirms that preventive maintenance performance is closely linked to the physical and organizational condition of the workplace. In other words, maintenance effectiveness depends not only on what is planned, but also on how the work environment supports execution.

The case study also validates the importance of using indicators as a basis for maintenance improvement. The comparison of maintenance performance before and after the intervention, using measures such as productivity, MTBF, and MTTR, allowed the effects of the implemented actions to be objectively assessed. This point is especially relevant because it places the improvement effort within a KPI-driven management logic rather than a purely anecdotal one. Literature has repeatedly emphasized that maintenance indicators are essential for monitoring performance, identifying losses, and guiding managerial decisions [8–10]. Pinto et al. [17] similarly highlighted the value of MTBF and MTTR in supporting maintenance improvement initiatives. The case study confirms this argument in a very practical way: without structured indicators, it would not have been possible to demonstrate that the implemented changes was associated with measurable operational improvements. Thus, the case validates the idea that maintenance improvement requires not only intervention but also measurement.

From a Lean perspective, the implemented maintenance improvements may also have contributed to reducing several forms of operational waste ("muda"), particularly waiting time associated with unexpected stoppages, unnecessary motion caused by disorganized workstations, overprocessing linked to repeated troubleshooting activities, and knowledge losses resulting from informal communication practices. Therefore, the proposed framework should not be interpreted solely as a maintenance initiative, but also as a broader operational stability and waste-reduction strategy.

The observed operational improvements should not be interpreted exclusively as the consequence of isolated technical interventions, but rather as the result of increased process discipline, improved standardization, enhanced operator awareness, and more effective communication between production and maintenance teams. This finding is consistent with the Lean philosophy, where sustainable performance improvement is frequently associated with the reduction of operational variability and the stabilization of routine execution conditions.

A particularly distinctive contribution of this case study lies in the digitalization of the maintenance request and support process through the implementation of Power Apps. The digital solution improved communication

between production and maintenance, enhanced traceability, and supported faster and more predictable intervention management. This is one of the elements that most clearly connects the case study to the more recent maintenance literature on digital support systems. Research on maintenance work progress monitoring has shown that visibility over task status and execution flow improves maintenance planning and responsiveness [27]. Likewise, digitalized manufacturing environments increasingly rely on decision support systems and smart maintenance logic to improve coordination and access to information [28–30]. The present case confirms these ideas at an applied level: even without advanced predictive technologies, the simple digitalization of maintenance communication and task handling created important operational benefits. This suggests that digital maturity in maintenance should not be understood only in terms of complex analytics, but also in terms of practical tools that improve flow, traceability, and responsiveness.

An additional relevant contribution of the study concerns the use of low-code digitalization tools as practical enablers of maintenance transformation in industrial environments with limited technological complexity or restricted investment capacity. Unlike highly sophisticated predictive maintenance architectures requiring advanced sensorization and AI-based analytics, the implemented Power Apps solution demonstrates that significant operational improvements may also be achieved through accessible, low-cost, and rapidly deployable digital infrastructures focused on communication standardization, traceability, and response management.

Beyond its operational contribution, the proposed digital solution also illustrates an alternative pathway towards maintenance digitalization that differs from conventional Industry 4.0 implementations. While many Industry 4.0 maintenance architectures rely on extensive sensor networks, Industrial Internet of Things (IIoT), digital twins, cloud platforms, and artificial intelligence for predictive maintenance, the present approach focuses on digitalizing maintenance workflows, communication, and knowledge management through an accessible low-code platform. Rather than replacing advanced digital technologies, this approach can be understood as a foundational stage of maintenance digital transformation, allowing organizations to establish structured data collection, standardized reporting, and digital traceability before investing in more sophisticated predictive solutions. This characteristic is particularly relevant for small and medium-sized enterprises (SMEs) and resource-constrained manufacturing environments, where financial, technical, and organizational barriers often limit the adoption of full Industry 4.0 infrastructures. Consequently, the proposed framework demonstrates that meaningful maintenance transformation can be achieved through pragmatic digitalization strategies that combine organizational change with affordable digital technologies, providing a scalable pathway towards future Industry 4.0 maturity.

Another relevant point is that the case study confirms the value of integrating different improvement approaches instead of relying on a single maintenance tool. The observed gains did not result solely from autonomous maintenance, or from 5S, or from digitalization taken separately. Rather, they emerged from the structured combination of asset prioritization, operator involvement, standardization, workplace organization, and digital communication support. This integrated character is one of the strongest aspects of the concept being validated. Literature often addresses these elements individually, but the case study shows that their combined implementation can generate mutually reinforcing effects. Operator involvement becomes more effective when supported by standard checklists; standardization becomes more useful when the workplace is organized; digital tools become more impactful when the process itself is already structured. The case, therefore, validates a systemic perspective on preventive maintenance improvement, in which organizational, technical, and informational elements must be developed together.

At the same time, the case study also helps clarify the practical meaning of preventive maintenance optimization. In many analytical studies, optimization is associated with mathematical scheduling, routing, or resource-allocation models [23–26]. While those contributions are important, the present case shows that in industrial practice, optimization may also take the form of reducing disorder, improving process discipline, increasing operator autonomy, and accelerating information flow. In this sense, the case broadens the practical interpretation of maintenance optimization. It demonstrates that relevant gains can be achieved not only through advanced quantitative models, but also through managerial and operational redesign of the maintenance system. This is particularly important for manufacturing companies where the main barriers to maintenance performance are still procedural and organizational rather than algorithmic.

The case also confirms that maintenance performance is highly dependent on the relationship between production and maintenance. The digital request system and the structured support documents improved communication, reduced ambiguity, and helped create better coordination between both functions. This is a critical contribution because many maintenance losses in industrial environments are not caused solely by technical failures, but by delays in reporting, incomplete information, poor prioritization, and fragmented communication. The improvements observed in the case, therefore, suggest that preventive maintenance management should be understood as an inter-functional process, not only as a maintenance department responsibility. This interpretation

is coherent with TPM principles and with broader maintenance-management literature, which emphasizes cross-functional responsibility for equipment performance [3,14,18].

Although the results strongly support the validity of the concept, the case study should also be interpreted within its contextual limitations. The findings derive from a specific industrial setting in the corrugated cardboard sector, with its own operational characteristics, organizational culture, and equipment constraints. For this reason, the exact magnitude of the improvements may not be directly transferable to other sectors. Nevertheless, the mechanisms behind the improvements appear robust and broadly consistent with the literature: clearer routines, greater operator involvement, better organization, stronger measurement, and improved information flow tend to support maintenance effectiveness across different industrial contexts [16,17,20]. Therefore, while the numerical outcomes may be context-dependent, the conceptual validity of the approach is reinforced by the coherence between the case results and previous empirical studies.

Overall, the case study validates the proposed concept by showing that preventive maintenance management can be significantly improved when it is approached as an integrated operational system rather than as a set of isolated maintenance tasks. The results confirm the relevance of autonomous maintenance, KPI-based monitoring, 5S, standardization, and digital support as mutually reinforcing components of a more reliable and responsive maintenance system. In this sense, the case does not merely illustrate the application of known maintenance tools; it demonstrates that their structured integration can produce measurable improvements in a real industrial environment. The study, therefore, contributes to bridging the gap between maintenance theory and practical implementation, especially in manufacturing settings where operational discipline and organizational structure remain decisive factors for maintenance success.

The results confirm that autonomous maintenance significantly improves equipment reliability when supported by:

- Standardized documentation,
- Clear visual controls,
- Operator training,
- Workplace organization.

The 5S improvements acted as a foundation for stable routines, consistent with prior literature [16–21].

Digitalization contributed to transparency and faster response, validating findings from studies on maintenance decision support systems [27–32].

The greatest improvements resulted not from isolated actions but from the combined effect of Lean, TPM, and digitalization, a synergy less explored in previous studies.

It is important to recognize that the implementation of autonomous maintenance does not automatically guarantee operational improvement. Its effectiveness strongly depends on organizational culture, operator engagement, management support, and the existence of standardized execution routines. In environments where production pressure systematically overrides maintenance discipline, the sustainability of autonomous maintenance practices may become difficult over time. Therefore, maintaining long-term gains requires continuous monitoring, supervision, and reinforcement of operational standards.

The contribution of this work should therefore not be interpreted as the isolated application of well-known Lean tools, but as the empirical validation of an integrated and sequential maintenance transformation logic. The case shows that autonomous maintenance becomes more effective when operators are supported by visual standards and technical checklists; 5S becomes more relevant when it directly supports maintenance execution; and digital tools become more valuable when they are connected to a previously standardized reporting and intervention process. This combination represents the main practical and academic contribution of the study, since it clarifies how established improvement tools can be operationally connected to produce measurable gains in reliability, maintainability, traceability, and production performance.

5.1. Framework Validation

Although all four components contributed to the observed maintenance improvements, their relative roles within the proposed framework are not equivalent. The results suggest that autonomous maintenance and standardized inspection routines constitute the primary drivers of reliability improvement by promoting early anomaly detection, increasing operator ownership, and reducing the progression of minor defects into functional failures. Asset criticality assessment played a strategic role by ensuring that improvement efforts were concentrated on the equipment with the greatest operational impact, thereby maximizing the effectiveness of the intervention. Digital traceability, although not directly responsible for improving equipment reliability, proved essential for integrating maintenance communication, recording operational knowledge, and supporting continuous performance monitoring. Likewise, the

implementation of 5S workplace organization stabilized routine execution and reduced operational variability, facilitating the consistent application of autonomous maintenance practices.

From a conceptual perspective, the framework should not be interpreted as a rigid sequence of isolated implementation stages. Instead, it represents an iterative maintenance-transformation architecture in which organizational learning, KPI monitoring, operator feedback, and digital traceability continuously reinforce subsequent improvement cycles. Although the framework was implemented sequentially during the intervention, its long-term operation follows a continuous improvement logic consistent with the PDCA philosophy. Furthermore, while the complete framework provides the greatest potential for sustainable maintenance transformation, some components—particularly the digital support tools—may be adapted or simplified according to the technological maturity and resource availability of different organizations, without compromising the fundamental maintenance principles on which the framework is based.

5.2. Industrial Application of the Integrated Maintenance Transformation Framework

The proposed framework was conceived not only as an analytical model but also as a practical guide for preventive maintenance transformation in manufacturing environments. Its implementation follows a structured sequence beginning with the diagnosis of the existing maintenance system and the identification of critical assets through a multi-criteria assessment. Once the pilot equipment has been selected, autonomous maintenance routines, standardized inspection procedures, and workplace organization practices are progressively introduced to establish stable maintenance processes before digitalization is implemented. This sequence helps ensure that digital technologies reinforce well-defined maintenance routines rather than compensate for poorly structured organizational practices.

From an industrial perspective, the framework provides maintenance managers with a structured roadmap for integrating organizational improvement, operator participation, standardized work, asset prioritization, and digital traceability within a unified maintenance system. Although the complete framework was validated in a corrugated cardboard manufacturing environment, its implementation logic is applicable to other manufacturing sectors because it is based on general maintenance management principles rather than sector-specific technical solutions. Organizations may also adapt the level of digitalization according to their technological maturity, beginning with accessible low-code platforms and progressively incorporating more advanced Industry 4.0 technologies as organizational capabilities evolve.

5.3. Transferability of the Proposed Framework

To evaluate the broader applicability of the proposed maintenance transformation framework, it is important to consider the extent to which its implementation can be transferred to different industrial contexts. Although the present study was conducted in a single corrugated cardboard manufacturing company and focused on one critical production asset, the proposed preventive maintenance transformation framework was intentionally designed around generic organizational and operational principles rather than equipment-specific technical solutions. The framework combines asset criticality assessment, autonomous maintenance, standardized work procedures, workplace organization through 5S, and digital maintenance traceability, all of which are widely applicable across discrete manufacturing environments. Consequently, the conceptual structure of the framework is expected to be transferable to other manufacturing sectors where production depends on critical equipment, repetitive operating routines, and close interaction between production and maintenance teams.

Nevertheless, successful replication requires several enabling conditions. These include management commitment, operator involvement, standardized maintenance procedures, adequate training, reliable performance indicators, and digital tools capable of supporting maintenance communication and traceability. Furthermore, the magnitude of the operational improvements should not be expected to be identical across industries, since equipment characteristics, production complexity, maintenance maturity, organizational culture, and resource availability differ substantially between industrial environments. Therefore, while the quantitative results reported in this study should not be directly generalized, the proposed framework provides a transferable maintenance improvement model that can be adapted to different manufacturing contexts according to their specific operational requirements.

5.4. Sustainability of the Proposed Framework

The long-term sustainability of the observed improvements is expected to depend on maintaining the organizational routines established during the intervention. Unlike isolated technical improvements, the proposed preventive maintenance transformation framework embeds maintenance activities into standardized daily routines supported by operator participation, digital traceability, KPI monitoring, and continuous feedback. These mechanisms

promote organizational learning, reinforce disciplined maintenance behavior, and facilitate continuous improvement, thereby increasing the likelihood that the observed gains in reliability and maintenance responsiveness can be sustained over time. Nevertheless, continued managerial commitment, periodic performance review, and reinforcement of operator engagement remain essential to preserve these benefits in the long term.

6. Study Limitations and Future Research

Although the results obtained demonstrate the practical effectiveness of the proposed maintenance improvement framework, some limitations of the present study should be acknowledged.

First, the intervention was conducted in a single industrial company and focused on one pilot asset (DRO 1628 NT), which may limit the direct generalizability of the results to other industrial sectors, production systems, or maintenance environments. Nevertheless, this limitation mainly concerns the quantitative magnitude of the observed improvements rather than the conceptual applicability of the proposed framework, whose transferability has been discussed in Section 5.3.

Second, the observation period after implementation was relatively short and constrained by the duration of the industrial internship during which the project was developed. Consequently, the long-term sustainability of the improvements obtained could not yet be fully assessed.

In addition, although substantial improvements were observed in productivity, MTBF, and MTTR, the study did not include formal statistical significance testing or multivariable sensitivity analysis capable of isolating the individual contribution of each implemented measure. The operational improvements should therefore be interpreted as the combined effect of the integrated Lean-based maintenance framework rather than as the isolated impact of a single tool.

Future research may extend the proposed framework through:

- longer monitoring periods,
- replication in other industrial environments,
- integration with predictive maintenance strategies supported by machine learning and digital twin technologies,
- application of statistical process control methods, and
- economic evaluation of maintenance-related savings and return on investment.

7. Conclusions

This study demonstrated that preventive maintenance management can be significantly improved when it is approached through an integrated combination of autonomous maintenance, standardization, workplace organization, asset prioritization, and process digitalization. Developed in a production unit of a major corrugated cardboard packaging manufacturer, the project focused on the DRO 1628 NT machine, the highest-ranked asset in the multi-criteria criticality assessment in the production system, and sought to increase equipment efficiency while reducing failures and improving maintenance responsiveness.

The case study confirmed that the proposed improvement approach was effective in a real industrial environment. The implementation of autonomous maintenance manuals, standardized verification sheets, 5S-based workplace organization, and a Power Apps solution for maintenance request traceability contributed to measurable gains in operational performance. The results obtained in the present study showed that the intervention was associated with a 14.0% increase in productivity, an 18.0% increase in MTBF, and a 43.3% reduction in MTTR, while also improving operator accountability, workplace conditions, and maintenance task management.

These results are especially relevant because they show that maintenance improvement did not depend on a single isolated tool. Instead, the benefits emerged from the structured integration of several complementary practices. The project showed that autonomous maintenance becomes more effective when operators are supported by clear documents and routines; that 5S reinforces maintenance discipline by improving organization and visual control; and that digital tools such as Power Apps can strengthen communication, traceability, and response speed in the interaction between production and maintenance. In this sense, the study supports a broader view of preventive maintenance as an operational system that must combine technical, organizational, and informational dimensions.

From a theoretical perspective, this study contributes to maintenance management literature by conceptualizing preventive maintenance transformation as the coordinated interaction of organizational, technical, and digital capabilities rather than as the isolated implementation of maintenance tools. The proposed framework extends current TPM- and Lean-based maintenance research by explaining the mechanisms through which asset prioritization, autonomous maintenance, workplace organization, and digital traceability collectively strengthen preventive maintenance capability.

Beyond its practical implications, this study contributes to the understanding of preventive maintenance transformation by showing that substantial improvements emerge from the coordinated interaction of organizational routines, operator involvement, standardized work, asset prioritization, and digital traceability, rather than from the isolated implementation of Lean or TPM practices. The proposed framework therefore provides a transferable conceptual perspective that explains how these complementary practices can be systematically integrated to strengthen preventive maintenance capability. Although empirically evaluated in a corrugated cardboard manufacturing environment, this perspective requires further assessment across additional industrial contexts before broader generalization.

From a managerial perspective, the study also highlights that preventive maintenance should be managed through performance indicators and not only through reactive intervention records. The use of operational indicators such as productivity, MTBF, and MTTR made it possible to objectively assess the effects of the implemented changes and demonstrate that the project produced consistent improvements. This reinforces the importance of KPI-based monitoring as a necessary support for maintenance decision-making and continuous improvement.

Although the results are positive, some limitations should be acknowledged. The study was developed in a single industrial unit and focused primarily on one critical machine, which means that the magnitude of the results may be influenced by the specific operational context of the production unit. In addition, the evaluation period covered a limited time horizon, which means that the long-term sustainability of the improvements still requires continued monitoring. The digital solution implemented also represented an important first step, but not yet a fully integrated maintenance information system. For these reasons, caution should be taken when generalizing the numerical results directly to other contexts.

Future work should therefore focus on consolidating and extending the approach. A priority is the replication of the autonomous maintenance model, verification sheets, and organizational standards to other machines in the unit. A second direction is the continued development of the digital maintenance process, including stronger data integration and broader analytical support for planning and prioritization. It would also be valuable to evaluate the long-term effects of the implemented practices on overall equipment performance and maintenance culture, as well as to explore the integration of more advanced monitoring or predictive approaches in the future. These developments would help strengthen the transition toward a more autonomous, visual, and digitally integrated maintenance system.

More fundamentally, the findings indicate that preventive maintenance transformation should be understood primarily as a socio-technical integration challenge rather than merely as a maintenance-management problem. Sustainable improvement depends on the coordinated alignment of organizational routines, operator engagement, standardized work practices, digital support systems, and technical maintenance activities.

Overall, the study concludes that improving preventive maintenance in industrial environments requires more than technical interventions alone. It requires structured routines, engaged operators, clear standards, organized workplaces, measurable indicators, and effective information flow. The case of this company shows that when these elements are combined coherently, preventive maintenance can become more reliable, more responsive, and more closely aligned with the operational needs of production.

The results obtained suggest that significant maintenance-performance improvements do not necessarily require highly complex predictive maintenance systems as a first industrial step. In many manufacturing environments, substantial gains may already be achieved through the disciplined integration of standardized preventive routines, operator-centered maintenance practices, workplace organization, and accessible digital support systems.

Author Contributions

R.C.: conceptualization; R.C., I.M.P.: methodology; I.M.P., A.F.V.P., R.C., R.L.: data curation, visualization; R.L.: writing—original draft preparation; J.F.: investigation; R.C.: supervision; I.M.P., R.L., A.F.V.P.: validation; I.M.P., R.C., A.F.V.P.: writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used ChatGPT to improve the quality of figures and tables. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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