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A Case Study on Integrating Lean, TPM, and RCM to Improve Equipment Availability in Peruvian Metalworking SMEs

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Abstract

This study addresses the persistent issue of low equipment availability in Peruvian SMEs within the metalworking industry. Previous research has highlighted the need for tailored maintenance strategies to enhance operational efficiency in similar contexts. This investigation focused on a small company specializing in office furniture manufacturing, which faced recurring downtime and insufficient maintenance practices. The proposed model integrated Lean Manufacturing, Total Productive Maintenance (TPM), and Reliability-Centered Maintenance (RCM) to foster sustainable improvements. Key actions included implementing autonomous maintenance for early fault detection, prioritizing equipment reliability through RCM, and establishing standardized maintenance procedures. Quantitative results demonstrated an 11.80% increase in equipment availability and a 20.73% reduction in cycle time. These enhancements not only improved productivity but also contributed to employee engagement and a proactive maintenance culture. Future research is encouraged to explore similar models in other SMEs, addressing sector-specific challenges and fostering industrial resilience in dynamic markets.

Keywords
Lean Manufacturing, Total Productive Maintenance, Reliability Centered Maintenance, Equipment Availability, Metalworking SMEs.

1. Introduction
Exploring the role of small and medium-sized enterprises (SMEs) in the metalworking industry is fundamental to understanding their impact on the global economy, especially in Latin America and Peru. This sector is crucial, as it represents a significant portion of industrial production and employment in many emerging economies. According to the International Labour Organization (ILO), SMEs are responsible for approximately 70% of employment in Latin America, highlighting their importance in income generation and economic stability (Vaidyanathan et al. 2012). In Peru, metalworking SMEs not only contribute to the national economy but are also essential to the supply chain of

various industries, from construction to advanced manufacturing (Sun & Gong 2020). The relevance of this sector is reflected in its ability to adapt to market demands and foster innovation, which is vital in a constantly changing economic environment (Kutschenreiter-Praszkiewicz 2020).

However, metalworking SMEs face numerous challenges, particularly in terms of production. One of the most critical issues is the low availability of machines in the production process, caused by poor maintenance management and a lack of standardization in production processes (Udroiu & Braga 2020). Research has shown that inefficiency in maintenance management can lead to significant downtime, directly impacting productivity and profitability (Stinga et al. 2020). Additionally, the lack of process standardization can result in variations in product quality and operational efficiency, which in turn may limit the competitiveness of SMEs in a globalized market (Pérez-Pérez et al. 2018). Therefore, addressing these issues is imperative to ensure the sustainability and growth of metalworking SMEs.

Addressing these issues is crucial, as improving machine availability and process standardization can lead to a significant increase in operational efficiency and product quality (Pérez-Campos et al. 2015). Implementing methodologies such as Lean Manufacturing, Total Productive Maintenance (TPM), and Reliability-Centered Maintenance (RCM) may be key to solving these challenges (Makua 2023). These methodologies not only promote efficiency and waste reduction but also foster a culture of continuous improvement within organizations (Habiba 2024). Adopting these practices can result in a notable improvement in the competitiveness of metalworking SMEs, enabling them not only to survive but to thrive in an increasingly demanding industrial environment (Choi et al. 2016).

Despite the growing literature on improving efficiency in metalworking SMEs, there is a significant knowledge gap in the practical application of these methodologies in specific contexts such as Peru (Haapala et al. 2013). The proposed research seeks to address this gap by developing a production model that integrates Lean Manufacturing, TPM, and RCM tools, adapted to the specific needs and characteristics of metalworking SMEs in the region (Rodríguez-Panes et al. 2018). This approach will not only provide a solid theoretical framework but also offer practical guidelines for effectively implementing these methodologies in the local environment (Thongbunchum et al. 2022). In doing so, it is expected to contribute to the sustainable development of metalworking SMEs, improving their ability to compete in the global market and fostering innovation and economic growth in Peru (Boseila 2024).

In conclusion, the importance of the metalworking SME sector is undeniable, and addressing their production issues is essential for their sustainability and growth. Research in this field will not only fill a critical gap in the literature but also provide a clear path towards improving efficiency and competitiveness in a sector vital to the economy of Peru and Latin America as a whole.

2. Literature Review

2.1 Lean Manufacturing in Metalworking SMEs

The Lean Manufacturing methodology has been the subject of numerous studies highlighting its effectiveness in process improvement within metalworking SMEs. This methodology focuses on waste elimination and resource optimization, resulting in more efficient production. For example, Dahab et al. (2023) conducted a study demonstrating how Lean implementation can improve overall equipment efficiency in an SME, leading to a significant increase in productivity (Dahab et al. 2023). Additionally, Maware et al. (2021) conducted a systematic review that concluded that SMEs adopting Lean practices experience improvements in product quality and reductions in cycle times, which are crucial to staying competitive in a constantly changing market (Maware et al. 2021).

Another important aspect is the adaptability of SMEs to Lean practices. According to Alexander et al. (2019), SMEs in the construction sector have shown that adopting Lean Six Sigma can be particularly beneficial, as it combines waste reduction with quality improvement, which is also applicable to metalworking (Alexander et al. 2019). This integrated approach enables companies not only to improve their internal processes but also to better meet customer demands, which is essential in a highly competitive environment.

Furthermore, a study by Mijatović et al. (2019) highlights that the implementation of Lean Six Sigma in metalworking SMEs not only improves operational efficiency but also fosters a culture of continuous improvement among employees, which is vital for the sustainable growth of the company (Mijatović et al. 2019). This cultural shift is a key component for the long-term sustainability of Lean practices, as it involves all organizational levels in the pursuit of operational excellence. Finally, a comparative analysis by Mijatović et al. (2019) suggests that SMEs implementing Lean Manufacturing not only achieve immediate efficiency improvements but also establish a solid foundation for future innovation, enabling them to adapt to market trends and new technologies (Mijatović et al.2019). This is particularly relevant in the current context, where adaptability is essential for SMEs' survival in a rapidly evolving industrial environment.

2.2 Standardized Work in Metalworking SMEs

Standardized work is another crucial methodology proven effective in process improvement within metalworking SMEs. This methodology involves creating clear procedures and protocols that guide employees in their daily tasks, resulting in greater consistency and production quality. According to a study by Kurniasih (2023), SMEs that implement standardized work practices report a significant reduction in production errors and an increase in customer satisfaction (Kurniasih 2023). This is because standardization allows workers to perform their tasks more efficiently and with less variability.

Moreover, standardized work facilitates the training of new employees, which is especially important in the SME context, where training resources may be limited. A study by Le and Chu (2023) highlights that companies adopting clear standards for their processes can more easily integrate new employees, reducing adaptation time and improving overall productivity (Le & Chu 2023). This approach benefits the company in terms of efficiency and contributes to a safer, more organized work environment.Implementing standardized work is also associated with continuous improvement. According to an analysis by Trifković (2017), SMEs establishing clear, measurable standards can more easily identify areas for improvement and systematically apply changes (Trifković 2017). This creates a feedback cycle that fosters innovation and process optimization, essential for maintaining competitiveness in an ever-evolving market.

Lastly, a study by Faeni et al. (2019) suggests that standardized work not only improves operational efficiency but also has a positive impact on employee morale by providing clarity and structure in roles and responsibilities (Faeni et al. 2019). This is fundamental to fostering a positive work environment, which in turn can lead to greater talent retention and better organizational performance.

2.3 Total Productive Maintenance (TPM) in Metalworking SMEs

Total Productive Maintenance (TPM) is a methodology aimed at maximizing equipment efficiency through the involvement of all employees in the maintenance process. This methodology has proven particularly effective in the context of metalworking SMEs, where equipment availability and performance are critical to production. According to a study by Mustafa et al. (2018), TPM implementation in SMEs has led to significant improvements in operational efficiency and reduced maintenance costs (Mustafa et al. 2018). This is because TPM promotes a proactive approach to maintenance, rather than a reactive one, minimizing unplanned downtime.

Additionally, TPM fosters a culture of shared responsibility among employees, which is essential for its success. An analysis by Antony et al. (2019) highlights that SMEs adopting TPM achieve greater employee engagement in equipment maintenance, which not only improves efficiency but also boosts staff morale and commitment (Antony et al., 2019). This sense of ownership can be a determining factor in TPM's effectiveness, as employees feel more motivated to care for and maintain equipment.The implementation of TPM is also associated with improved product quality. According to a study by Díaz et al. (2014), SMEs applying TPM experience a reduction in production defects, resulting in higher customer satisfaction and a better market reputation (Schreck 2015). This is especially relevant in the metalworking industry, where product quality is a critical success factor.Finally, a study by Valdez-Juárez et al. (2019) suggests that TPM not only improves efficiency and quality but also contributes to the long-term sustainability of metalworking SMEs by reducing waste and optimizing resource use (Domenech et al. 2022). This sustainable approach is increasingly important in a business environment where environmental responsibility is a growing priority.

2.4 Autonomous Maintenance in Metalworking SMEs

Autonomous Maintenance is a practice that enables machine operators to take responsibility for the basic maintenance of the equipment they use. This methodology has proven effective in improving operational efficiency in metalworking SMEs. According to a study by Mijatović et al. (2019), the implementation of Autonomous Maintenance in SMEs has led to a significant reduction in downtime and an increase in equipment availability

(Mijatović et al. 2019). This is because operators, being more involved in maintaining their machines, can identify and resolve minor issues before they escalate into major failures.

Moreover, Autonomous Maintenance fosters a more collaborative and empowered work environment. An analysis by Kılıç and Uyar (2017) suggests that when employees are trained to perform maintenance tasks, they feel more valued and engaged with their work, which can lead to higher job satisfaction and lower staff turnover (Kılıç & Uyar 2017). This sense of empowerment is crucial for the success of Autonomous Maintenance, as employees become advocates for efficiency and quality in their respective areas.

Implementing Autonomous Maintenance also contributes to continuous improvement. According to a study by Valdez-Juárez et al. (2019), SMEs adopting this methodology can establish feedback loops that allow them to identify areas for improvement and apply changes systematically (Domenech et al. 2022). This not only improves operational efficiency but also creates a work environment where innovation and improvement are integral to the organizational culture.Lastly, a study by Faeni (2016) highlights that Autonomous Maintenance not only improves efficiency and quality but also contributes to the long-term sustainability of metalworking SMEs by reducing waste and optimizing resource use (Faeni 2016). This sustainable approach is increasingly important in a business environment where environmental responsibility is a growing priority.

2.5 Reliability-Centered Maintenance (RCM) in Metalworking SMEs

Reliability-Centered Maintenance (RCM) is a methodology focused on ensuring that systems continue to do what their users require in their operational context. This methodology has proven effective in improving the reliability and availability of equipment in metalworking SMEs. According to a study by Mbonyane et al. (2023), RCM implementation in SMEs has led to a significant reduction in maintenance costs and an increase in operational efficiency (Mbonyane et al. 2023). This is because RCM allows companies to prioritize maintenance efforts based on equipment criticality and its functions.Furthermore, RCM promotes a culture of continuous improvement and organizational learning. An analysis by Bondonio et al. (2022) suggests that SMEs adopting RCM can establish feedback processes that proactively identify and address issues, resulting in greater reliability and efficiency (Bondonio et al. 2022). This proactive approach is essential for maintaining competitiveness in a constantly changing industrial environment.

RCM implementation is also associated with improved product quality. According to a study by Díaz et al. (2014), SMEs applying RCM experience a reduction in production defects, which translates into higher customer satisfaction and a better market reputation (Schreck 2015). This is especially relevant in the metalworking industry, where product quality is a critical success factor.Finally, a study by Umar and Kunda-Wamuwi (2019) highlights that RCM not only improves efficiency and quality but also contributes to the long-term sustainability of metalworking SMEs by reducing waste and optimizing resource use (Umar & Kunda-Wamuwi 2019). This sustainable approach is increasingly important in a business environment where environmental responsibility is a growing priority.

The literature review on the application of continuous improvement methodologies in the production process of metalworking SMEs reveals that implementing Lean Manufacturing, standardized work, TPM, Autonomous Maintenance, and RCM can lead to significant improvements in efficiency, quality, and sustainability for these companies. Each of these methodologies offers a unique approach to addressing the challenges faced by SMEs in a competitive and ever-evolving industrial environment. Adopting these practices not only enhances productivity and product quality but also fosters a culture of continuous improvement and employee empowerment, which is essential for the long-term success of metalworking SMEs.

3. Methods

3.1 Basis of the Proposed Model

In figure 1, a maintenance management model is presented, based on the integration of Lean Manufacturing, Total Productive Maintenance (TPM), and Reliability Centered Maintenance (RCM) tools. This model was designed to increase equipment availability in a small metal engineering company, addressing common issues of low availability such as the absence of basic maintenance, an inadequate maintenance plan, and non-standardized production processes. The implementation began with autonomous maintenance, a key principle of TPM, involving operators in basic preventive maintenance tasks, allowing for early detection of failures and reducing downtime. Subsequently, the principles of reliability-centered maintenance were applied, which optimized maintenance plans based on the criticality of equipment and its impact on operations. The final stage involved standardized work, built upon best practices identified during the improvement process. This approach contributed to increased equipment availability by developing adequate maintenance plans aligned with operational reality and standardizing production processes, ensuring continuous and sustainable improvement in the company's operations.

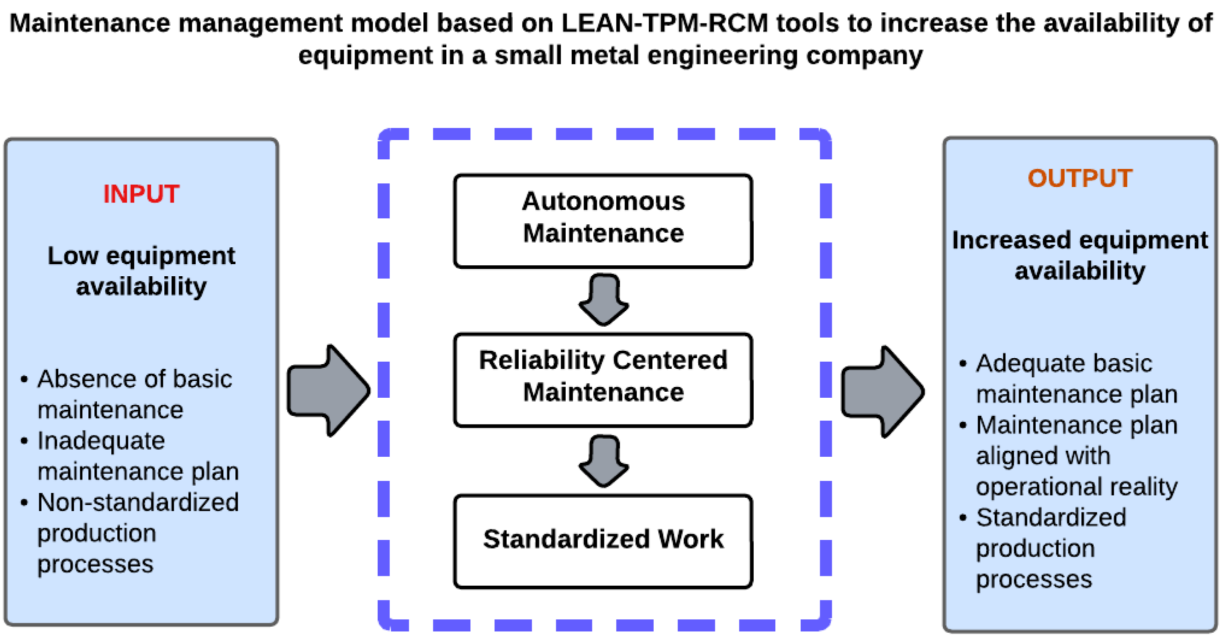


Figure 1. Proposed Model

3.2 Description of the model components

The proposed model, illustrated in the attached figure, is based on the integration of three key approaches within industrial engineering: Lean Manufacturing, Total Productive Maintenance (TPM), and Reliability Centered Maintenance (RCM). This model emerged as a response to the needs identified in small companies within the metal engineering sector, where equipment availability is often low due to the lack of adequate maintenance, the absence of standardized production processes, and deficient maintenance plans. The relevance of this model lies in its ability to address these issues from a holistic perspective, integrating proven tools that not only increase equipment availability but also enhance operational efficiency and the sustainability of the production system.

The model was designed for a small metal engineering company, focusing on addressing recurring issues of low equipment availability that negatively impacted the company's production capacity. During the initial diagnostic phase, several deficiencies were identified, which were grouped into three categories: the absence of basic maintenance, the lack of an adequate maintenance plan, and non-standardized production processes. These conditions led to a high frequency of equipment failures and prolonged downtime. The model's proposal was based on the implementation of autonomous maintenance, followed by reliability-centered maintenance (RCM), and standardized work through the use of Lean tools, which allowed for the establishment of a more robust maintenance plan aligned with the company's operational reality. Figure 1 shows the sequence of the model's phases, with their corresponding inputs and outputs, highlighting how the implementation of these tools contributed to increased equipment availability.

Stage 1: Autonomous Maintenance

The first component of the model, autonomous maintenance, was implemented to encourage the active participation of operational personnel in maintenance tasks. This phase of the model was based on TPM principles, which promote operator autonomy in performing simple preventive and corrective maintenance tasks, reducing the reliance on specialized personnel. Autonomous maintenance included basic activities such as cleaning, lubrication, and minor adjustments, allowing for early detection of equipment problems. This approach also improved operators' understanding of the machines' condition, which in turn reduced unexpected downtime and improved overall operational efficiency. This initial phase of the model fostered a culture of preventive maintenance within the company, promoting discipline and shared responsibility among the operators.

Stage 2: Reliability-Centered Maintenance (RCM)
Once the foundations of autonomous maintenance were established, reliability-centered maintenance (RCM) was implemented, which is a methodology focused on optimizing maintenance strategies based on equipment criticality. This phase of the model involved a detailed analysis of each piece of equipment in the plant, identifying those that had the greatest impact on operations. The goal of RCM was to ensure that maintenance resources were allocated efficiently, prioritizing equipment with a higher risk of failure and whose unavailability would significantly affect production. The analysis performed during this stage included the study of failure modes and their effects (FMEA), which allowed for the development of more specific maintenance plans tailored to the company's real operational needs. This phase was crucial in reducing maintenance costs by avoiding unnecessary interventions on less critical equipment and ensuring greater availability of critical equipment.

Stage 3: Standardized Work
The third stage of the model, standardized work, was a fundamental step in consolidating the improvements achieved in the previous phases. Process standardization was necessary to ensure that maintenance activities, both preventive and corrective, were carried out consistently and followed best practices. This phase of the model involved creating detailed procedures for each maintenance task, ensuring that operators and maintenance personnel followed a clearly defined set of steps. Standardization not only improved the efficiency of maintenance interventions but also facilitated the training of new operators, reducing adaptation time and minimizing the risk of human error. Additionally, standardized work contributed to better planning of maintenance activities, as the time and resources required for each task were clearly defined.

Model Impact on Equipment Availability
The model's impact on equipment availability was significant. The combination of autonomous maintenance, RCM, and standardized work not only increased equipment availability but also improved equipment reliability and lifespan. By implementing a maintenance plan tailored to the company's real operational conditions, it was possible to reduce unplanned interruptions, improve response times to failures, and optimize the use of available resources. The model also fostered greater integration between production and maintenance teams, contributing to continuous improvement in production processes. The results demonstrated that by adopting an integrated approach based on Lean, TPM, and RCM, sustainable improvements in equipment availability could be achieved, translating into greater competitiveness for the company.

The proposed maintenance management model, described in figure 1, proved to be an effective solution for addressing low equipment availability issues in a metal engineering company. By integrating Lean Manufacturing, TPM, and RCM tools, the model not only succeeded in increasing equipment availability but also improved operational efficiency and the long-term sustainability of production processes. The implementation of this model allowed the company to optimize its maintenance resources, reduce downtime, and improve equipment reliability, contributing to higher productivity and competitiveness in the market. This model can be replicated in other companies with similar characteristics, offering a proven solution for improving equipment availability and, consequently, overall operational efficiency.

3.3 Model Indicators
Specialized metrics were developed to monitor and evaluate performance throughout the case study to evaluate the impact of the maintenance management model that incorporates Lean Manufacturing, Total Productive Maintenance, and Reliability Centered Maintenance tools. These metrics served as a reliable foundation for the examination of critical components of a small metal-working company's maintenance management. This methodical approach enabled a comprehensive examination of critical performance indicators, thereby guaranteeing precise monitoring and promoting ongoing enhancements in production and maintenance processes.

Rate Availability
This indicator measures the percentage of time that equipment is available for production compared to the planned operating time. It reflects operational efficiency by minimizing downtime.

(1)

$$Availability\ Rate = \left(\frac{Operating\ Time}{Planned\ Operating\ Time}\right) \times 100$$

Mean Time Between Failures (MTBF)
MTBF is the average time that elapses between failures of a system during operation, indicating equipment reliability. Higher MTBF values represent improved reliability.

$$MTBF = \frac{Total\ Operating\ Time}{Number\ of\ Failures} \tag{2}$$

Cycle Time
This is the time taken to complete one production cycle from start to finish. Reducing cycle time enhances productivity by optimizing processes.

$$Cycle\ Time = \frac{Total\ Production\ Time}{Units\ Produced} \tag{3}$$

4. Validation
4.1 Validation Scenario
The validation scenario was conducted in a case study within the metalworking sector, specializing in the design and manufacturing of office furniture and accessories, with office modules as its main product. The company had over 13 years of experience in the national market, standing out for its ability to offer customized solutions to its clients. However, it faced critical issues related to the low availability of its two main machines: a CNC laser and a CNC folding machine. These issues were primarily due to unplanned stoppages and the non-completion of scheduled stops, which negatively impacted its production capacity. The company aimed to improve its equipment availability by implementing autonomous maintenance, reliability-centered maintenance (RCM), and standardized work processes, which were key tools designed to increase operational efficiency and reduce downtime.

4.2 Initial Diagnosis
In figure 2, the problem tree summarizes the diagnostic performed in the case study to identify the causes behind the low performance in the availability of the company's office module manufacturing equipment. The analysis revealed that the equipment availability rate was 80.5%, below the industry standard of 90%, representing a significant technical gap. The main problem of low equipment availability had an estimated economic impact of 1,004,862 PEN per year, equivalent to 12.82% of the company's annual revenue. The causes identified at level 1 included unplanned machine downtime, responsible for 82.14% of the downtime, and the non-completion of scheduled stops, which accounted for 17.27%. At level 2, the root causes of unplanned downtime were attributed to a lack of basic maintenance (36.39%) and a maintenance plan not aligned with operational reality (45.75%). On the other hand, the non-completion of scheduled stops was due to non-standardized production processes. These findings underscore the need to improve maintenance management and process standardization to reduce economic losses and close the technical gap in equipment availability.

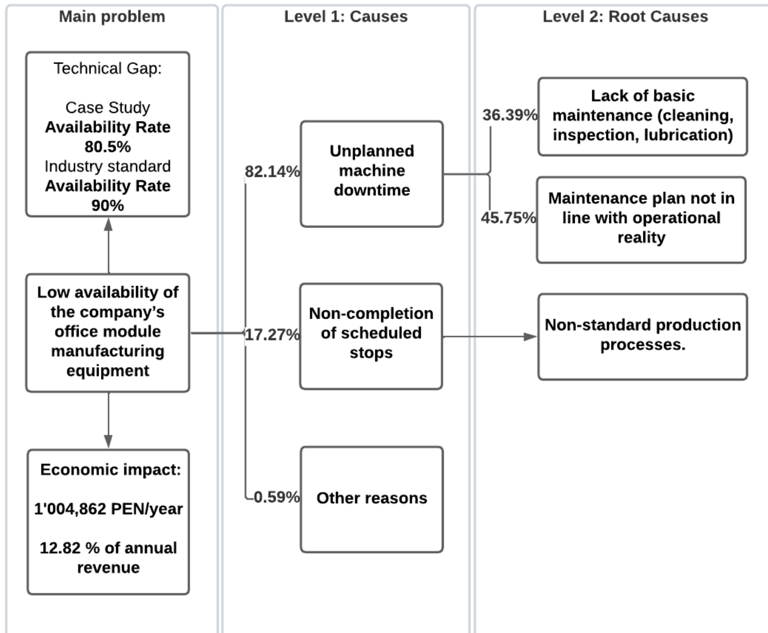


Figure 2. Problem Tree

4.3 Implementation of the model in the case study

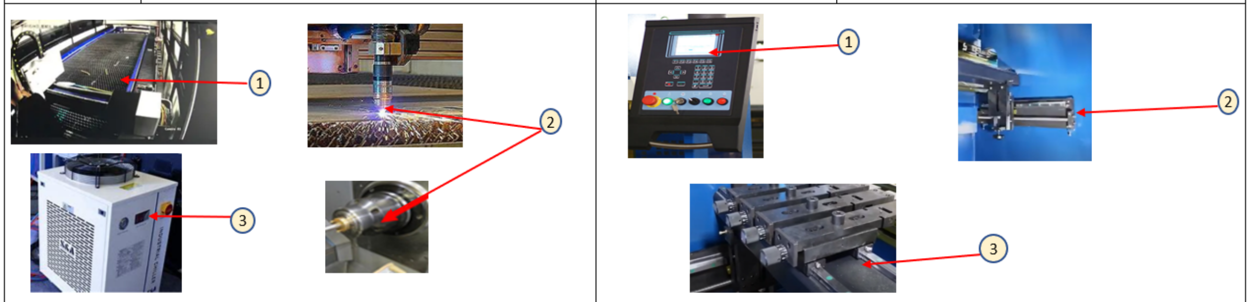
The implementation of the maintenance management model focused on improving equipment availability in the case study by implementing the Lean Manufacturing, Total Productive Maintenance (TPM) tool-based model and Reliability-Centered Maintenance (RCM). The main objective was to optimize the availability of critical equipment and reduce economic losses associated with unscheduled downtime, resulting in significant improvements in key performance indicators. Throughout the different phases of the model, quantitative tools were used to measure and evaluate the impact of the actions implemented.

4.4 Implementation of Autonomous Maintenance

Autonomous maintenance was implemented as the first phase of the model, with the aim of directly involving operators in the preventive maintenance of critical machines in the case study, such as the CNC laser machine and the CNC press brake. Before the implementation, operators lacked in-depth knowledge of the machines' condition, leading to frequent stoppages and mechanical failures. To address this, training programs were implemented, including instruction on basic maintenance tasks such as cleaning, inspection, and lubrication. These actions enabled operators to identify issues before they became major failures. Quantitative results showed a 36.39% reduction in unplanned stoppages. This change boosted equipment availability from 80.5% to 90%, representing an 11.80% improvement. Additionally, the implementation of these maintenance practices contributed to improving operators' morale, as they took on greater responsibility for the equipment's performance.

Figure 3 illustrates the standard maintenance program for two key pieces of equipment: the CNC laser machine and the CNC bending machine. The left side of the figure details the maintenance plan for the CNC laser machine, focusing on cleaning and inspection activities across three main components: the worktable, the laser head and feeders, and the water cooling system. Each component has specific tasks, such as ensuring the worktable is free from metallic particles and the cooling system operates within the correct pressure range. Tools required include brushes, gloves, masks, and goggles, with most tasks performed at the end of each shift.On the right side, the CNC bending machine's maintenance program emphasizes inspection, lubrication, and cleaning tasks for the control system, torque synchronization system, and quick anchor system. Key activities include lubricating control systems and bearings using synthetic grease. The frequency of tasks ranges from weekly to monthly, ensuring the equipment operates smoothly and efficiently. Both programs are structured to maintain optimal equipment functionality while promoting safety through the use of protective gear.

PROGRAMA ESTÁNDAR DE LIMPIEZA E INSPECCIÓN (máquina Laser CNC)		PROGRAMA DE LIMPIEZA, INSPECCIÓN Y LUBRICACIÓN (máquina Plegadora CNC)	
Código del equipo:		Código del equipo:	
Proceso:		Proceso:	



N°	Componente	Actividad	Descripción de la antividad	Herramientas y materiales	Frecuencia	N°	Sistema	Actividad	Descripción de la antividad	Herramientas y materiales	Frecuencia
1	Mesa de trabajo	Limpieza e inspección	La mesa de trabajo debe estar libre de particulas metálicas	Escobillon, uso de guantes, lentes, mascarilla y casco.	Al finalizar el turno	1	Control NC	Limpieza e inspección	. Debe estar libre de particulas . correcta función digital	. Uso de paño industrial, lentes, mascarilla y guantes . Manual del equipo	. Al finalizar el trabajo . Semanal
2	Cabezal y alimentadores	Limpieza	Accesorio libre de particulas metálicas	Limpieza con trapo industrial y lentes, mascarilla y casco.	Al finalizar el turno	2	Sistema de control de torque sincrónico	Inpección y lubricación	Lubricación del sistema de control	Colocar grasa sintetica Molycote BG-20 y uso de lentes, tapabocas y guantes	Mensaul
3	Sistema de enfriador de agua	Inspección	El sistema digital debe estar en 600 - 650 psig (dar aviso al Ing. Mantenimiento)	Uso de guantes y lentes	Al inicio de trabajo	3	Anclaje rápido	Inpección y lubricación	Lubricación al sistema de rodamientos y limpieza al anclaje	Colocar grasa sintetica Molycote BG-20, trapo industrial y uso de lentes, tapabocas y guantes	. Mansual . Al finalizar el trabajo

Figure 3. Standard maintenance program Autonomous (CNC laser machine and CNC bending machine)

4.5 Reliability-Centered Maintenance (RCM)

The second phase of the model involved the use of the RCM methodology, which allowed for the prioritization of maintenance based on the criticality of the equipment and the analysis of failure modes and effects (FMEA). This detailed analysis focused on key equipment that had a significant impact on production, identifying critical points that required a more rigorous preventive approach. As a result, the mean time between failures (MTBF) increased from 243 hours to 272.5 hours, representing a 12.14% improvement. This increase in MTBF indicated greater equipment reliability and a reduction in unscheduled downtime. Furthermore, RCM enabled the company to better redistribute its maintenance resources, assigning personnel and materials where they were most needed, which helped to reduce overall operating costs.

Figure 4 presents an analysis of critical equipment failure modes and their effects for the CNC laser machine and CNC bending machine used in the office module manufacturing process. The table identifies functional failures, failure modes, effects, and consequences for key components of both machines. For example, the CNC laser machine exhibits failures in the storage tank due to wear, leading to intermittent machine stoppages with a severity rating of 2. This is followed by the assessment of controls, showing that there are no preventive measures in place, and detection relies on quarterly inspections. Similarly, the CNC bending machine experiences issues such as contamination in the headstock, which causes vibrations and imbalances. Preventive measures include monthly line cleaning, and detection is managed through regular inspection and cleaning routines.

The analysis also incorporates risk assessment using the Severity-Occurrence-Detection (SOD) method, assigning risk priority numbers (RPN) to each failure. Higher RPNs indicate a greater need for intervention. For example, the failure in the filters of the CNC laser machine was rated with an RPN of 32, prompting biweekly inspections and cleaning. Overall, this analysis informs decision-making for maintenance prioritization and resource allocation.

Process	Machinery	Functional Failure	Failure Mode	Effect and Consequence of the Failure	Severity	Occurrence	Detection	Current Preventive Controls	Current Detection Controls	Actions Taken	Severity	Occurrence	Detection	RPN
Office Module Manufacturing	CNC Laser Machine	Failure in storage tank	Wear	Intermittent machine stoppage	2	2	4	None	Quarterly Inspection	Quarterly Inspection	2	2	4	32
Office Module Manufacturing	CNC Laser Machine	Failure in suction filters	Adjustment failure	Intermittent machine stoppage	3	3	3	None	Quarterly Inspection	Quarterly Inspection	3	3	3	27
Office Module Manufacturing	CNC Laser Machine	Failure in gear pumps	Wear	Oil does not perform its function; the machine	4	3	4	Annual Inspections	Cleaning	Inspection by trained personnel	4	3	3	48
Office Module Manufacturing	CNC Laser Machine	Failure in flexible couplings	Damage or wear	Conveyor belts malfunctioned	4	3	5	Annual Inspections	Cleaning	Inspection and preventive maintenance	4	3	5	60
Office Module Manufacturing	CNC Laser Machine	Failure in hydraulic cylinder	Wear	Production stoppage	3	2	4	Semi-annual inspections	Quarterly Inspection	Quarterly Inspection	3	2	4	24
Office Module Manufacturing	CNC Bending Machine	Failure in the bed	Dirt	Production stoppage	2	2	4	None	Cleaning every week	Cleaning	2	2	4	32
Office Module Manufacturing	CNC Bending Machine	Failure in the fixed headstock	General wear	Causes vibrations and imbalances	3	3	4	Monthly Line Cleaning	Cleaning every week	Monthly Line Cleaning	3	3	4	48
Office Module Manufacturing	CNC Bending Machine	Failure in the main carriage	Dirt	Production stoppage	3	3	4	None	Monthly Line Cleaning	Inspection Program	3	3	4	48

Figure 4. Analysis of critical equipment failure mode and effect

Figure 5 presents the annual maintenance plan for critical equipment, specifically the CNC laser machine and CNC bending machine. The plan details the frequency of maintenance activities, ranging from quarterly to biannual tasks. Each row outlines the machine, the specific task required (e.g., inspection of storage tanks, lubrication of flexible couplings), and the responsible maintenance personnel. The frequency column indicates whether the task is to be performed quarterly, annually, or semi-annually. The right section of the figure shows a month-by-month schedule for the entire year, with each week (labeled as S1, S2, etc.) clearly marked to indicate when specific maintenance activities should occur. For example, the inspection of the CNC laser machine's storage tanks is scheduled on a quarterly basis, with tasks planned in the first weeks of January, April, July, and October. The detailed structure ensures that preventive maintenance is consistently performed throughout the year, reducing the risk of unexpected equipment failure and optimizing machine performance.

No.	Machine	Detail	Responsible	Frequency	January				February				March				April				May				June			
					S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4
1	CNC Laser Machine	Inspection of storage tank	Maintenance	Fortnightly	■		■		■		■		■		■		■		■		■		■		■		■	
2	CNC Laser Machine	Suction filter adjustments	Maintenance	Fortnightly		■		■		■		■		■		■		■		■		■		■		■		■
3	CNC Laser Machine	Check the oil level in gear pumps	Maintenance	Annual			■																					
4	CNC Laser Machine	Lubrication of flexible couplings	Maintenance	Annual					■																			
5	CNC Laser Machine	Fit on the hydraulic cylinder keys	Maintenance	Semi-annual														■										
6	CNC Bending Machine	Clean the bed	Maintenance	Fortnightly	■		■		■		■		■		■		■		■		■		■		■		■	
7	CNC Bending Machine	Check the fixed headstock	Maintenance	Semi-annual			■																					
8	CNC Bending Machine	Fixed head adjustment	Maintenance	Weekly						■																		

No.	July				August				September				October				November				December			
	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4
1	■		■		■		■		■		■		■		■		■		■		■		■	
2		■		■		■		■		■		■		■		■		■		■		■		■
3																								
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5															■									
6	■		■		■		■		■		■		■		■		■		■		■		■	
7		■																						
8						■																		

Figure 5. Annual maintenance plan

4.6 Work Standardization

The final phase of the model focused on standardizing production processes, directly addressing variability in procedures and cycle times. The previous lack of standardization had led to inconsistencies in production, resulting in extended cycle times and quality issues. By implementing standardized work, inefficiencies in processes were eliminated, and cycle times were significantly reduced. Results showed a reduction in cycle time from 164 minutes to 130 minutes, representing a 20.73% improvement. This standardization not only improved operational efficiency but also facilitated the training of new employees, who were able to follow clear and repeatable procedures, reducing the margin for error.

Overall, the proposed management model, based on the implementation of autonomous maintenance, RCM, and standardized work, provided tangible improvements in the operational performance of the case study. Equipment availability increased by 11.80%, MTBF improved by 12.14%, and cycle time was reduced by 20.73%. These quantitative results demonstrate the effectiveness of the tools implemented to address the problem of low equipment availability. Moreover, the positive impact on operational efficiency allowed the company to significantly reduce economic losses associated with equipment downtime, thereby increasing its competitiveness in the market.

Figure 6 illustrates the current route plan based on standardized processes within the production facility. The layout includes key areas such as storage and dispatch, assembly, painting, cutting, welding, and bending. The red line represents the movement of materials through the various stages of production, starting from the storage and dispatch area. The route follows a sequence where materials are first processed in the welding area, then proceed to the bending section, followed by the cutting area, painting, and finally assembly, before returning to the storage and dispatch section.

This layout shows a continuous flow of materials, optimizing the movement between each stage to minimize travel time and improve process efficiency. The standardized route ensures that all materials follow the same path, reducing bottlenecks and streamlining operations. The diagram provides a clear visual representation of how standardized processes contribute to a more efficient production workflow.

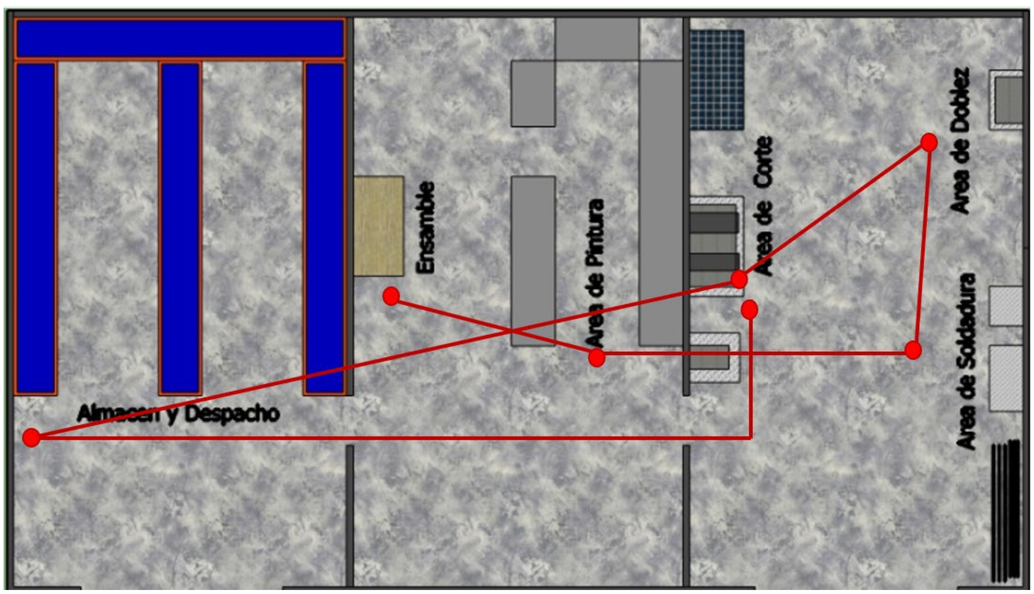

Figure 6. Current route plan by standardized processes

Table 1 provides a summary of the current production process, classifying activities into three categories: activities that add value to the process (VA), those that add value to the customer but not the process (NNVA), and those that add no value to either the process or the customer (NVA). The table shows that 25 activities (66%) add value to the process, consuming 108 minutes. Activities that add value to the customer but not the process account for 13 activities (20%), taking 33 minutes. Lastly, 7 activities (14%) neither add value to the process nor the customer, totaling 23 minutes. The total production time for all activities is 164 minutes.

Table 1. Summary of the current production process

Activity	Classification	No. of Activities	Minutes	%
Adds value to the process	VA	25	108	66%
Adds value to the customer, but not to the process	NNVA	13	33	20%
Adds no value to the process nor to the customer	NVA	7	23	14%
Total		45	164	100%

Table 2. Procedure for the cutting process (Laser CNC) and Bending (CNC Bending)

Elements	Time (Minutes)	Responsible	Detail
Turn on CNC Laser Machine	0.5	Operator	Specifications are reviewed and if all are met, the machine is turned on.
Move the metal sheet to the base of the laser machine	1	Operator	The metal sheet is moved to the base of the laser machine.
Verify and clean the cutting nozzle	1	Operator	The laser nozzle is checked to ensure it meets the specifications.
Select the product drawing	0.5	Operator	The labeled drawing from the folder is selected.
Program the machine according to the product	1	Operator	The drawing specifications are reviewed, and the laser machine is programmed.
Cut the pieces according to measurements	8	Operator	The cutting button is pressed, and the pieces are cut according to the drawing's measurements.
Remove the pieces from the laser machine	2	Operator	The pieces are removed, and the quantity is verified to meet specifications.
Remove the leftover material	1	Operator	The leftover material is removed and placed in the appropriate bin.
Verify and release the cut pieces	0.5	Operator	The cuts are checked to ensure they meet the drawing's measurements, and the product is released for the next process.
Move the pieces to the bending area	2	Operator	The labeled pieces are moved to the bending area.
Operator verifies the quantity of product delivered	1	Operator	The number of pieces is verified according to the work order.
Search for and select the product drawing	0.5	Operator	The corresponding drawing for the product is selected.
Turn on CNC Bending Machine	1	Operator	Specifications are reviewed, and if all are met, the bending machine is turned on.
Program the machine according to the product	1	Operator	The drawing specifications are reviewed, and the bending machine is programmed.
Perform the bending of the pieces	3	Operator	The pieces are bent according to the drawing's measurements.
Verify and release the bent pieces	1.5	Operator	The bending is checked to ensure it meets the drawing's measurements, and the product is released for the next process.
Move the bent pieces to the welding area	3	Operator	The labeled bent pieces are moved to the welding area.

Table 2 outlines the detailed procedure for the cutting process using the CNC laser machine and the bending process using the CNC bending machine. The table includes the elements of each task, the time required (in minutes), the responsible party (typically the operator), and a description of the tasks.For the CNC laser machine, the process begins with turning on the machine, verifying the equipment specifications, and moving the metal sheet to the laser base. The operator is responsible for tasks such as verifying and cleaning the cutting nozzle, selecting the product's blueprint, programming the machine, and executing the cutting according to the specified measurements. Each task has a specified time requirement, such as 8 minutes for cutting the pieces and 2 minutes for removing them from the machine. The process also includes verification of cut accuracy and moving the pieces to the bending area.

For the CNC bending machine, the procedure starts similarly with turning on the machine, reviewing specifications, and programming the machine for the bending task. The operator then performs the bending, checks the bent pieces to ensure accuracy, and moves the finished pieces to the welding area. The total time for bending tasks includes 3 minutes for the bending operation and 1.5 minutes for verifying and releasing the bent pieces.This table provides a step-by-step guide to the cutting and bending processes, detailing the time and responsibility for each task to ensure efficient and accurate production workflows.

5. Results

In Table 3, the results of the validation of the proposed maintenance management model, which integrates Lean, TPM, and RCM methodologies, are presented. The data highlight a notable improvement in the key performance indicators. The availability rate of the equipment increased from 80.50% to 90%, representing an 11.80% enhancement. Furthermore, the mean time between failures (MTBF) saw a significant rise, increasing by 12.14%, from 243 to 272.5 hours. The cycle time was also reduced from 164 to 130 minutes, marking a 20.73% decrease, which demonstrates the efficiency gains achieved through the implementation of the proposed model.

Table 3. Results of validation of the proposed model

Indicator	Unit	As-Is	To-Be	Results	Variation (%)
Rate Availability	%	80.50%	90%	90%	11.80%
MTBF (Mean time between failures)	hours	243	280	272.5	12.14%
Cycle Time	minute	164	130	130	-20.73%

6. Conclusions.

The conclusions of this study demonstrate the effectiveness of a maintenance management model integrating Lean Manufacturing, TPM, and RCM in improving equipment availability in Peruvian metalworking SMEs. The results indicate an 11.80% increase in equipment availability and a 20.73% reduction in cycle time, underscoring the potential of these methodologies to optimize operational efficiency. These findings are significant, given that equipment availability is crucial for maintaining competitiveness in a dynamic market. This research contributes to the field by providing a model adapted to the operational conditions of SMEs, addressing both the need for proactive maintenance and the importance of process standardization. This holistic approach is particularly relevant in resource-constrained environments where efficiency and waste reduction are imperative for sustainability.

This study provides a solid theoretical framework and practical recommendations that can be replicated in similar companies, facilitating systematic implementation of improvements. Additionally, it highlights the importance of involving employees in autonomous maintenance, fostering a culture of shared responsibility and enhancing team morale. The RCM phase enables more efficient allocation of maintenance resources by prioritizing critical equipment and optimizing costs. Process standardization, on the other hand, not only ensures consistency in maintenance activities but also facilitates training for new operators, reducing adaptation time and the risk of human error. This comprehensive structure has the potential to transform the approach toward maintenance and continuous improvement in SMEs within the sector.

The research also underscores the socioeconomic impact of implementing an efficient maintenance model in Peruvian metalworking SMEs, a sector that significantly contributes to local economy and employment. By improving equipment availability and reducing operational costs, these companies can not only increase profitability but also strengthen their competitive position in a globalized environment. Furthermore, reducing downtime and production defects enhances customer satisfaction, improving the companies' market reputation. In a context where sustainability is increasingly valued, this model offers a viable alternative that incorporates environmentally responsible practices through resource optimization and waste reduction, aligning with sustainable development goals.

For the future, further research is suggested to explore this model's application in other industrial sectors and geographic contexts to validate its effectiveness and adaptability. Additionally, it would be valuable to investigate the impact of emerging technologies, such as artificial intelligence and the Internet of Things (IoT), in maintenance management, as these can improve fault detection accuracy and further optimize resources. Finally, it is recommended to investigate the long-term impact of implementing this model on the organizational culture of SMEs, examining how the benefits of a culture of continuous improvement and employee empowerment can be sustained amid changing conditions.

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