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Lean maintenance 4.0: Enhancing welding machine reliability in steel galvanizing processes

L. Matos[a] 0009-0000-7925-5687, N. Torre[a,*] 0000-0003-4260-2686,
A. Bonamigo[b] 0000-0002-6670-9755

[a] *Escola de Engenharia Industrial Metalúrgica de Volta Redonda-UFF, Programa de Pós-Graduação em Engenharia de Produção, Volta Redonda, Brasil;*

[b] *Universidade Federal de Santa Catarina (UFSC), Programa de Pós-Graduação em Engenharia de Produção, Santa Catarina, Brasil*

ABSTRACT

Maintenance is a critical function in the steel industry, playing a key role in production performance. Lean methodologies are extensively implemented in industrial settings, emphasizing practices that drive continuous improvement. Industry 4.0 has emerged through intelligent technologies designed to digitalize industrial processes. The combination of these approaches creates meaningful synergies that can assist both researchers and practitioners in enhancing the operational efficiency of organizational assets. The objective of this study is to investigate how Lean 4.0 principles can enhance maintenance management and operational efficiency in a welding machine within a steel galvanizing process. This research applies Lean 4.0 principles through an empirical case study of a welding machine in a steel galvanizing line, focusing on ensuring welding quality and optimizing maintenance processes. The findings reveal a considerable reduction in production downtime: by standardizing disc replacement procedures, introducing a machine checklist, and providing staff training, the continuous galvanizing line achieved a reduction of 375 minutes per year in total welding machine downtime, compared to the historical baseline of 496 minutes per year specifically associated with welding disk failures. This optimization resulted in organizational improvements and a more competitive industrial environment with skilled personnel.

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*Corresponding author:
Nuno Torre
nuno_torre@id.uff.br

1. Introduction

Lean 4.0 is transforming production by helping companies face the pressures of increasing market competition. Studies highlight that Lean practices and Industry 4.0 technologies complement each other, making the adoption of digital and smart manufacturing solutions more effective when a Lean culture is already established [1].

The steel industry ranks among the most significant industrial sectors, playing a crucial role in the global economy. Consequently, minimizing waste in operational processes is essential, making the implementation of Lean tools a critical factor. Lean practices improve production efficiency, enhance product quality, and foster a culture of continuous improvement [2].

Implementing Industry 4.0 technologies in steel plants increases productivity, reduces costs, and promotes sustainability. Digitalization improves supply chain management, quality control, maintenance, and production planning. IoT sensors provide real-time data on production processes. This enables

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faster, more precise decision-making and optimizes plant performance [3].

According to [4], equipment maintenance is critical for steel industries, as it ensures safe operations, prevents costly downtime, and supports continuous, efficient production. Maintenance plays a key role in industrial operations, as equipment failures can lead to serious consequences, including environmental harm, safety risks for workers, and significant financial losses. Implementing effective maintenance practices helps maintain operational continuity, reduces unplanned downtime, and ensures that production systems operate at their optimal efficiency levels [5].

As per [6], the continuous galvanizing line is an integral part of steel industry processes. This process provides excellent corrosion resistance for products such as pipes and automotive components. Steel is coated with zinc, and the coating quality depends on both the zinc composition and the steel surface. The process involves immersing the steel in a zinc bath and using rollers and gas knives to achieve a uniform finish [7].

In continuous galvanizing lines, laser welders are critical assets that connect steel strips and ensure uninterrupted production. Predictive maintenance using machine learning allows early detection of potential failures, minimizing downtime and maintaining operational efficiency in steel plants [8].

Several studies have highlighted the importance of structured maintenance practices for improving equipment reliability [9]-[11]. Recent research also explores the integration of Industry 4.0 technologies with Lean maintenance approaches, demonstrating potential benefits for production efficiency and asset performance [12]-[14]. However, these studies are predominantly conceptual, simulation-based, or focused on short-term case analyses, lacking robust longitudinal validation in real industrial environments, particularly in steel galvanizing processes.

In contrast, this study advances the current state of research by providing a five-year longitudinal empirical analysis of a welding machine in an industrial galvanizing line, enabling a deeper understanding of failure patterns, maintenance performance evolution, and the sustained impact of Lean 4.0 interventions over time. Thus, the main contribution lies in moving beyond theoretical and short-term evidence, offering validated, real-world insights into how Lean 4.0 improves maintenance reliability and operational performance in a critical industrial context.

In this context, this research aims to support maintenance managers in developing strategies to reduce unplanned downtime through the application of Lean 4.0 principles within a steel galvanizing production line. Unlike previous studies, this research adopts an integrated Lean 4.0 approach combining action-research methodology, real-time data analysis, and structured problem-solving tools (e.g., Ishikawa, 5W1H, and TPM 4.0) applied in a real industrial environment.

The novelty of this study lies both in the applied approach, linking Lean maintenance practices with Industry 4.0 technologies through a longitudinal and intervention-based framework, and in the proposed solutions, which include standardized procedures, real-time monitoring systems, and data-driven maintenance indicators validated in practice. The study seeks to minimize production losses by strengthening maintenance planning, improving condition monitoring, and increasing equipment reliability, thereby enhancing overall operational performance.

The research problem is grounded in a longitudinal analysis of maintenance and production data collected over a five-year period. During this time, the analysed galvanizing production line experienced significant productivity losses due to frequent corrective maintenance interventions on welding machines, highlighting the need for more structured, data-driven maintenance management practices, as welding systems are recognised as critical sources of downtime in continuous galvanizing processes[8].

The objective of this study is to investigate how Lean 4.0 principles can enhance maintenance management and operational efficiency in a welding machine within a steel galvanizing process. This study addresses the following research question: How does the application of Lean 4.0 principles to maintenance management influence operational efficiency and maintenance performance of welding machines in steel galvanizing processes?

To achieve this objective, the study adopts an integrated theoretical and empirical approach, examining how the combination of lean practices and digital technologies contributes to improving equipment reliability and maintenance effectiveness. The research evaluates the impact of data-driven maintenance strategies, real-time condition monitoring, and standardized maintenance procedures on reducing downtime and increasing machine availability.

This paper is organized into six sections: Section 1 introduces the topic, Section 2 reviews the literature, Section 3 presents the methodology, Section 4 reports the results, Section 5 discusses the findings, and Section 6 concludes the paper.

2. Literature review

2.1 Industry 4.0

Organizations operate in increasingly uncertain and competitive environments, driven by rising customer expectations and market pressures. The Fourth Industrial Revolution - Industry 4.0, has introduced a range of technologies to modernize industrial operations, including Artificial Intelligence (AI), Internet of Things (IoT), Cloud Computing, and Big Data [15]. These technologies enable interoperability, real-time data exchange, and decentralized decision-making in industrial systems.

In maintenance management, Industry 4.0 supports predictive capabilities, condition monitoring, and data-driven interventions, allowing a transition from reactive to proactive maintenance strategies [9]. Furthermore, these capabilities support the integration of maintenance with continuous improvement approaches, such as Lean Maintenance, reinforcing the foundations of Lean Maintenance 4.0 [12].

2.2 Lean Maintenance and Machine Reliability

In steel plants, assets operate under harsh conditions such as high temperatures, corrosion, erosion, and wear, which directly impact performance and increase maintenance costs. Sophisticated equipment is often prone to random failures, making an effective maintenance strategy essential for operational efficiency. Proper maintenance not only extends equipment life but also reduces production costs, ensuring smoother and more reliable plant operations [16].

Lean was developed to eliminate waste and promote continuous improvement. It is a gradual, long-term strategy aimed at covering every productive process. Paired with Industry 4.0 technologies, Lean emphasizes: value, value-stream mapping, continuous flow, pull systems, the pursuit of perfection, and the role of people and teamwork [17].

Lean Maintenance applies Lean principles to maintenance, repair, and overhaul activities to improve efficiency across all operations. It focuses on optimizing inventory, controlling costs, preventing breakdowns, and training personnel. The approach aims to maintain required product reliability while minimizing maintenance expenses. By integrating Lean methods, organizations can enhance operational performance and reduce waste in maintenance processes [18].

According to [19], organizations adopt lean-based maintenance to reduce waste and create greater value in maintenance activities. In this context, lean maintenance focuses on minimizing common wastes such as downtime, excess inventory, and rework, and promotes structured criteria and standardized procedures to support more reliable equipment performance. By systematically identifying and eliminating these wastes, maintenance teams can improve asset availability and strengthen overall machine reliability.

2.3 Conceptual Integration of Lean Maintenance and Industry 4.0

Building on the technological capabilities of Industry 4.0 and the efficiency-driven mindset of Lean Maintenance, this convergence creates a synergistic effect. Lean 4.0 and Lean Maintenance 4.0 emerge as approaches focused on systematic waste elimination, supported by real-time data and intelligent automation. This integration enhances decision-making, improves asset reliability, and promotes efficient and continuously improving maintenance systems [12], [17], [20].

The application of Lean Manufacturing to maintenance activities reflects Lean 4.0 principles, where waste reduction is supported by data-driven practices. In the context of Industry 4.0, maintenance evolves from reactive to more structured and performance-oriented approaches. This alignment improves maintenance effectiveness and equipment reliability [9], [21].

Integrating Lean principles with Industry 4.0 technologies enhances maintenance management by enabling data-driven decision-making and continuous improvement. This synergy improves the monitoring, planning, and execution of maintenance activities, contributing to higher operational performance and sustainability in industrial systems [9], [12], [22].

2.4 Quality Management Tools

To operationalize this conceptual integration in practical industrial settings, traditional Quality Management tools are employed to bridge the gap between data acquisition and continuous improvement. According to Feitosa et al. [23], within Quality Control Circles (QCCs) the PDCA cycle (Plan–Do–Check–Act) functions as more than a problem-solving framework: it provides a data-driven, repeatable structure that guides teams through planning actions, testing solutions on a small scale, evaluating outcomes, and then standardizing or refining changes

— thus embedding continuous improvement and organizational learning into daily practices.

Moso and Olanrewaju [24] described Five Whys as a core lean technique applied after identifying the type of waste, where it "assists in finding the reason for the problem occurrence" by repeatedly probing why the issue emerged, thereby deepening the root cause analysis prior to further categorization with Ishikawa analysis.

Brainstorming is a technique for fostering group creativity where ideas and thoughts are spontaneously shared among members to reach solutions for practical problems, making these sessions particularly appropriate for increasing productivity in learning-specific situations [25].

Alarcón et al. [26] stated that the Ishikawa diagram serves to identify the potential factors responsible for variability in the main components of the products, organizing these causes into major categories such as Methods, Environment, Facilities, Materials, Staff, and Measurement, thereby supporting a structured and comprehensive root-cause analysis.

Total Productive Maintenance (TPM) is a comprehensive strategy aimed at boosting overall industrial productivity and equipment reliability by establishing the principle that responsibility for equipment care is shared collaboratively among all employees, including both operators and dedicated maintenance staff [27].

3. Research Method

This study was conducted in a continuous galvanizing line of a Brazilian steel manufacturer. The methodological approach was designed to analyse the causes of downtime associated with the welding machine responsible for joining coils at the entry section of the line, and to propose improvements supported by Lean Maintenance 4.0 concepts.

The research is applied in nature and has descriptive and exploratory objectives. A quantitative approach was used to examine empirical data, while qualitative techniques such as literature review and contextual document understanding were also employed. This study adopts an action-research methodology, which, according to [28], is particularly suitable for operational studies because it allows the researcher to simultaneously investigate and intervene in real operational settings. This approach fosters collaborative problem-solving and practical improvements. It involves participants in identifying problems, developing solutions, and implementing improvement actions.

In this study, improvement actions were developed and implemented with active researcher involvement, ensuring that theoretical insights were directly integrated with practical interventions. The research followed sequential stages aligned with the action-research cycle [28], as presented in Table 1.

From a Lean 4.0 perspective, preventing high operational costs requires structured strategies for technology adoption. Effective asset management integrates Industry 4.0 technologies with maintenance practices to improve performance indicators such as availability, reliability, and serviceability, supporting more assertive and transparent managerial decisions [29].

The problem was structured according to a nine-step action-research cycle to integrate Lean 4.0-related tools:

Table 1. Action-research cycle

Action research cycle	Stage	Description	Step Aim
Plan	1	Definition of the research theme	State the topic and its operational relevance.
	2	Bibliographic survey	Select key studies related to maintenance, steel industry, Lean, and Industry 4.0
	3	Data collection	Gather process data for diagnostic purposes.
	4	Data analysis	Identify root causes affecting performance.
	5	Action plan	Propose improvement actions based on the findings.
Act	6	Implement of actions	Apply the interventions in the operational setting.
Describe	7	Evaluate of results	Assess the impact of the implemented actions.
Evaluate	8	Standardization	Formalize the improved procedures.
	9	Results Validation and Synthesis	Summarize the research-action cycle and outcomes.

The first step identified the research problem, associated with production line downtime resulting from corrective maintenance in the welding machine, a factor recognized as the central issue.

The second step comprised a bibliographic review using the Scopus database, selected for its comprehensive coverage of engineering studies, to align the research with the theoretical pillars of Lean 4.0 [1].

The third step involved collecting five years of maintenance data (2020-2024) from the SAP system, including downtime records, failure types, maintenance interventions, and equipment history. The brainstorming session and subsequent focus group involved a purposive sample of 12 professionals, including 4 maintenance engineers, 3 production supervisors, and 5 senior operators, all with over 10 years of experience in the galvanizing line to formulate initial hypotheses on downtime causes [25].

The fourth step focused on analysing the collected data by classifying the causes identified during brainstorming within an Ishikawa diagram to map the variables affecting the welding machine's performance. A focus group methodology supported this process, facilitating collaborative discussions to ensure that the identified solutions were aligned with Lean 4.0 principles [12]. To objectively prioritise the root causes, a structured impact–frequency evaluation matrix was applied during the focus group sessions. The 12 experts scored each brainstormed cause from 1 (low) to 5 (high) according to two dimensions: occurrence frequency in SAP historical maintenance records and potential operational impact on downtime. Causes achieving a combined mean score equal to or greater than the predefined threshold of 4.0 were selected by consensus as critical factors and highlighted in red in the Ishikawa diagram.

The fifth step consisted of developing an action plan using the 5W1H method to mitigate corrective maintenance based on the key factors selected from the Ishikawa diagram.

The sixth step involved the implementation of the actions defined in the plan.

The seventh step consisted of the evaluation of the results through an analysis of operational data to identify trends in downtime and production losses, as well as the overall effectiveness of the improvement actions.

The eighth step addressed the standardization of the improved processes, carried out through the Floor Management Development System (FMDS) to ensure visual management and routine adherence on the shop floor. In cases of complex failures, the engineering department is systematically involved, utilizing the PDCA cycle as a structured framework to analyse deviations, implement corrective actions, and establish standards to prevent recurrence [22].

The ninth step presented the results validation and synthesis. The outcomes were validated through a comparative analysis of the baseline period versus the post-intervention period, and findings were presented to the plant's technical board for formal approval. This stage highlights how the synergy between Lean production and Industry 4.0 technologies supports maintenance managers, demonstrating how data-driven decision-making and real-time monitoring enable more effective maintenance management policies, moving from reactive to proactive strategies [30].

To improve the clarity of the methodological sequence, a visual representation of the action-research cycle was developed according to Figure 1, illustrating the nine stages organized into four macro-phases (Plan, Act, Describe, and Evaluate) and the tools applied in each step.



Figure 1. Action-research cycle. *Authors own work*

4. Results

This section presents the results following the action-research cycle, structured into four main stages: (i) problem identification and data analysis, (ii) development of the action plan, (iii) implementation of improvement actions, and (iv) evaluation and standardization of results. This structure is intended to improve clarity and guide the reader through the sequence of the applied methodology.

4.1 Plan

4.1.1 Definition of the research theme

Analysis of data extracted from the SAP system, the company's management software, revealed that the production line has accumulated five years of downtime associated with the corrective maintenance index of the galvanizing line, as shown in Figure 2. This scenario highlights the need for an empirical investigation to improve maintenance management and operational performance. Furthermore, a Power BI analysis identified the welding machine as the equipment with the highest unavailability rate within the production line.

4.1.2 Bibliographic survey

The main terms of this research were selected from the Scopus database for the period 2020–2025. The inclusion criteria restricted the search to articles and reviews written in English. The results were summarized using the following search combinations: "Maintenance" AND "Lean" AND "Steel Industry" (8); "Lean" AND "Industry 4.0" AND "Steel Industry" (8); "Maintenance" AND "Industry 4.0" AND "Steel Industry" (43); "Maintenance" AND "Lean" AND "Industry 4.0" (66), totalizing 125 scientific articles. Subsequently, the 50 most relevant articles to the subject were selected.

4.1.3 Data collection

Based on data collected from the welding machine, it was identified that over the last five years the production line has experienced an average annual downtime of 10.9 hours, corresponding to 654 minutes per year due to corrective maintenance. Of this total, failures related to the welding disks account for 496 minutes, representing the most critical share of the downtime. Considering a production rate of 53 tons per hour, this disc-related downtime results in an estimated annual production loss of approximately 438 tons.

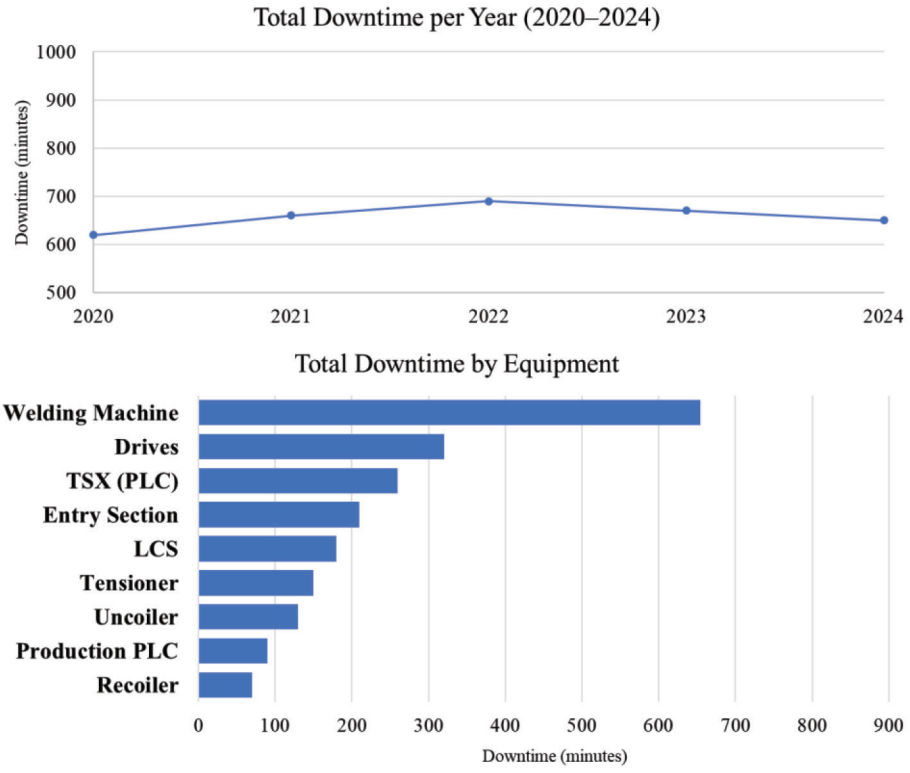


Figure 2. Production line's downtime. *Authors own work*

In financial terms, this loss corresponds to an estimated impact of about R$ 2,847,000.00 per year, based on a unit value of R$ 6,500.00 per ton. A more detailed analysis of the operational data subsequently identified the most frequent failure mode in the system, namely a short circuit occurring between the welding disks, as shown in Figure 3.

To investigate the underlying causes, a brainstorming procedure was conducted, as illustrated in Figure 4, in order to identify the key factors or variables that may lead to corrective maintenance events.

4.1.4 Data analysis

Operational problems are common in organizations, and managers must make accurate decisions to support continuous improvement. Due to the significant production losses caused by corrective mainte-

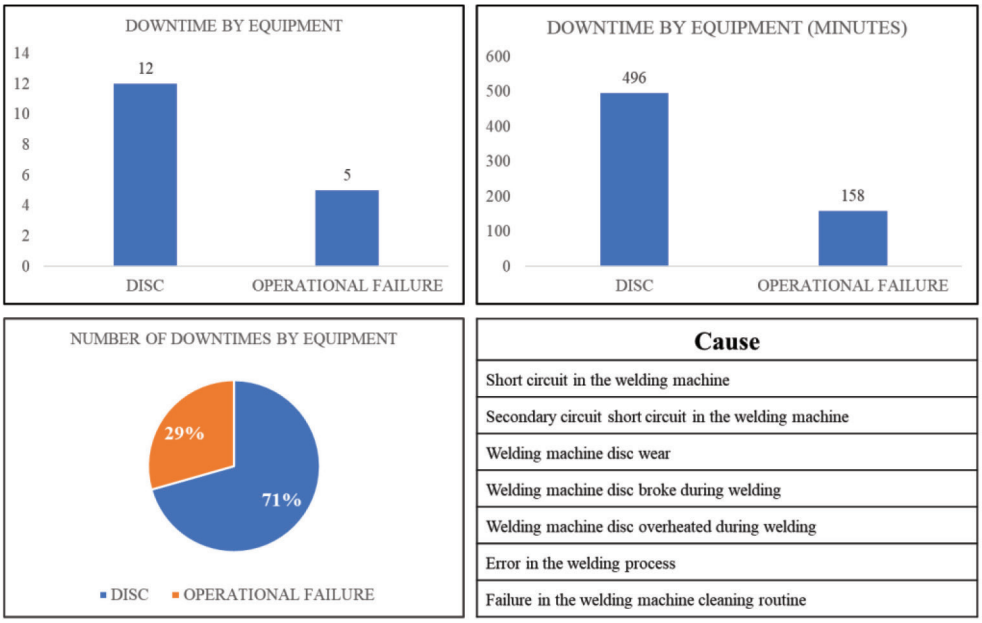


Figure 3. Welding machine downtime. *Authors own work*

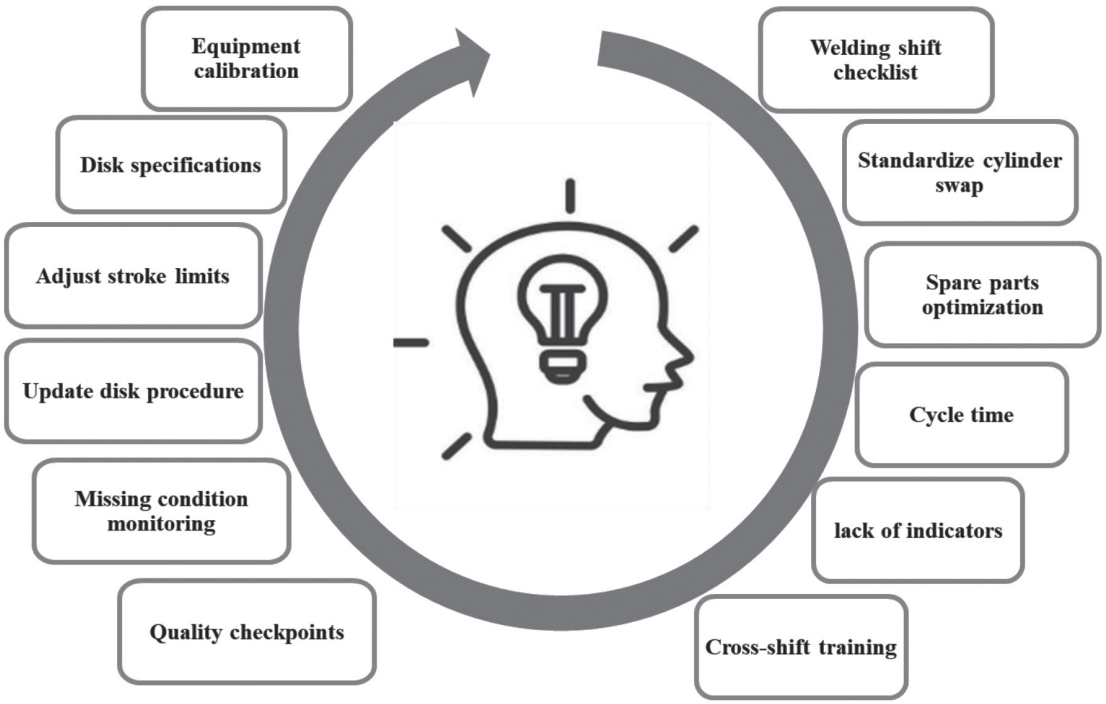


Figure 4. Brainstorming. *Authors own work*

nance, the causes identified during the brainstorming stage were organized using an Ishikawa diagram. This tool provides a clear overview of the factors influencing the process and supports decision-making. The factors considered most impactful, based on expert consensus, supported by the frequency of occurrence observed in the historical maintenance data, are highlighted in red in Figure 5. This consensus-driven selection was formalized through the impact–frequency ranking matrix, in which the identified causes were evaluated according to their occurrence frequency and operational impact on downtime. This process filtered out minor variables and isolated the major technical failures (e.g., stroke limit deviations, missing sensors, and outdated procedures) that statistically represented over 70% of the recorded welding line breakdown events.

4.1.5 Action Plan

Following the comprehensive analysis conducted using the Ishikawa diagram, a detailed action plan was developed and subsequently implemented to address and significantly reduce the corrective maintenance rate. This strategic plan is structured utilizing the 5W1H matrix framework while incorporating the principles of the 6M classification. Table 2 provides a detailed and organized overview of all the proposed and implemented actions.

4.1.6 Implement the actions

In line with the established action plan, the implemented measures are summarized according to four categories: (i) Manpower, (ii) Machine, (iii) Method, and (iv) Measurement, improving the readability and organization of the results.

a) Man power

Cross-Shift Training – The company revised the disc-replacement procedure and provided specific training to designate one qualified employee per shift, ensuring that only trained personnel perform this task. Training was conducted by internal specialists, strengthening man–machine interaction and supporting continuous improvement. The adoption of TPM 4.0 principles enhanced operator autonomy and reduced response time for problem resolution, contributing to more effective lean maintenance planning.

[22] argue that Industry 4.0 has revolutionized production through advanced data analytics, enabling TPM to strongly converge with I4.0 technologies within a Lean Production perspective. This comprehensive TPM 4.0 strategy enhances operational efficiency in manufacturing environments by emphasizing core pillars like autonomous maintenance and formalized training and education.

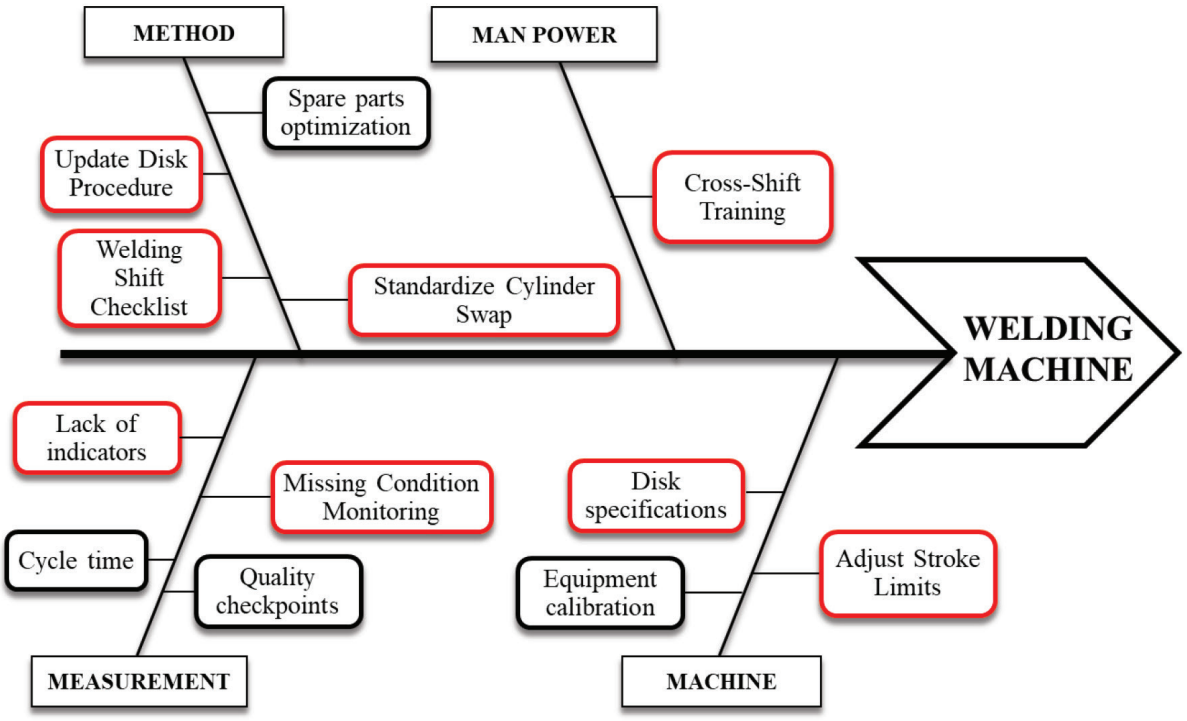


Figure 5. Ishikawa diagram. *Authors own work*

Table 2. Action plan

	What?	Who?	Where?	Why?	When?	How?
Man power	Cross-Shift Training	Maintenance and production department	On-site knowledge sharing	Enhance employees' technical knowledge	Continuous	By revising and standardizing the disc-replacement procedure and providing cross-shift training led by internal specialists
Machine	Disk specifications	Area and Engineering staff	Engineering Department	Ensure compliance with technical specifications	08/2024	By consulting suppliers to verify compliance with specifications
	Adjust Stroke Limits	Area and Engineering staff	On field	Ensure compliance with technical specifications	08/2024	By measuring the cylinder stroke and adjusting it via the rod eye
Method	Welding Shift Checklist	Maintenance and production department	On field	Ensure process compliance	08/2024	Identify key points and record welding parameters each shift
	Update Disk Procedure	Area and Engineering staff	Engineering Department	Improve procedure reliability	08/2024	Review procedure points and parameters with technical team
	Standardize Cylinder Swap	Area and Engineering staff	Engineering Department	Prevent incorrect cylinder stroke	08/2024	Define replacement procedure with rod eye adjustment
Measurement	Lack of indicators	Area and Engineering staff	Production monitoring dashboard	Support decision-making	08/2024	Implement decision-support metrics decision-making
	Missing Condition Monitoring	Area and Engineering staff	Welding machine	Monitor parameters in real time and update indicators	08/2024	Trigger alerts when parameters exceed permitted ranges

b) Machine

Disk specifications – Design drawings were reviewed and suppliers were consulted to verify potential issues. The analysis confirmed compliance with technical specifications and no recent supplier changes. Based on these findings, a supplier validation routine was established, requiring certified vendors only. This action improved process reliability and equipment availability.

Adjust Stroke Limits - During the welding process, a short circuit occurred between the disks due to an excessive gap caused by insufficient pneumatic-cylinder stroke. Although the technical drawing specifies a closing stroke of 88.9 mm, the value measured on the shop floor was 86 mm. The cylinder was adjusted through the rod eye to restore the correct stroke. These actions are aligned with TPM and Lean 4.0 practices, ensuring process stability and preventing recurrence.

Following the approach of [31], the integration of Industry 4.0 technologies with Lean 4.0 and TPM practices enables real-time monitoring and adjustment of equipment. This approach supports verification of component specifications, timely correction of deviations, and enhances process stability. As a result, operational reliability and equipment availability are significantly improved.

c) Method

Welding Shift Checklist - During a meeting, key points to be checked each shift were identified, and a checklist was created to record the main welding machine parameters for each shift, including welding current, voltage, electrode pressure, disk condition (wear and alignment), cylinder stroke, and cooling system performance.

Update Disk Procedure - During a meeting with the equipment's technical team, the points of the procedure with persistent issues were discussed, and certain parameters were reviewed. Among other benefits, this initiative enabled Lean Maintenance management to contribute to the achievement of the established objectives.

Standardize Cylinder Swap – Due to the cylinder

stroke failure described in Section 4.4.5, it is recommended to establish a procedure for replacing the cylinder, including instructions for the correct adjustment. The incorrect stroke occurred because new cylinders were installed without properly adjusting the rod eye.

Smart sensors enabled real-time monitoring and early fault detection, supporting predictive maintenance and reducing unplanned downtime [32].

d) Measurement

Lack of indicators – In accordance with TPM 4.0 and Kaizen 4.0 principles, performance metrics were implemented to support managerial decision-making. These measures provided a more accurate and objective view of asset conditions, enhancing the quality and transparency of the decision-making process.

Missing Condition Monitoring – The implementation of a digital condition monitoring infrastructure, using transducers for welding current and voltage, ensured accurate data acquisition. Specifically, the continuous variables were monitored using a sampling frequency ranging from 60 to 1200 Hz (10 to 20 samples per cycle) to capture the RMS values within a time scale of 100 to 300 ms. The operational thresholds were rigorously defined as follows: the mechanical actuation performed by pneumatic cylinders targeted a vertical alignment of 0.00 mm; welding current was monitored within a 45–50 kA operational window; and voltage limits were established between 8.5 V and 10.5 V, dynamically adjusted according to transformer closure and material characteristics.

These sensors were integrated into a local Programmable Logic Controller (PLC), which transmitted real-time process data to monitoring dashboards developed in Power BI. The dashboard displayed emergency stop occurrences, welding current and voltage trends, downtime duration, alarm history, and failure stratification by equipment and maintenance area, supporting predictive and corrective maintenance decision-making. This architecture enabled the generation of automated alerts sent directly to maintenance devices, allowing faster intervention by technical teams.

For example, when the system detected electrical insulation leakage associated with pressure loss in the pneumatic cylinders, an automated alert was immediately transmitted to the maintenance technician before a short circuit could occur between the welding discs.

Integrating TPM 4.0 and Kaizen 4.0 principles, the sensor system enabled real-time updates of maintenance indicators and allowed immediate action whenever parameters deviated from acceptable limits. As a result, on-site inspection rounds became leaner, since alerts were automatically issued to operators.

[30], highlight that implementing Lean 4.0 methods allows performance improvements, where deploying indicators can reduce response times and operational workload, while also enhancing communication between employees and assets through improved human–machine interaction.

4.1.7 Evaluate the results

Over the past five years, the production line recorded an average of 8.27 hours (496 minutes) of downtime per year associated with welding disk failures. After the implementation of the improvement actions, production time lost due to disc-related corrective maintenance of the welding machine was reduced by 375 minutes per year, representing a reduction of approximately 6.25 hours.

Considering a production rate of 53 tons per hour, this improvement corresponds to a recovery of about 331 tons of production per year. Based on a unit value of R$ 6,500.00 per ton and an initial annual loss of approximately R$ 2,847,000.00, the implemented actions resulted in an estimated annual financial gain of R$ 2,151,500.00, supporting the production line in meeting its targets. This performance improvement was driven by a cultural shift in maintenance and production practices, supported by full employee engagement. Figure 6 illustrates the trend of production-time losses in minutes.

The implementation of TPM pillars, including autonomous maintenance, focused improvement, planned maintenance, quality maintenance, and employee training, proved essential for effective maintenance management. TPM empowered operators, reducing response times for troubleshooting, while the 5S methodology enhanced workplace organization and standardization.

TPM 4.0 was enabled through intelligent sensors that transmit equipment data via cloud computing for analysis using Big Data, allowing maintenance engineers to simulate scenarios and optimize intervention timing. The integration of Industry 4.0 and Lean Maintenance significantly decreased corrective maintenance, improved connectivity and process visibility, increased welding machine reliability, and enhanced production line efficiency. Overall, Lean 4.0 tools facilitated better decision-making, minimized downtime, and supported leaner, more efficient maintenance strategies.

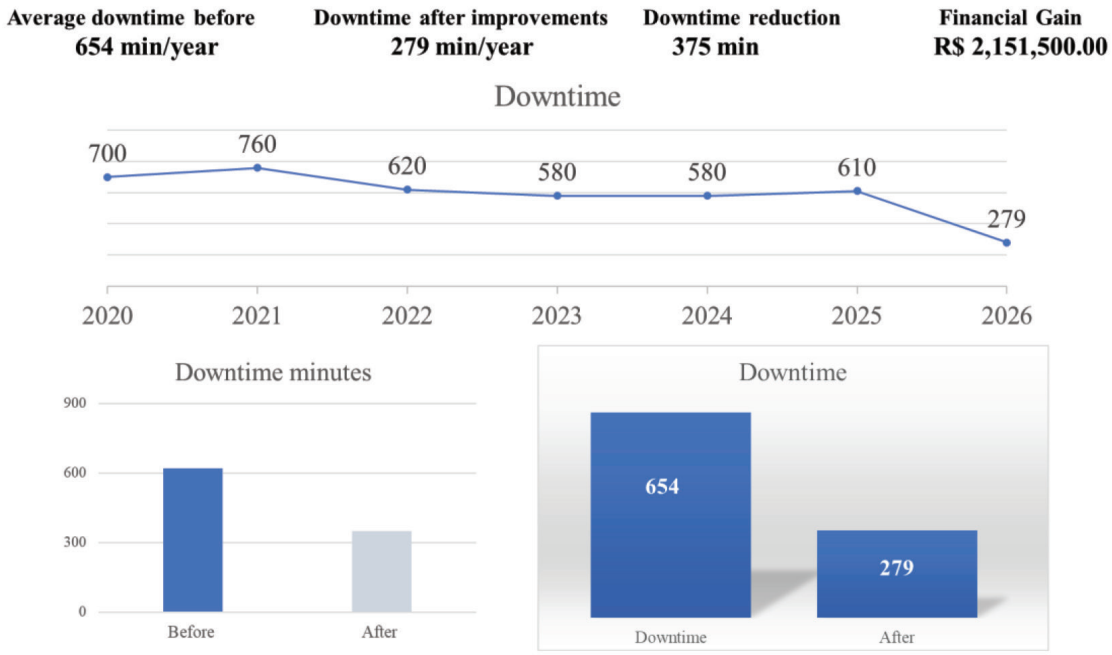


Figure 6. Trend of production-time losses in minutes. *Authors own work*

Integrating sensors and data analytics enables predictive maintenance in Industry 4.0, allowing early fault detection and reducing reactive interventions. Real-time monitoring supports optimized planning and minimizes downtime. Combining Lean Maintenance with digital technologies enhances reliability and operational performance processes [10], [17], [33].

Table 3 presents a summary of key performance indicators before and after the implementation of the improvement actions, highlighting the operational and financial impact of Lean 4.0.

4.1.8 Standardization

After the positive results, the procedures for disc replacement, the welding machine checklist, and employee training were standardized, improving operational efficiency and reducing the likelihood of failures. This standardization followed the FMDS method, and complex failures are forwarded to the engineering department, which applies the PDCA cycle when necessary.

With the Lean 4.0 implementation, employees will receive training through internal programs, and maintenance decisions will be guided by operational performance indicators to support appropriate management policies.

Standardizing procedures, checklists, and training improves operational efficiency and supports proactive maintenance decisions within an Industry 4.0 framework. Real time performance indicators provide objective feedback for planning and execution, reducing failures and aligning maintenance actions with continuous improvement. Integrating digital KPIs with Lean 4.0 principles enhances both work-

Table 3. Key performance indicators

KPI	Before (Baseline)	After (Lean 4.0)	Improvement
Annual downtime	654 min/year	279 min/year	↓ 375 min/year
Disc downtime	496 min/year	121 min/year	↓ significant reduction
Downtime reduction	–	375 min/year	↓ 57% (≈)
Production loss	438 ton/year	–	–
Recovered production	–	331 ton/year	+331 ton/year
Financial impact (loss)	R$ 2,847,000/year	–	–
Financial gain	–	R$ 2,151,500/year	+R$ 2,151,00 /year

force competence and overall maintenance performance [12], [34].

The implementation of the PDCA cycle ensured the prevention of recurrence. This phase demonstrates that the integration of Lean 4.0 concepts into daily management (FMDS) is a primary contribution of this research. While traditional maintenance often lacks data continuity, this study shows that digital standardization acts as a catalyst for long-term reliability in the steel industry [22]. This finding aligns with the research's originality: providing a replicable framework for maintenance management in complex industrial assets [32], [33] .

4.1.9 Results Validation and Synthesis

The integration of Industry 4.0 technologies with Lean principles, known as Lean 4.0, enhanced equipment availability and staff efficiency, reducing corrective maintenance on the welding machine. TPM 4.0 empowered employees by enabling faster responses to equipment failures through intelligent sensors that transmit monitored values to management software. Sensor implementation reduced the need for physical inspections, making them leaner and more efficient. Management indicators now provide a clearer view of asset conditions, improving transparency and supporting decision-making through TPM and Kaizen 4.0 practices. Overall, Lean 4.0 boosted production line efficiency, increased employee autonomy, and improved workplace organization using the 5S methodology.

This synthesis demonstrates that the integration of Industry 4.0 technologies with Lean and TPM practices enhances equipment availability, supports real time monitoring and decision making, and empowers operators to improve maintenance performance and efficiency [9], [20], [29],[30], [32].

5. Discussion

5.1 Theoretical Implications

This research is part of an ongoing investigation into how Lean Systems and Industry 4.0 can be applied in the steel industry. Recent analyses indicate an increasing connection between these approaches, highlighting their potential to enhance industrial processes. The study reinforces this interaction by showing that Lean 4.0 provides a structured framework to integrate digital tools into maintenance management. These findings are consistent with previous studies [9], [12], which highlight the benefits of integrating Lean and Industry 4.0, prior research is often limited to conceptual or short-term analyses, whereas this study provides longitudinal empirical evidence in a real industrial environment.

Combining TPM pillars with intelligent sensors and real-time data analytics enhances asset reliability and reduces corrective maintenance. It contributes theoretically by explicitly demonstrating how Lean maintenance concepts can be operationalized through Industry 4.0 technologies within a structured, data-driven, and longitudinal framework. This extends the literature by showing how this integration can be systematically implemented and sustained over time in an industrial setting.

Data-driven approaches support proactive decision-making and operational continuity, particularly in steel galvanizing processes. Unlike prior studies, the results demonstrate sustained performance improvements supported by real operational data. Overall, the results confirm the relevance of this integration for industrial modernization and efficiency.

5.2 Practical Implications

The implementation of Lean 4.0 in the welding machine of a continuous galvanizing line demonstrated significant operational benefits. These included a reduction in downtime (average 6.25 hours per year), equivalent to 331 tons of production recovered annually, and a financial gain of approximately R$2, 151,500.00 per year. Operator empowerment and real-time monitoring via intelligent sensors enabled faster responses to equipment failures. Leaner inspection routines and standardized procedures enhanced process efficiency and reduced human error.

The integration of TPM 4.0 and Kaizen 4.0 promoted continuous improvement and better planning of maintenance activities. 5S practices improved workspace organization and communication, contributing to higher employee satisfaction.

Real-time data monitoring performance supported proactive decision-making. Overall, combining Lean principles with Industry 4.0 tools effectively reduced unplanned downtime and increased production performance. The approach can be transferred to similar industrial contexts, particularly in continuous production systems, provided that there is availability of historical data, management support, and integration between maintenance teams and digital monitoring systems.

5.3 Advantages and disadvantages of this study

This research serves as a theoretical reference for organizations facing maintenance challenges and offers solutions through Lean 4.0 implementation.

Advantages include a combined theoretical and empirical framework, use of five-year operational data from a steel galvanizing line, and measurable improvements in downtime, production, and financial performance. Disadvantages involve costs for adapting assets and training personnel.

Limitations include focus on a single welding machine, which restricts external validity, requiring ongoing management support to sustain cultural changes, and dependence on accurate sensor data and proper Industry 4.0 integration. Additionally, the absence of a control group limits the ability to isolate the effects of the intervention, and results may be influenced by contextual operational factors.

6. Conclusions

The steel industry operates in a highly competitive environment where effective maintenance is essential for quality, cost reduction, and asset optimization. Lean 4.0, through the integration of Lean practices and Industry 4.0 technologies, enhances asset availability, reduces waste, and minimizes production losses.

This study demonstrated, through a five-year longitudinal analysis, that the application of Lean 4.0 principles in a welding machine of a galvanizing line resulted in a reduction of 375 minutes per year in welding disk-related downtime, corresponding to approximately 331 tons of recovered production and an estimated financial gain of R$ 2,151,500.00 per year.

These results provide robust empirical evidence that combining TPM practices, standardized procedures, and real-time monitoring systems improves maintenance performance and equipment reliability in industrial environments. Unlike prior studies, this research demonstrates sustained improvements based on longitudinal industrial data.

From a theoretical perspective, it validates the integration of Lean maintenance and Industry 4.0 within a data-driven and intervention-based framework, while from a practical standpoint, it offers a replicable approach to reduce unplanned downtime and improve operational efficiency.

TPM pillars empowered operators, improved workplace organization via 5S, and real-time monitoring with intelligent sensors supported data-driven decisions and reduced downtime. Overall, the findings confirm that Lean 4.0 is not only conceptually relevant but also operationally effective when systematically implemented and supported by real industrial data.

6.1 Limitations and Future Research

Although this study demonstrates significant operational gains and efficiency improvements, it is limited to the analysis of a specific welding machine. Future research could explore the application of Lean 4.0 across multiple production lines, the integration of advanced predictive maintenance models, and the long-term impact on workforce skills, operational sustainability, and organizational culture, providing further insights into the scalability and strategic benefits of this approach.

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