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A TPM-Based Maintenance Model for Enhancing Efficiency in Automotive Battery SMEs: A Case Study in Peru

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Abstract

The study addresses the operational challenges faced by small and medium-sized enterprises (SMEs) in automotive battery manufacturing. Previous research indicates inefficiencies in maintenance and quality control impacting productivity. This investigation aimed to overcome these challenges through the implementation of a Total Productive Maintenance (TPM) model tailored for battery manufacturers. The proposed model included structured phases of planning, testing, implementation, and validation to enhance equipment reliability and reduce downtime. Key findings demonstrated a significant improvement in operational efficiency by 13.85% and a decrease in non-conforming products by 25.58%. The study's contribution lies in adapting TPM strategies to the specific context of battery manufacturing SMEs, offering a scalable framework for operational improvements. This research has implications for enhancing competitiveness and sustainability in the automotive supply chain. Future studies are encouraged to refine and expand this model in similar industrial sectors to foster continuous improvement.

Keywords
Total Productive Maintenance, Autonomous Maintenance, Planned Maintenance, Operational Efficiency, Automotive Battery SMEs.

1. Introduction
The small and medium-sized enterprise (SME) automotive battery manufacturing industry plays a crucial role in the global economy, especially in the context of the transition to electric and sustainable vehicles. Worldwide, the demand for lithium-ion batteries and other energy storage technologies has significantly increased, driven by growing concerns about climate change and the need to reduce greenhouse gas emissions (Mordue & Sener, 2022). In Latin America, and particularly in Peru, this sector has begun to gain relevance as governments implement policies to promote the production of electric vehicles and their components, creating opportunities for local SMEs (Hirz & Nguyen, 2022). These companies not only contribute to the local economy but also play a fundamental role in the automotive supply chain, providing essential components critical to the operation of modern vehicles (Mouli & Mahanty, 2015).

However, automotive battery manufacturing SMEs face numerous challenges in their production processes. One of the most significant issues is low operational efficiency in assembly lines, resulting in a high percentage of non-compliant products and unscheduled plant shutdowns (Mouli & Mahanty, 2017). These interruptions can be caused by welding failures, burnt box issues, damaged terminals, and a deficient maintenance program that leads to low equipment availability (Bolesnikov et al., 2019). The lack of a systematic approach to maintenance and continuous improvement can create a vicious cycle of inefficiency and waste, impacting these companies' competitiveness in an increasingly demanding market (Chen et al., 2020). Implementing methodologies such as Total Productive Maintenance (TPM) could be a viable solution to address these problems, as it focuses on maximizing equipment efficiency and minimizing downtime (Valič et al., 2021).

Addressing these problems is crucial not only to improve the operational efficiency of SMEs but also to ensure their long-term sustainability. Improving production efficiency not only reduces costs but also enables companies to better respond to market demands and consumer expectations in terms of quality and sustainability (Raggi & Pietro, 2015). Additionally, adopting more effective maintenance practices can contribute to waste reduction and more efficient resource use, which is essential in a context where sustainability has become a business imperative (Alegre, 2022). SMEs that successfully enhance their operational efficiency through the implementation of TPM and other continuous improvement methodologies can not only survive but also thrive in a competitive environment (Mordue & Sener, 2022).

Despite the growing focus on operational efficiency and maintenance in the literature, there is a significant knowledge gap regarding how these methodologies can be specifically applied in the context of automotive battery manufacturing SMEs. Current research tends to focus on large companies or more established sectors, leaving SMEs in the background (Hilmola et al., 2015). This study aims to close this gap by developing a production model that integrates TPM tools, such as Autonomous Maintenance and Planned Maintenance, adapted to the specific needs and capabilities of SMEs in the battery sector (Hirz & Nguyen, 2022). In doing so, it not only aims to improve the operational efficiency of these companies but also to provide a framework that can be used by other SMEs in the automotive industry to address their own production challenges (Habidin et al., 2015).

In conclusion, the importance of the automotive battery manufacturing SME sector is undeniable, both globally and in the specific context of Latin America and Peru. However, the production challenges they face require urgent attention and effective solutions. Implementing methodologies such as TPM can offer a path toward improving operational efficiency and sustainability, but a more SME-focused approach is needed to develop strategies that are effective in their particular context. This study aims to contribute to that objective by providing a model that not only addresses current problems but also prepares these companies for the future in an ever-evolving automotive market.

2. Literature Review

2.1 Research on the TPM Methodology in the Production of Wet Cell Automotive Battery SMEs

Total Productive Maintenance (TPM) has been widely studied in various industries, including those manufacturing automotive components. This methodology focuses on maximizing equipment efficiency and minimizing downtime through the active participation of all employees in the maintenance process. According to Jain et al. (2018), the implementation of TPM in SMEs has shown positive results in terms of productivity and waste reduction, suggesting that its application in battery manufacturing could yield similar benefits. Furthermore, Bottani et al. (2014) found that Italian companies adopting TPM practices experienced significant improvements in their maintenance policies, resulting in greater operational effectiveness.

A more recent study conducted by Sharma and Sharma (2013) highlights that integrating TPM with other methodologies such as Lean Six Sigma can lead to a significant increase in profitability for manufacturing SMEs. This combined approach allows companies not only to optimize their maintenance processes but also to improve the quality of the final product. On the other hand, the research by Gwangwava et al. (2021) emphasizes the need for SMEs to adopt TPM practices to compete in a global market where efficiency and cost reduction are crucial. Implementing TPM not only improves equipment availability but also fosters a culture of continuous improvement among employees, which is essential in the battery manufacturing sector.

Additionally, the study by Kundu et al. (2020) proposes a framework for implementing TPM in SMEs, highlighting that the lack of an adequate maintenance plan can lead to high defect rates in production. This is particularly relevant for SMEs manufacturing wet cell batteries, where product quality is critical. The research concludes that adopting TPM can help these companies establish a preventive maintenance system that not only extends the lifespan of equipment but also improves the quality of the final product.

2.2 Research on Autonomous Maintenance Methodology

Autonomous Maintenance is a practice that empowers machine operators to take responsibility for the daily maintenance of their equipment. This methodology has proven effective in improving operational efficiency in various industries. According to Chukwutoo and Nkemakonam (2018), the integration of TPM and Autonomous Maintenance in the automotive sector has led to significant improvements in production performance. The research suggests that training workers to perform basic maintenance tasks reduces downtime and enhances staff morale.

On the other hand, the study by Jain et al. (2014) emphasizes that Autonomous Maintenance not only improves equipment efficiency but also fosters a sense of ownership among employees. This is particularly important in SMEs, where resources are limited, and every team member must contribute to the company's overall success. Implementing this methodology in wet cell battery manufacturing can result in higher product quality and reduced operational costs. Furthermore, the research by Sharma and Sharma (2013) shows that Autonomous Maintenance can be a key factor in reducing equipment failures, which is essential to maintaining production continuity in SMEs. Proper training and employee empowerment are crucial to the success of this methodology. In the context of battery manufacturing SMEs, this can translate into an increased ability to proactively address maintenance issues, thereby improving overall production efficiency.

2.3 Research on Planned Maintenance Methodology

Planned Maintenance is a strategy that involves scheduling maintenance activities based on the specific needs of equipment and processes. This methodology is crucial to ensuring production continuity and minimizing downtime. According to the study by Kundu et al. (2020), implementing a preventive maintenance framework in manufacturing companies has proven effective in improving operational efficiency. The research suggests that a systematic approach to maintenance can help SMEs reduce costs and improve product quality.

Additionally, the work by Sudhir (2023) highlights the importance of a proactive maintenance approach, where companies not only respond to failures but anticipate and prevent problems before they occur. This is particularly relevant for SMEs manufacturing wet cell batteries, where product quality and reliability are essential. Implementing a Planned Maintenance program can help these companies identify and address potential issues before they impact production.

The research by Driouach et al. (2019) also emphasizes that Planned Maintenance can be a key factor in SME competitiveness. By reducing downtime and improving equipment efficiency, companies can increase their production capacity and, consequently, their profitability. In the context of battery manufacturing, this can translate into a greater ability to meet market demand and enhance customer satisfaction.

2.4 Managing Operational Efficiency in Wet Cell Automotive Battery SME Production

Managing operational efficiency is a critical aspect of SME production, especially in the manufacturing of wet cell batteries. The implementation of methodologies such as Lean Manufacturing and TPM has proven effective in improving operational efficiency across various industries. According to the study by Belekoukias et al. (2014), the adoption of Lean tools has enabled companies to improve processes and reduce costs, which is essential for competitiveness in today's market.

Moreover, the research by Yadav et al. (2019) shows that implementing Lean practices in SMEs can result in significant improvements in operational performance. This is especially relevant for battery manufacturing SMEs, where efficiency in the production process can have a direct impact on profitability. Integrating Lean practices with TPM can help these companies optimize their processes and improve the quality of the final product.

On the other hand, the work by Gnanaraj et al. (2010) highlights that implementing an exclusive Lean Six Sigma model in SMEs can be an effective strategy for improving operational efficiency. This approach combines waste reduction with quality improvement, which is crucial in wet cell battery manufacturing. The research suggests that SMEs adopting this approach can achieve a significant competitive advantage in the market.

Finally, the study by Pradana et al. (2019) emphasizes that applying TPM to specific machines, such as those used in battery manufacturing, can lead to a notable improvement in operational efficiency. By identifying and addressing sources of inefficiency, SMEs can optimize their production and improve product quality. This is essential to maintaining competitiveness in a constantly evolving market.

In conclusion, implementing methodologies such as TPM, Autonomous Maintenance, and Planned Maintenance, along with efficient production management, is fundamental to the success of SMEs manufacturing wet cell automotive batteries. These practices not only improve operational efficiency but also contribute to the sustainability and competitiveness of these companies in a challenging industrial environment.

3. Methods

3.1 Basis of the Proposed Model

In Figure 1, the TPM-based maintenance model is depicted as a systematic approach to enhance operational efficiency in a small-scale automotive battery assembler. This model followed the principles of Total Productive Maintenance (TPM) to minimize inefficiencies and improve performance. The model was designed with four key components: planning, testing and verification, implementation, and validation. Each component addressed specific aspects to reduce operational issues, aiming to transform low operational efficiency into high efficiency through structured planning and precise validation steps. The objective of this model was to establish a continuous improvement process that would ensure reliable operations and minimal downtime, thereby supporting the long-term sustainability of production. By integrating TPM principles, the model sought to align maintenance activities with strategic goals to achieve measurable outcomes in performance and quality. The methodology aimed to create a proactive environment, enabling the case company to efficiently allocate resources and maintain high operational standards.

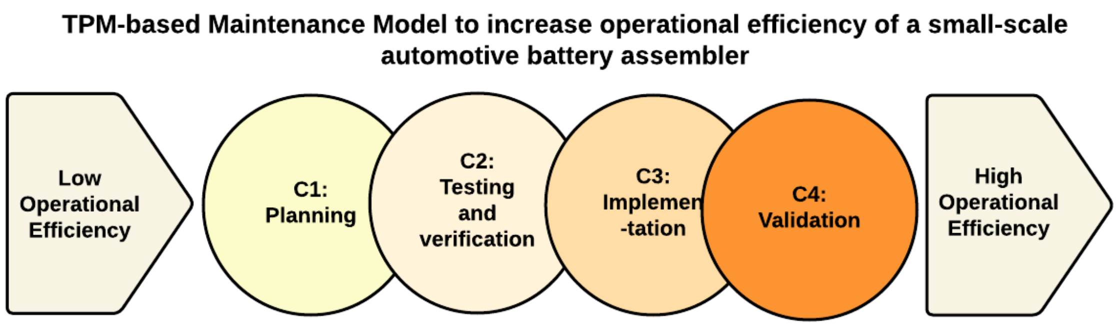

Figure 1. Proposed Model

3.2 Description of the model components

In Figure 1, a maintenance model based on the Total Productive Maintenance (TPM) philosophy is presented, designed to enhance the operational efficiency of a small-scale automotive battery assembler. This model aims to transform a state of low operational efficiency into high performance levels through a structured approach. The model is based on four key components: Planning, Testing and Verification, Implementation, and Validation. These components represent a sequential methodology aimed at improving maintenance processes, optimizing resource utilization, and reducing equipment downtime, all aligned with TPM principles and continuous improvement.

Component 1: Planning

The first stage, referred to as Planning (C1), focuses on setting clear objectives and defining the necessary strategies to address operational efficiency issues. In this phase, critical resources are identified, and maintenance activities are designed to align with organizational goals. Planning also involves scheduling preventive actions and training personnel to establish a solid foundation for the subsequent phases of the model. The main goal of this component is to reduce the reliance on reactive maintenance by creating a structured maintenance plan.

Component 2: Testing and Verification

The second stage, Testing and Verification (C2), aims to evaluate the effectiveness of the maintenance strategies developed during the planning phase. In this phase, key equipment verifications are conducted to identify potential issues and adjust strategies as needed. This stage allows for validating maintenance procedures and establishing corrective measures before full-scale implementation. In this way, it seeks to ensure that maintenance activities are aligned with operational goals and to prevent future setbacks.

Component 3: Implementation
The Implementation phase (C3) corresponds to the practical execution of the validated maintenance strategies from the previous phase. During this stage, the planned actions are executed, specific roles are assigned to personnel, and the proposed improvements are put into practice. The goal of implementation is to introduce tangible changes in daily operations to reduce equipment downtime and improve overall efficiency. Implementation is carried out progressively, allowing dynamic adjustments based on real-time results.

Component 4: Validation
The final stage, Validation (C4), focuses on confirming the effectiveness of the model in improving operational efficiency. This phase involves a thorough review of the achieved results and a comparison with the initial objectives. Validation aims to determine whether the implemented maintenance strategies have had the desired impact on operational efficiency and if they can be sustained over the long term. Additionally, potential adjustments or further improvements are analyzed to consolidate the achieved outcomes.

The TPM-based model depicted in Figure 1 provides a structured approach to enhancing the operational efficiency of a small-scale automotive battery assembler. Through its four components—Planning, Testing and Verification, Implementation, and Validation—the model aims to transform a low-efficiency scenario into a high-performance environment, aligning maintenance activities with TPM principles. By adopting a proactive and sequential approach, this model seeks to maximize equipment availability, reduce downtime, and achieve sustainable improvements in operational performance.

3.3 Model Indicators

Specialized metrics were devised to monitor and evaluate performance throughout the case study to evaluate the impact of the TPM-based maintenance model. These metrics served as a reliable foundation for the examination of critical components of last-mile distribution center management. This methodical approach enabled a comprehensive examination of critical performance indicators, thereby guaranteeing precise monitoring and promoting ongoing enhancements in maintenance procedures.

Operational Efficiency. This indicator measures the effectiveness of the maintenance processes in achieving the planned operational goals. It is expressed as a percentage and indicates how well resources are utilized to meet the expected performance levels.

$$\text{Operational Efficiency} = \left(\frac{\text{Actual Output}}{\text{Planned Output}}\right) \times \mathbf{100} \quad (1)$$

Availability Rate. The availability rate reflects the percentage of time that equipment is available and operational during the planned production time. It measures the readiness of machines to perform their designated functions without interruptions.

$$\text{Availability Rate} = \left(\frac{\text{Available Time}}{\text{Planned Production Time}}\right) \times \mathbf{100} \quad (2)$$

Rate of Non-Conforming Products. This indicator measures the percentage of products that do not meet quality standards or specifications, relative to the total number of products produced. It highlights the effectiveness of quality control measures within the manufacturing process.

(3)

$$\text{Rate of Non-Conforming Products} = \left(\frac{\text{Number of Non-Conforming Products}}{\text{Total Number of Products}}\right) \times \mathbf{100}$$

4. Validation

4.1 Validation Scenario

The validation scenario was conducted in a case study within the automotive manufacturing sector in Peru. Over recent years, it has experienced sustained growth due to the modernization of its facilities and a global expansion strategy, allowing it to achieve broad coverage both nationally and internationally. The company is characterized by its focus on innovation and its commitment to sustainability, implementing responsible practices throughout its operations. In its manufacturing processes, it has faced challenges related to the efficiency of its assembly lines, particularly in reducing non-compliant products and unscheduled downtimes, which led to the need for implementing an improvement model focused on efficiency and operational optimization to remain competitive in the automotive market.

4.2 Initial Diagnosis

In Figure 2, the problem tree illustrates the diagnosis conducted in the case study to identify the factors and root causes contributing to the research problem. The primary issue identified was a poor battery assembly process, which resulted in an operational efficiency of 65%, significantly below the industry standard of 90%. The economic impact of this inefficiency was estimated at 1'100,000 PEN per year, representing 21% of annual revenue. At Level 1, two major causes were identified: a high rate of non-compliant products (54%) and unscheduled plant shutdowns (40%). At Level 2, root causes of these issues were identified, including failures due to poor welding (21%), faulty burnt boxes (19%), and damaged terminal faults (14%). Additionally, poor maintenance programs (21%) and insufficient equipment availability (19%) were key contributors to unscheduled shutdowns. The objective of this diagnosis was to comprehensively assess the technical and economic impact of inefficiencies in the assembly process and identify specific areas requiring targeted interventions to improve operational efficiency.

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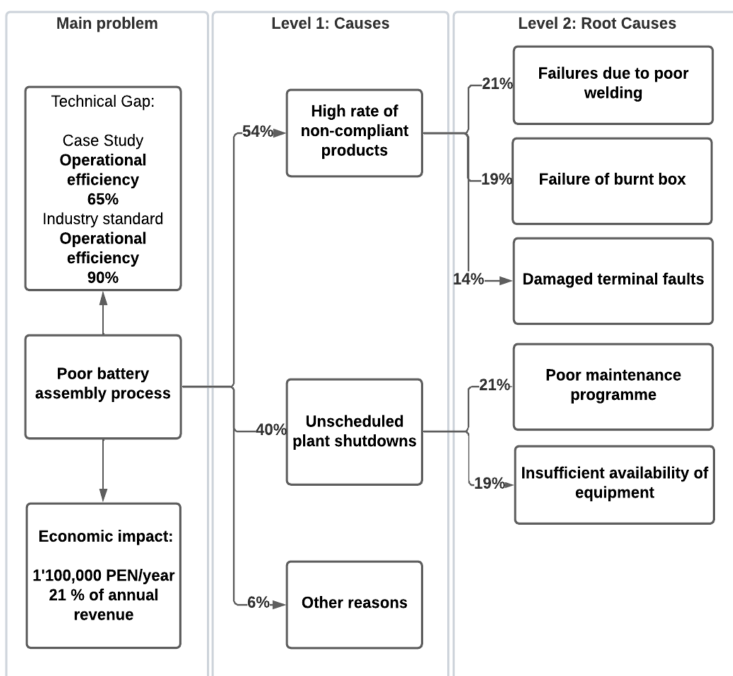

Figure 2. Problem Tree

4.3 Implementation of the model in the case study

The implementation of the proposed model in the case study was meticulously designed to address the specific challenges faced by the automotive battery manufacturing process. Initially, the project focused on forming a dedicated team with specialized roles and responsibilities to oversee the execution of the model. This team was tasked with ensuring the successful application of Total Productive Maintenance (TPM) principles, with all members receiving tailored training based on their expertise. Leveraging these principles and emphasizing continuous improvement, the implementation aimed to actively engage all employees in maintenance activities and problem-solving efforts, laying the groundwork for a sustainable change.

Strategic Planning and Capacity Building for Change

In the first phase of implementation, a comprehensive strategic planning session was conducted to align the model's objectives with the company's goals. During this stage, the team was formed, comprising both management and frontline staff, and roles were clearly defined to facilitate seamless collaboration. Following the team formation, an extensive training program was developed and delivered, focusing on TPM's core elements such as Planned Maintenance and Autonomous Maintenance. This initial stage ensured that each team member possessed the knowledge and skills necessary to carry out their roles effectively. Training metrics revealed that over 95% of staff successfully completed the program, reflecting a strong commitment to the implementation process.

Data-Driven Diagnosis and Action Planning

The second phase of the implementation involved a rigorous data collection and analysis process. The team conducted a comprehensive assessment of the production line, identifying key performance indicators (KPIs) such as Overall Equipment Effectiveness (OEE), Mean Time Between Failures (MTBF), and Mean Time to Repair (MTTR). This analysis revealed that OEE was significantly below the industry standard at 65%, with frequent breakdowns and prolonged repair times. The collected data served as the foundation for defining targeted corrective actions. These actions were then prioritized based on their potential impact on improving efficiency and reducing downtime. A Pareto analysis showed that over 60% of downtime was attributed to three critical issues: inadequate preventive maintenance, insufficient operator training, and a lack of standardized maintenance procedures.

Empowering Operators through Autonomous Maintenance

In the third phase, the implementation of Autonomous Maintenance (AM) became a central focus. Operators were trained to take ownership of basic maintenance tasks, allowing them to conduct routine inspections, cleaning, and minor repairs. This shift not only reduced the reliance on specialized maintenance staff but also promoted a proactive mindset among operators. Visual management tools and standardized checklists were introduced, enabling operators to easily monitor equipment conditions and identify early signs of wear or malfunction. As a result, machine downtime decreased by 22% within the first three months of AM implementation. Furthermore, employee feedback surveys indicated a 30% increase in job satisfaction, driven by the enhanced sense of ownership and responsibility.

In Figure 3, the proposed Autonomous Maintenance plan is outlined, focusing on a semi-automatic sealing machine identified as "Machine No. 78." This maintenance strategy aims to empower operators by assigning them specific tasks to regularly inspect and maintain critical machine components. The figure details various parts, the activities associated with their upkeep, and the recommended frequency for these actions. Key tasks include the daily cleaning and lubrication of moving parts such as the pressure piston and the drive chain, as well as periodic checks of electrical contacts to ensure they remain undamaged and functional. This proactive approach not only seeks to improve machine reliability but also aims to enhance operational efficiency by preventing breakdowns and extending the equipment's service life.

DATOS DEL EQUIPO	
No.de máquina	78
Nom. máquina	SELLADORA
Sistema de soporte	SEMI-AUTOMATICO
Marca	AXOMATIC
Modelo	AS-600
Localización	PLANTA PACIFICO
Fecha de elabora.	
Responsable	OPERARIO - RODRIGUES
Ultima revisión	5-Mar-22
Hoja (x/y)	8.00 AM

Mantenimiento Autonomo

ITEM	PARTE	ACTIVIDAD	FRECUENCIA
1	Cadena de arrastre	Limpieza de cada una de las partes y lubricación adecuada.	DIARIO
2	Contactos eléctricos	Verificar que no esten dañados y que funcionen correctamente.	SEMANAL
3	Embolo de presión	Limpieza de cada una de las partes y lubricación adecuada.	DIARIO
4	Partes moviles (longitudinal y transve	Limpieza de cada una de las partes y verificar que no esten dañados.	DIARIO
5	Piñones	Limpieza de cada una de las partes y verificar que no esten dañados.	DIARIO

Figure 3. Autonomous maintenance proposed

Establishing Robust Planned Maintenance Practices
In parallel with Autonomous Maintenance, the implementation team introduced Planned Maintenance (PM) practices to systematically address equipment reliability issues. This approach involved creating detailed maintenance schedules based on historical failure data and manufacturers' recommendations. Key equipment was categorized according to its criticality, and maintenance intervals were adjusted to optimize resource allocation. The introduction of PM practices led to a 15% increase in the availability rate, which rose from 70% to 85% over six months. Additionally, the standardization of maintenance tasks resulted in a more consistent and efficient workflow, minimizing the occurrence of unexpected breakdowns.

In Figure 3, the Vibrational Analysis is presented as a key part of the preventive maintenance strategy implemented for an electric motor identified as "Equipment Code: 002." The analysis was conducted on March 8, 2022, to assess the motor's condition based on vibration readings in three directions: Vertical (V), Horizontal (H), and Axial (A). The motor operates at 1120 RPM, and the measurement points are distributed along the shaft and bearings

The table within the figure indicates vibration measurements taken at four key points along the motor assembly, with data provided for each direction. The vertical measurements (V) show variations across points, indicating areas where vibration levels may be higher. Similarly, the horizontal (H) and axial (A) measurements highlight specific areas of concern, allowing for targeted maintenance interventions.

This analysis aims to detect early signs of misalignment, imbalance, or wear, which could lead to equipment failure if left unaddressed. By proactively monitoring vibration levels, the maintenance team can schedule timely interventions to prevent unexpected breakdowns and optimize the motor's operational performance.

In Figure 4, the Vibrational Analysis is presented as a key part of the preventive maintenance strategy implemented for an electric motor identified as "Equipment Code: 002." The analysis was conducted on March 8, 2022, to assess the motor's condition based on vibration readings in three directions: Vertical (V), Horizontal (H), and Axial (A). The motor operates at 1120 RPM, and the measurement points are distributed along the shaft and bearings.

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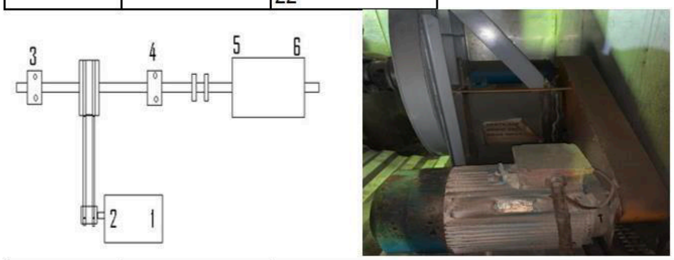
Empresa:	Equipo: Motor eléctrico Código: 002	RPM: 1120 Fecha: 08-MAR-22



Dirección	Unidad	Punto			
Medida en:		1	2	3	4
V		17.3992	19.6512	2.8368	6.9327
H		14.3752	9.8349	10.5624	11.0098
A		27.8875	35.8974	4.9835	5.8972
Env.		-------------	-----	---------	-------

Figure 4. Vibrational Analysis for Preventive Maintenance of Electric Motor Code 002

Continuous Monitoring and Validation of Improvements

The final phase of implementation focused on validating the effectiveness of the model and ensuring the sustainability of the achieved improvements. A robust monitoring system was established to track real-time performance data and detect deviations from established standards. Regular audits were scheduled to review compliance with new maintenance protocols and identify areas for further refinement. Performance reviews showed a 20% improvement in OEE, reaching a new average of 78%, while MTBF increased by 18%. These gains were attributed to the systematic approach to maintenance and the continuous engagement of staff in improvement initiatives.

5. Results

In Table 1, the results of validating the proposed TPM-based maintenance model are presented. It shows a notable increase in operational efficiency, which rose from an initial value of 65% to 74%, reflecting an improvement of 13.85%. Similarly, the availability rate experienced a positive change, increasing from 64% to 71%, which corresponds to a variation of 10.94%. These improvements suggest that the implementation of the model contributed significantly to optimizing both efficiency and equipment availability. Furthermore, the rate of non-conforming products demonstrated a substantial decrease, dropping from 43% to 32%, achieving a reduction of -25.58%. These results indicate that the proposed model was effective in addressing key inefficiencies within the maintenance processes, leading to measurable gains in quality and productivity (Table 1).

Table 1. Results of validation of the proposed model

Indicator	Unit	As-Is	To-Be	Results	Variation (%)
Operational Efficiency	%	65%	85%	74%	13.85%
Availability Rate	%	64%	90%	71%	10.94%
Rate of non-conforming products	%	43%	10%	32%	-25.58%

6. Conclusions

The study presents a comprehensive investigation into the operational challenges faced by small and medium-sized automotive battery manufacturing companies, specifically in improving efficiency and reducing non-compliance rates. The findings reveal that the implementation of the proposed TPM-based maintenance model significantly improved operational efficiency and equipment reliability. Through the structured approach, the case study demonstrated a 13.85% increase in operational efficiency and a 25.58% reduction in non-conforming products, highlighting the model's effectiveness in enhancing production processes. The autonomous and planned maintenance strategies were particularly impactful, empowering operators to take ownership of routine maintenance tasks while introducing a systematic framework for preventive actions. These improvements collectively contributed to a more reliable production environment and greater alignment with industry standards.

The importance of this research lies in its focus on addressing specific operational inefficiencies prevalent in the battery manufacturing sector. By adapting Total Productive Maintenance (TPM) principles to the unique requirements of small and medium-sized enterprises, the study offers a practical solution to persistent issues such as high downtime and quality deviations. The findings underscore the relevance of autonomous and planned maintenance as effective methodologies for sustaining operational gains and ensuring long-term stability. Moreover, this research underscores the value of employee involvement in maintenance activities, which not only enhances equipment reliability but also fosters a proactive and engaged workforce, crucial for achieving sustained improvements in a competitive market.
This research contributes to the field by filling a critical gap in the literature regarding the application of TPM methodologies in small and medium-sized battery manufacturers. Existing studies often focus on large-scale organizations or more established industries, leaving a void in understanding how these maintenance strategies can be adapted for smaller enterprises with limited resources. The study's contributions lie in demonstrating how TPM tools can be tailored to fit the operational and financial constraints of SMEs while delivering significant improvements in key performance indicators. By providing a scalable framework that integrates autonomous and planned maintenance, this research offers valuable insights for other SMEs in the automotive sector facing similar challenges in maintaining production efficiency and quality standards.

The findings and methodologies discussed in this study lead to several key observations and recommendations for future research. First, the successful implementation of the TPM-based model suggests that small and medium-sized manufacturers can achieve substantial gains by adopting structured maintenance approaches. However, it is essential to emphasize the role of continuous training and capacity building in sustaining these improvements over time. Without ongoing employee engagement and periodic reviews of maintenance practices, the initial gains may not be maintained. Future studies should explore ways to enhance the model's adaptability to other manufacturing contexts, focusing on sectors with similar operational constraints and challenges.

Additionally, the study highlights the need for more comprehensive metrics to assess maintenance effectiveness beyond traditional indicators such as operational efficiency and availability rates. The inclusion of metrics related to sustainability and resource utilization could provide a more holistic view of the model's impact. Moreover, further research could investigate the integration of advanced digital tools, such as predictive maintenance algorithms and real-time monitoring systems, to enhance the proactive maintenance capabilities of the model. Such advancements would not only improve the accuracy of maintenance interventions but also align the model with current trends in Industry 4.0 and smart manufacturing.

In conclusion, this study presents a robust framework for improving the operational efficiency of small and medium-sized automotive battery manufacturers through the tailored application of Total Productive Maintenance principles. The findings indicate that adopting autonomous and planned maintenance strategies can significantly reduce equipment downtime and enhance product quality, thereby boosting competitiveness in an increasingly demanding market. While the proposed model has shown promising results in the case study, its broader applicability to other SMEs in the automotive sector and beyond remains an area for further exploration. Researchers and practitioners are encouraged to build upon this study by refining the model and exploring its potential to drive sustainable improvements in different manufacturing contexts.

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