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Optimizing Mill Bolt Production Efficiency in a Metal Mechanical Firm via Digital Twin Technology and Lean Methodologies

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ABSTRACT

Objective: This study evaluates the impact of integrating Digital Twin technology with Lean methodologies on the operational efficiency of a firm in the Peruvian metal-mechanic sector, focusing on a mill-bolt production line. The company currently experiences substantial operational challenges, including high variability in production times, an inadequate facility layout, and limited technological integration. These deficiencies contribute to a low overall efficiency level of 44.04%. The purpose of this research is to demonstrate how the combined application of Digital Twin–based modeling and Lean process improvement strategies can enhance system performance, reduce operational inefficiencies, and strengthen organizational productivity.

Methods: This study employs an applied research approach using a quasi-experimental design. Data was collected through informal conversations with production operators and the review of historical production records. The methodological process was structured in two phases. In the first phase, model validation was conducted through pilot experimentation focused on Lean methodologies. In the second phase, the proposed enhancements were evaluated and validated through computational simulations, enabling a controlled assessment of their impact on system performance.

Results: The findings indicate an increase in operational efficiency from 44.04% to 61.66%, demonstrating the effectiveness of integrating Digital Twin technology with Lean methodologies. These results support the significance of the combined model in enhancing system performance and reducing operational inefficiencies

Conclusion: The results of this study underscore the substantial impact that a comprehensive, integrated intervention can have on the operational efficiency of metal-mechanic production environments. The research highlights the critical value of uniting traditional process-improvement approaches with emerging digital tools. This integration not only enhances decision-making and process control but also strengthens the organization's capacity for continuous improvement and long-term competitiveness.

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1. Introduction

The global metal mechanic industry represents one of the fundamental pillars of the manufacturing economy, with an estimated market value of more than 4.3 trillion dollars in 2023 and a projected compound annual growth (CAGR) of 5.7% until 2030, driven by automation, digitalization, and growing demand in sectors such as mining. construction, automotive, and energy. However, this growth is conditioned by the need to optimize processes, reduce waste, and increase operational efficiency, especially in developing countries, where digital transformation still has significant gaps (World Steel Association, 2024). In Peru, the metal mechanical industry plays a strategic role in the development of the industrial sector, the strengthening of national infrastructure, and the support of essential production chains such as mining, construction, and agribusiness. Among the key products it manufactures are mill bolts, which are fundamental components in crushing equipment used in mining processes. The metal mechanical industry maintains a share of 11.2% in the manufacturing Gross Domestic Product (GDP) and 1.4% in the national GDP (Institute of economic and social studies (IEES), 2023). However, it has registered a negative average rate of -2.3% in its recent economic evolution, which reflects a loss of dynamism and competitiveness. This situation is exacerbated by the low level of technological maturity observed in many Peruvian companies in the sector, which operate with semi-automatic machinery, require operator intervention, have partial monitoring, and have limited digital connectivity. According to recent models, this classification corresponds to medium levels of maturity (phase 2 of 5), where only partial integration of technologies has been achieved, without a continuous flow of data or cloud systems.

In recent decades, numerous studies have highlighted the challenges of low operational efficiency in manufacturing environments, particularly in settings dominated by semi-automated processes and suboptimal plant layouts. Continuous improvement methodologies, such as Lean Manufacturing, have demonstrated significant success in minimizing waste, eliminating non-value-added activities, and streamlining workflows (Medyński et al., 2023). The adoption of the 5S methodology, for instance, has led to measurable improvements in workplace organization, cleanliness, and material accessibility (Yalico-Luciano et al., 2023a). Additionally, planning tools like Systematic Layout Planning (SLP) have proven effective in redesigning plant layouts, resulting in reduced transfer times and fewer flow interruptions (Hongliang et al., 2021).

The integration of SLP with digital simulation technologies—particularly digital twins—has further enhanced layout optimization and material flow management. These technologies support real-time process monitoring, improve traceability, and enable data-driven decision-making (Choi et al., 2024). Case studies show that the combined application of Lean Manufacturing principles and SLP tools not only facilitates process standardization but also contributes to reduced travel times and increased profitability (Rega et al., 2021). Consequently, the use of innovative approaches such as digital twins is proving instrumental in bridging the gap between current operational limitations and a more efficient, profitable manufacturing model (Salins et al., 2024).

The motivation for this research stems from the urgent need to enhance efficiency in the manufacturing sector. This is a challenge that many companies encounter within a highly competitive, dynamic, and increasingly automation-driven environment. This issue is particularly pronounced in metal mechanical companies, where numerous plants still operate with intermediate levels of technological maturity. Their processes often rely on manual intervention, which restricts their ability to adapt, operate effectively, control operations, and utilize resources efficiently.

The main contribution of this research is the development of a hybrid model for operational improvement. This model integrates traditional industrial engineering methodologies with emerging digital tools, creating a comprehensive approach to enhance efficiency in the production lines of companies with moderate technological maturity.

The article is structured into five sections. First, the Introduction outlines the context of the problem, the current state of the metal mechanical industry, and the motivation behind the study. The second section is the Literature Review, which examines previous advancements and the use of tools in operational improvement processes. In the third section, we present the theoretical and practical contributions, including a discussion and an innovative proposal based on the results obtained from the implementation and validation of the proposed solution. Finally, the Conclusions section summarizes the main findings of the study, their practical implications, and outlines potential directions for future research.

2. Literature review

The literature review for the state of the art focused on studies applying SLP, 5S, standardization, and digital twins, key tools to improve efficiency in the mill bolt production line at the company. The search was conducted in recognized databases, ensuring access to relevant and high-quality research.

2.1 Efficiency

In this study, operational efficiency (%) is defined as the ratio of actual monthly production to the nominal monthly capacity of the production line (Huertas-Reyes et al., 2022).

$$Efficiency = \frac{Actual\ production}{Capacity} \tag{1}$$

The baseline operational efficiency used in this study is 44.04%, calculated as the annual average for 2024 using the defined efficiency formula. All reported values—whether in text, tables, or figures- adhere to this definition and are consistently rounded to two decimal places.

2.2 Application of SLP in a metal mechanical company

The implementation of the SLP methodology, especially when combined with tools such as 5S, has proven to be highly effective in improving productivity in manufacturing plants. Various studies report significant reductions in travel distances (up to 87.8%) and physical effort (88.5%) (Cancho-Alvaro et al., 2023), as well as improvements in organization that reduce the time of access to tools and materials by 60%. In addition, there has been a 30% reduction in transfer times(Jara et al., 2023), a 70% decrease in manufacturing costs and a 30% decrease in handling costs (Mohamadi et al., 2019), and a 10% to 38% increase in overall productivity (Silvestre et al., 2022), by intervening on problems such as excessive travel, operational disorder, and inefficient material handling.

2.3 Application of 5S in the production process of a metal mechanical company

According to research, metal mechanical companies are looking to optimize their production processes by implementing the 5S methodology to improve not only the work environment but also increase operational efficiency. As a result of these improvements, a significant reduction in machining time on the lathe is achieved, increasing efficiency by up to 74.18%. It has also been shown to be effective in addressing issues related to space organization and the arrangement of materials (Quiroz-Flores & Vega-Alvites, 2022). In one manufacturing plant, it was able to reduce material search times by 25% and 4.40% of total operating time, thus improving efficiency in operations (Shahriar et al., 2022) in addition, the application of the 5S tool reduces production cycle time, enabling a 50% increase in production volume and a 10 to 15% increase in production volume, thereby meeting a higher demand. Thus, achieving a reduction in errors and machine change times (Orellana-Nuñez et al., 2022a; Espinoza-Huamash et al., 2022).

2.4 Standardization of work in the production process of a metal mechanical company

The standardization of procedures has been key to ensuring consistency in production processes. The implementation of operational standards in a manufacturing company made it possible to reduce operational errors by 15% and ensure greater uniformity in production times. This tool not only ensures that procedures are executed correctly, but also contributes to improved production efficiency, effectiveness, stability, and continuous improvement of the operation, ensuring that variability in processes is kept to a minimum (Realyvásquez-Vargas et al., 2020; Yalico-Luciano et al., 2023b). In addition, it increases the workload of operators by 5%, improving the distribution of work and increasing efficiency in several stations between 12% and 31% (Kumar et al., 2023).

Inefficiency due to long times in operations affects productivity. For three months, Lean Manufacturing tools were implemented, such as process standardization. As a result, operating times were reduced by an average of 23%, with operations 20 and 50 standing out, while overall process efficiency increased from 66% to 83% (Pawlak et al., 2023; Kuryło et al., 2023).

2.5 Implementing digital twins in a metal mechanical company

According to the research conducted, as industries rapidly move towards automation and intelligence, digital twins play a critical role in improving factory efficiency and production management (Liu & Wu, 2024). The method focuses on predicting these failures using digital twins, which minimizes unplanned downtime (Kaid et al., 2024). The sensors provide the user's position with a certain degree of accuracy, enough to prevent errors in locating and tracking small objects (Alatawi et al., 2023).

One study proposes a model that integrates a tracking system equipped with sensors and a gateway, enabling comprehensive data acquisition, transmission, storage, and visualization across both mobile and fixed devices (Sheikh et al., 2021). Similarly, Mendes et al. (2023) emphasize that minor stoppages—often caused by raw material accumulation or other irregularities—can be mitigated through improved process integration and enhanced information flow. Furthermore, C. Liu et al. (2022) highlight that the availability of large volumes of production data, when analyzed using deep learning (DL) techniques, allows for the identification of complex correlations within mass production processes.

3. Methodology

The methodology employed in this research adopts an applied approach, utilizing a quasi-experimental design, aimed at enhancing operational efficiency in a production line within the metal mechanical sector. The study was conducted in a Peruvian company with a medium level of technological maturity, utilizing a combination of Lean Manufacturing tools, systematic plant planning, and partial integration of Industry 4.0 technologies.

3.1 Background

The company under study has been operating for over 25 years, specializing in the manufacture and export of bolts and hardware. Mill bolts account for approximately 33% of the plant’s total output, with primary markets including the mining, foundry, and construction sectors. Within the national industrial landscape, Más Acero plays a key role in the metalworking value chain linked to mining and construction. Its intermediate level of technological maturity and diverse product mix make it a suitable candidate for Lean-SLP interventions. Moreover, the validation and application of digital twin technologies present a strategic opportunity to enhance operational efficiency and support data-driven process optimization.

3.2 Problem Analysis

To identify the primary causes of low efficiency in the mill bolt production line, a comprehensive diagnostic was conducted, consisting of a technical walkthrough of the various process stations, interviews with operators and supervisors, and an analysis of historical production records. This assessment revealed that the most significant bottlenecks were concentrated in inter-station transfer activities, tool-searching tasks, and non-productive times resulting from the absence of standardized procedures.

Cycle times per station, material flow, and operating conditions observed in the plant were analyzed, which allowed the identification of the main deficiencies. From these findings, cause-and-effect diagrams were developed to delve deeper into the roots of the problem, which revealed disorder in the work environment, an inefficient plant layout, and a lack of traceability of the flow of materials.

Likewise, the lack of standardized procedures and the absence of digital tools for process tracking were evident, which prevented anticipating bottlenecks or operational delays. Based on this analysis, a solution model was formulated through the integration of four complementary tools: the 5S methodology, to improve the organization of the work environment; work standardization, to reduce operational variability; SLP, to redesign the physical distribution of the system; and Digital Twins, to create virtual replicas of processes that strengthen traceability, enable scenario analysis, and improve the availability of information for decision-making.

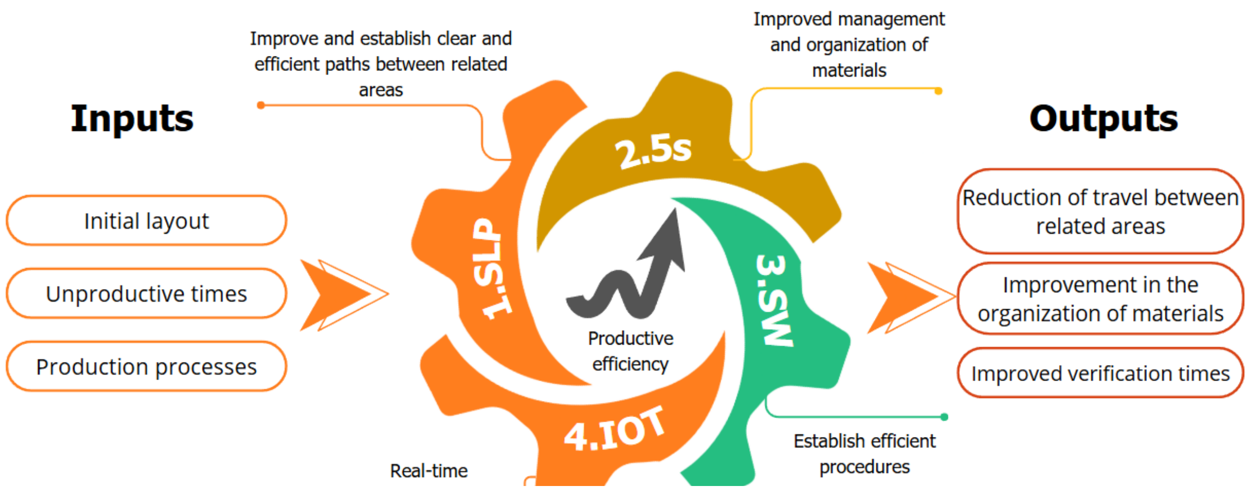

Figure 1. Proposal template

3.3 Validation of the proposed model

Model validation was conducted through pilot implementation at the plant and a computational simulation. The pilot focused on applying 5S and work standardization in critical areas to address disorganization, prolonged search times, and process variability. A continuous improvement team led the 5S deployment through audits and collaborated with operators—particularly in the furnace area—to develop standardized procedures.

In the second phase, the improvement proposal was digitally validated through computational simulation using SIMIO software, modeling both the current system and the proposed one.

This simulation focused on redesigning the plant layout using the SLP methodology. It considered functional relationships, physical constraints, material flow, and safety conditions. Additionally, a digital model was developed incorporating virtual sensors to capture variables such as waiting times, accumulation at stations, and travel times.

4. Contribution

The research proposes a comprehensive model of operational improvement aimed at industries with intermediate technological maturity, such as the Peruvian metal-mechanic sector, combining classic industrial engineering tools (5S, work standardization, and SLP) with accessible digital technologies such as digital models. Its coordinated approach makes it possible to address critical aspects such as layout, non-productive times, and operational dynamics, achieving tangible improvements without requiring full automation or large-scale investments.

4.1 Model Rationale

The proposed model involves implementing an integrated solution through a digital framework (Ou et al., 2024), complemented by Lean tools designed to optimize production times and material flow in the metalworking plant (Khan et al., 2022). This approach responds to the need to reduce non-productive time and inefficiencies in material handling (Tamer et al., 2023). By combining Lean methodologies with Digital Twin technology, the company achieved a 44.04% improvement in operational efficiency—surpassing the limitations of traditional methods and enabling more effective resource flow (Tang et al., 2022). The strategic use of Lean tools reinforces structured operational practices, proving essential for enhancing productivity and profitability in manufacturing (Fatima et al., 2024).

Rational design of functional area layouts is a key factor in improving operational efficiency, as it eliminates waste caused by unnecessary movement and contributes to smoother production scheduling, cost reduction, and better space utilization through simulation tools (Lu et al., 2024 ; Dube & Gupta, 2023, Grznar et al., 2022. Work standardization further supports resource optimization and enhances production efficiency by addressing downtime, bottlenecks, and variability—common causes of low productivity and potential stoppages (Balcıoğlu et al., 2023).

4.2 Proposed Model

The proposed model is a methodological tool designed to improve operational efficiency in production lines with intermediate technological maturity. It integrates three classic approaches of industrial engineering: SLP, the 5S methodology, and work standardization, complemented by the use of a digital model as an enabling technology.

The model follows an input, process-output logic. It is based on three key inputs: the diagnosis of the layout, the identification of non-productive times, and the nature of the production process. From these, the selected tools are applied to intervene in the flow of materials, the work environment, and operational standardization. As a result, a reduction in routes, improvement in organization, decreased variability, and greater traceability are expected.

As shown in Figure 1, the model articulates these components in a logical, adaptable, and modular structure, designed for progressive application in companies in the metal mechanical sector.

4.3 Model Description

Based on the analysis of the production system and the definition of the key indicators, the design was structured under a sequential transformation logic, which starts from operational inputs identified in the diagnosis and culminates in the generation of measurable outputs. The main inputs that feed the model are: The initial layout of the plant, characterized by long routes; the unproductive times associated with the search for materials, waiting, and transfers; and non-standardized operational processes, which generate variability in the execution of critical tasks.

The proposed model deploys an integrated set of tools and technologies in four methodological stages. First, the 5S methodology is implemented to optimize the work environment, eliminating unnecessary elements, defining fixed locations, and fostering a culture of order and cleanliness, which reduces search times and improves the availability of materials. Then, the standardization of work is applied through the documentation of key procedures to reduce variability between operators. In a third stage, the SLP methodology is used to redesign the physical distribution of the plant, considering factors such as proximity relationships, sequence of processes, and spatial limitations, to minimize unnecessary routes and travel times. Finally, Digital Twin is integrated as transversal support, providing material flow traceability through simulated sensors, thereby facilitating the detection of bottlenecks, supporting informed decision-making, and reinforcing the continuous improvement system.

As part of the structuring of the model, key indicators were defined to evaluate their impact on operational efficiency. These indicators were selected based on their direct relationship with the objectives of the model: to reduce non-productive times, improve the flow of materials, and standardize procedures. Table 1 summarizes the main indicators used.

Table 1. Key indicators

Number	Indicator	Unit	Actual	Expected
1	Operational efficiency	%	44.04	74.00
2	Search time	h/month	87.45	12.51
3	Cycle Time	Min/Piece	66.55	53.24
4	Transfer time	min	5040.88	2945

5. Results

5.1 Problem Analysis

As a starting point for the validation of the proposed model, the operational efficiency of the mill bolt production line in the metal mechanical company under study was analyzed. Table 2 presents the actual monthly production, installed capacity, and efficiency achieved in each period during 2024. The results show that operational efficiency was, in most months, considerably lower than the baseline of 74%, with an annual average below 50%. This production gap confirmed the need for intervention.

Table 2. Monthly mills bolt production line efficiency

2024				
My	**Actual Production (Und)**	**Capacity (unit)**	**Current efficiency**	**Referential efficiency**
January	2,065	7,776	26.56%	74%
February	2,495		32.09%	
March	3,873		49.81%	
April	2,830		36.40%	
May	5,306		68.23%	
June	2,780		35.75%	
July	3,514		45.19%	
August	3,500		45.01%	
September	2,219		28.53%	
October	3,191		41.03%	
November	5,023		64.59%	
December	4,302		55.33%	

In addition to the quantitative analysis, an operational diagnosis revealed several inefficiencies: disorganized workspaces, prolonged search times due to a lack of visual management, inconsistent work methods stemming from absent standard procedures, excessive travel times caused by a poorly designed layout, and limited monitoring tools that hindered traceability and effective decision-making.

Based on these findings, a comprehensive improvement proposal was designed by applying specific tools to each problem detected, allowing an analysis as a baseline for the validation of the model.

Table 3. Main causes of downtime in the production line – year 2024

Causes	Downtime (min/year)	% Frequency
Extensive tours between related areas	60,490.56	36.60%
High machinery repair times	9,960.00	6.03%
Delays in PM delivery	4,860.00	2.94%
Disorganized placement of materials	53,968.32	32.66%
No procedures are followed	35,979.84	21.77%
Total	**165,258.72**	**100.00%**

Additionally, the main causes of production line downtime throughout the year were quantified, which allowed prioritizing areas of intervention. Table 3 shows the time lost associated with each cause and its relative frequency. The main sources of inefficiency are the extensive routes between related areas (36.60%) and the disorganized location of materials (32.66%), which together represent more than 69% of the total inactivity recorded. Other relevant causes include non-compliance with standard procedures and high machinery repair times.

5.2 Validation

The validation of the proposed model was carried out through the implementation of Lean Manufacturing tools and Industry 4.0 technologies, applied according to the initial diagnosis. The actions were divided into two phases: a pilot intervention in the plant (5S and standardization), and a digital simulation (SLP and digital twin), which made it possible to measure the real and simulated impact of the proposal on operational efficiency.

The implementation of the proposed model was carried out following a combined strategy of pilot testing in the field and digital simulation, according to the nature of each tool involved.

5.3 5S Component

The 5S methodology was implemented as the base tool of the proposed model, with the aim of improving the order, cleanliness, and organization of the working environment in the critical areas of the mill bolt production line. Its application was carried out on a pilot basis in all stations, where the initial diagnosis showed high search times, unnecessary accumulation of materials, and lack of visual control.

During the SEIRI phase, unnecessary materials and obsolete items blocking work areas were removed, freeing up space and improving tool visibility. The impact was assessed with an area-by-area audit (1S verification form) before and after the intervention. The results show an increase in overall compliance from 44.23% to 59.62%, with notable improvements in Forging (+20.0 pp; 32.50% -> 52.50%) and Cutting (+16.2 pp; 50.00%→66.20%), where the accumulation and disposal of scrap was most critical. Chamfering, Deburring, Grinding, and Threading also showed consistent increases (≈+15 pp), a result of sorting, removing, and redesigning temporary storage locations. This advancement in 1S reduces operational clutter and lays the foundation for 2S (Seiton), directly impacting the reduction in search times and the immediate availability of supplies and tools. The percentage by area corresponds to the degree of compliance with the 1S checklist, and the TOTAL reflects the average of the audited areas. All figures are standardized to two decimal places and were obtained using the same assessment instrument.

Table 4. 1s compliance by area: Seiri

Area	Current %	% Enhanced
Court	50.00%	66.20%
Bevel	57.50%	63.00%
Forge	32.50%	52.50%
Deburring	43.80%	58.50%
Grinding	41.10%	59.00%
Threaded	40.50%	58.50%
TOTAL	**44.23%**	**59.62%**

The Seiton phase established locations for tools, materials, and supplies with visual signage, colored tape, pictograms, and identifiers, achieving an overall increase in compliance from 30.00% to 50.00%. At the area level, consistent improvements are observed: Forging (16.10%→41.20%; +25.10 pp), Grinding (30.80%→52.00%; +21.20 pp), Cutting (32.10%→52.10%; +20.00 pp), Deburring (32.00%→51.30%; +19.30 pp), Threading (31.00%→50.00%; +19.00 pp), and Chamfering (38.00%→53.40%; +15.40 pp). These advances reflect immediate access to resources and a logical layout of the environment, which translates into shorter search times (consistent with the study's KPI) and paves the way for 3S (Seiso) and visual standardization. The percentages correspond to the degree of compliance with the 2S checklist by area; the total is the average of the audited areas, with figures standardized to two decimal places under the same instrument, the results of which are presented in Table 5.

Table 5. 2s compliance: Seiton

Area	Current %	% Enhanced
Court	32.10%	52.10%
Bevel	38.00%	53.40%
Forge	16.10%	41.20%
Deburring	32.00%	51.30%
Grinding	30.80%	52.00%
Threaded	31.00%	50.00%
TOTAL	**30.00%**	**50.00%**

The implementation of daily and weekly cleaning routes, with shift managers and visual checklists, increased overall compliance from 36.37% to 50.00%. By area, the greatest absolute increases occurred in Forging (17.20% → 41.20%, +24.00 pp, +139.53% relative), where the accumulation of scale and burrs was most critical; followed by Deburring (35.60% → 51.30%, +15.70 pp, +44.10%), Cutting (40.20% → 52.10%, +11.90 pp, +29.60%), Threading (38.60% → 50.00%, +11.40 pp, +29.53%), Grinding (41.50% → 52.00%, +10.50 pp, +25.30%) and Chamfering (45.10% → 53.40%, +8.30 pp, +18.40%). These quantitative increases indicate fewer obstructions and metal waste at the station, a lower risk of part contamination, and fewer micro-stops due to corrective cleaning, paving the way for 4S (Seiketsu) and the sustainability of the order achieved. All figures correspond to the degree of compliance with the 3S checklist by area, rounded to two decimal places, and the total is the average of the areas audited. The results of compliance by area are presented in Table 6.

Table 6. Compliance six

Area	Current %	% Enhanced
Court	40.20%	52.10%
Bevel	45.10%	53.40%
Forge	17.20%	41.20%
Deburring	35.60%	51.30%
Grinding	41.50%	52.00%
Threaded	38.60%	50.00%
TOTAL	**36.37%**	**50.00%**

The standardization of Seiri-Seiton-Seiso practices through checklists, visual sheets, and signage increased overall compliance from 28.45% to 42.87%, consolidating daily control and the sustainability of the previous 3S. By area, the greatest absolute advances were observed in Forging (18.40%→36.50%; +18.10 pp; ≈+98.4% relative), Grinding (26.20%→43.60%; +17.40 pp; ≈+66.4%), and Deburring (31.60%→47.60%; +16.00 pp; ≈+50.6%). Threading (32.50%→47.50%; +15.00 pp; ≈+46.2%), Cutting (32.00%→45.00%; +13.00 pp; ≈+40.6%), and Chamfering (30.00%→37.00%; +7.00 pp; ≈+23.3%) also improve. The quantitative pattern shows that areas with a lower baseline (e.g., Forging) capture larger proportional leaps by institutionalizing standards and verification roles. These 4S levels facilitate routine monitoring, reduce rework and micro-stops due to disorder/dirt, and pave the way for achieving higher goals (>50–60%) with periodic audits, shift feedback, and training focused on the gaps detected. (Percentages reflect the degree of compliance with the 4S checklist by area; the TOTAL is the average of the audited areas, rounded to two decimal places.). The compliance values are shown in Table 7.

Table 7. Seiketsu compliance

Area	Current %	% Enhanced
Court	32.00%	45.00%
Bevel	30.00%	37.00%
Forge	18.40%	36.50%
Deburring	31.60%	47.60%
Grinding	26.20%	43.60%
Threaded	32.50%	47.50%
TOTAL	**28.45%**	**42.87%**

Interpretation of Table 8 (5S – Shitsuke). The Shitsuke phase—aimed at consolidating habits through staff engagement, feedback, and self-assessments—increased overall compliance from 37.13% to 57.15% (+20.02 pp; ≈+53.9% relative). By area, the absolute increases were: Cutting (42.10%→60.60%; +18.50 pp), Chamfering (37.00%→59.10%; +22.10 pp), Forging (26.40%→42.60%; +16.20 pp), Deburring (37.40%→59.30%; +21.90 pp), Grinding (39.40%→60.50%; +21.10 pp), and Threading (40.50%→60.80%; +20.30 pp). In relative terms, the greatest percentage gains were seen in Forging (≈+61%) and Beveling (≈+60%), suggesting that where the baseline was lower, discipline and shift follow-up routines captured the most pronounced improvements. This performance confirms that Shitsuke is sustaining what was achieved in 1H–4H, reducing setbacks (disorder/dirt), and standardizing daily behavior. To continue the improvement curve, it is advisable to establish periodic audits (weekly/monthly), visual gap boards by area, and verification roles (shift leader/and on stoppage) with short-term goals of >60%–70%. The results are summarized in Table 8.

Table 8. Shitsuke compliance

Area	Current %	% Enhanced
Court	42.10%	60.60%
Bevel	37.00%	59.10%
Forge	26.40%	42.60%
Deburring	37.40%	59.30%
Grinding	39.40%	60.50%
Threaded	40.50%	60.80%
TOTAL	**37.13%**	**57.15%**

Finally, Figure 2 summarizes the process followed for the implementation and validation of the 5S component, from field intervention to the analysis of results obtained through audits and compliance indicators.

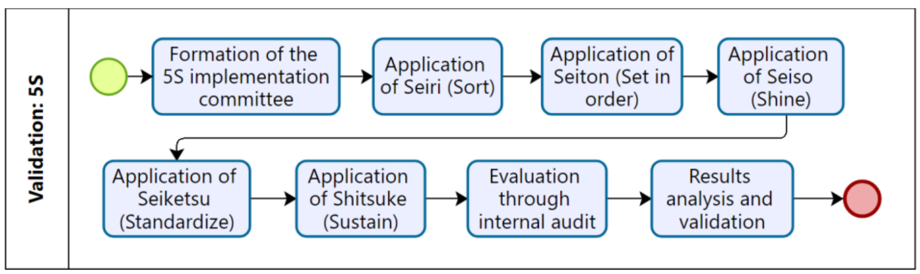

Figure 2. 5S validation flowchart

It can be seen in Figure 3 that the Seiri, Seiton, and Seiso stages present significantly higher values, with a current compliance of 59.62%, 50.00%, and 63.64%, respectively. These results are consistent with the activities carried out during the first four weeks of implementation, which focused precisely on these first three phases. In contrast, the Seiketsu and Shitsuke stages have not yet been fully developed, showing current levels of only 28.57% and 37.14%, as they are contemplated to be executed in the remaining weeks of the implementation plan.

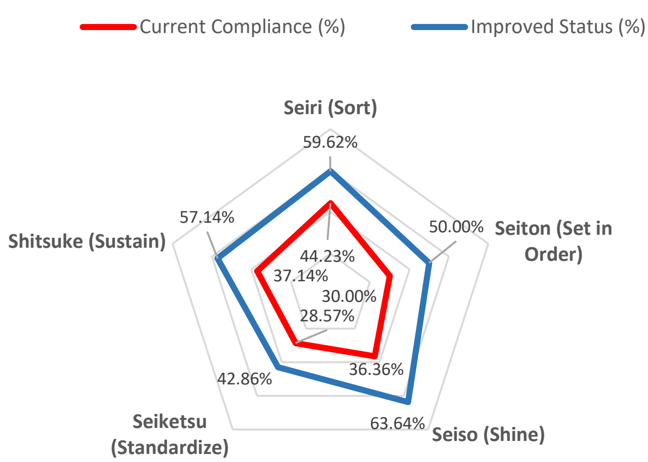

Figure 3. 5S Compliance

As part of the validation process of the 5S methodology, the conditions of order and cleanliness at the critical stations of the production process were visually documented before and after the intervention. The purpose of this photographic validation is to highlight the changes achieved after the progressive application of the first phases of the methodology: Seiri, Seiton, and Seiso.

Figure 4 presents the visual comparison of four key areas of the plant: forging, kiln, grinding, and the tool area. In each case, a significant improvement can be observed in the organization of the environment, the delimitation of spaces, the functional arrangement of materials, and the reduction of unnecessary elements.

Figure 4. Impact Assessment: Before and After 5S Methodology Implementation in Critical Production Stations.

Figure 5 shows a reduction in average daily tool search time from 85.3 minutes to 21.9 minutes, representing a 74.33% improvement. This data was recorded by direct observation and timing at three key stations, during regular working days, before and after the Seiri and Seiton phases were applied. This enhancement reflects the removal of unnecessary tools, the reorganization of space, and the implementation of resource-specific locations.

Second, the general order percentage at workstations increased from 10% to 70%.

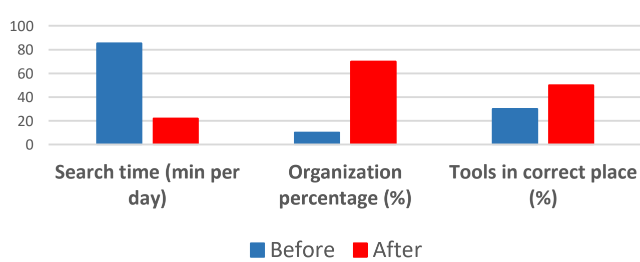

Figure 5. 5S Compliance

5.4 Standardization Component

Work standardization was implemented as a key part of the model to reduce operational variability between stations and operators, improve process repeatability, and ensure stable production conditions. This tool was specifically applied in threading, deburring, and grinding operations, where the initial diagnosis showed unstable times, differences in criteria between operators, and the absence of formal instructions.

	ACTIVITY	**SYMBOLS**					**REMARKS**	**TIME**
		●						
OVEN	Checking the Oven	●	■	➡	D	▼	Review of initial conditions	5
	Transport of the billet to the oven			●			Manual movement with tools	2
	Loading the billet in the oven	●					Careful positioning	3
	Heating the oven	●					Operating temperature range	20
	Heating the billet	●					Variable time depending on billet size	10
	Wait for coordination				●		Lack of synchronization with other areas	3
	Removing the billet from the oven	●					Using Security Tools	2
	Transport of the billet to the next process			●			Movement to the forging area	2
	Temporary storage					●	Waiting for the next stage of production	5

Figure 6. Furnace Area PDO

Figure 6 presents an example of a standardized procedure format used in the kiln area, which included step sequence, visual references, suggested times, and quality alerts. Based on the applied nature of the study and considering operational restrictions of time and access to the evaluated area, it was decided to work with a confidence level of 90%. Under these parameters, the minimum sample size required was 65 observations. Given that 80 observations were collected, it is concluded that the data obtained are statistically representative to support the evaluation of compliance with the work standardization (2).

$$n = \frac{Z^2 \times p \times (1-p)}{e^2} \tag{1}$$

Table 9 shows the percentage of compliance per step observed during the pilot test phase. 80 executions were evaluated through checklists, which showed that all the steps of the standardized procedure reached an overall average of 93.59%.

Table 9. Compliance percentage per observed step

Step	Number of successful executions	Total observations (80)	% Compliance
Step 1	70	80	87.50%
Step 2	71	80	88.75%
Step 3	80	80	100.00%
Step 4	80	80	100.00%
Step 5	80	80	100.00%
Step 6	75	80	93.75%
Step 7	75	80	93.75%
Step 8	68	80	85.00%
Average Total			**93.59%**

Figure 7 summarizes the process followed for the validation of the proposed design using the standardization tool.

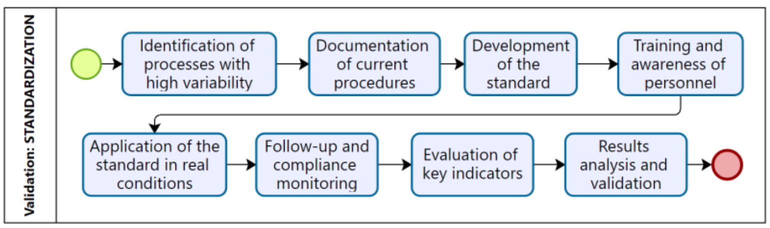

Figure 7. Standardization validation flowchart

To evaluate the impact of the standardization of work on the production line, indicators related to compliance with established procedures, total process time, and the elimination of waiting times for coordination were applied.

Table 10. Standardization indicators

Indicator	Initial situation	Situation with standard	Improvement (%)
Total Processing Time (min)	54	49	9.26%
Standby time per coordination (min)	3	0	100%
% Method Compliance		93.59%	

In terms of operational efficiency, the results showed a reduction in total process time from 54 to 49 minutes, equivalent to an improvement of 9.26%. Likewise, it was possible to eliminate waiting times for coordination between areas, which initially represented a loss of 3 minutes per cycle. These results are presented in Table 10.

SLP Component

The validation of the SLP component was conducted through digital simulation in the SIMIO software, comparing the performance of the current layout against the proposed layout in terms of material travel and total transfer time.

The validation process began with the collection of data from the current system, including travel times between stations, actual distances, frequency of transfer per product, and use of human resources in manual movements. From this information, the model of the current layout in SIMIO was built, faithfully replicating the spatial and logical arrangement of the real flow.

Subsequently, the optimized proposal obtained through SLP was modeled, incorporating improvements such as unidirectional routes, fewer crossings between operators, reduction of dead zones, and a more logical and continuous flow sequence. In both models, key processes were represented, and routes, mobile operators, buffers, and conditional events were configured to simulate the real behavior of the system.

To validate the impact of the redesign, the SIMIO software was used to simulate both scenarios: the current layout and the proposed layout. Figure 7 shows the simulation environment created in the SIMIO software to represent both the current layout and the proposed layout. In this simulation, the routes, workstations, mobile operators, and material flow rules were configured to compare both scenarios under similar operating conditions. In addition, virtual sensors were integrated to represent the monitoring of the passage and accumulation of parts in key areas.

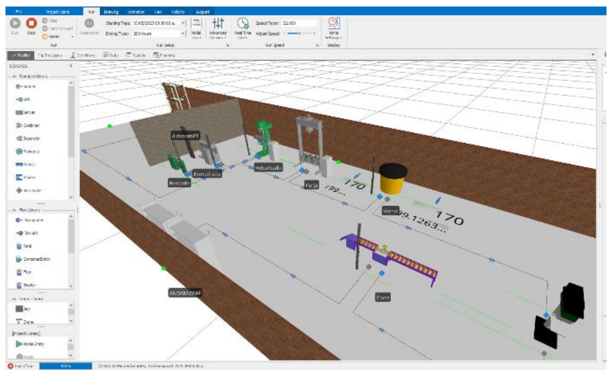

Figure 7. Simulation in SIMIO

After the implementation of the proposed design using the SLP methodology and its validation in the digital simulation environment, significant results were obtained regarding the improvement of the flow of materials and efficiency in transfers. The simulation was executed in the SIMIO software, comparing the current layout with the proposed layout, under equivalent operating conditions.

Table 11. SLP indicators

SLP Indicators	Current Layout	Proposed Layout	% improvement
Total distance traveled (m/month)	41,040.10	25,425.96	38.05%
Total travel time (min/month)	5,040.88	3,814.34	24.33%

The simulation demonstrated a 38.05% reduction in the distance traveled, which translates into decreased physical strain, reduced reliance on human resources for material transport, and a more balanced distribution of workloads. Furthermore, the total transfer time was reduced by 24.33%, enhancing the utilization of the line's operational capacity, as summarized in Table 10. Additionally, three critical process paths were examined, and their corresponding results are presented in Table 11.

Table 12. Travels

Travels	Transfer time to current day(s)	Time saved per day(s)	% improvement
Beveling - Threading	384.15	274.39	28.57%
Threading - PT Warehouse	373.88	169.9	54.56%
Grinding - Threading	351.91	284.29	19.22%

Figure 8 summarizes the process followed for the validation of the proposed design using the SLP tool and its simulation in the digital environment.

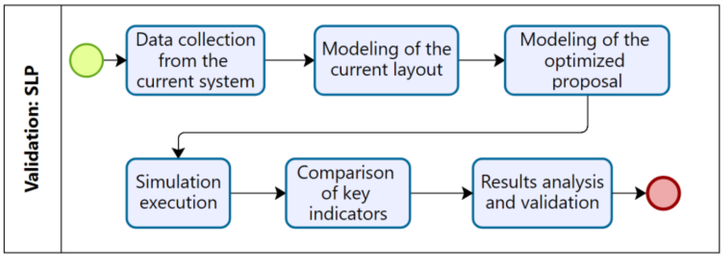

Figure 8. SLP validation flowchart

Digital twin Component

The Digital Twin simulation included the virtual installation of inductive sensors at strategic points along the production line. These sensors enabled real-time tracking of operator and material movements, facilitating the identification of bottlenecks and congestion areas. Figure 9 illustrates the simulation model, highlighting the placement of virtual sensors throughout the production flow..

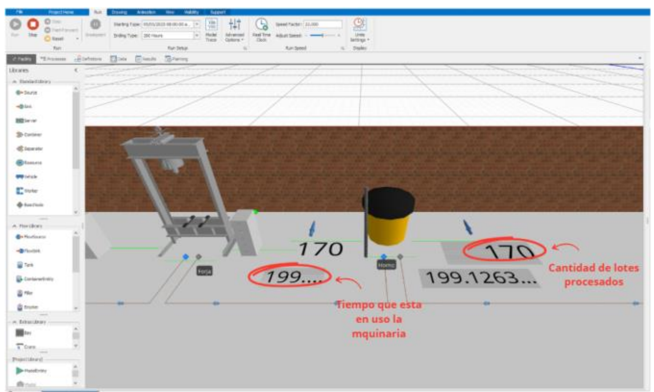

Figure 9. Simulation Model in IMS

The dynamic visualization of the internal flow, shown in Figure 10, provided critical insights that supported informed decision-making aimed at the continuous improvement of the process.

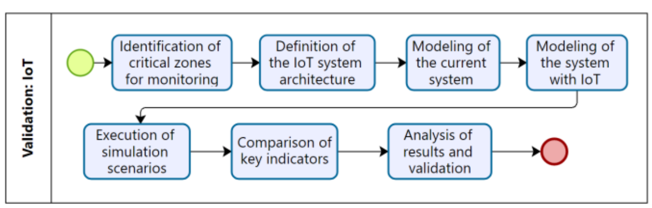

Figure 10. Digital twin validation flowchart

Comparing scenarios with and without virtual sensor monitoring demonstrated the value of process traceability in intermediate stages, revealing clear benefits in identifying inefficiencies.

Table 13 shows the main indicators generated with the inclusion of sensors in the model:

The simulated installation of inductive sensors enabled the collection of previously unavailable operational data, such as monthly batch counts, enhancing production control and traceability. The analysis revealed an oven utilization rate of 47.35%, indicating idle capacity and highlighting bottlenecks due to poor coordination with adjacent stations.

Additionally, sensor-based monitoring allowed for the calculation of total accumulated processing time—5,681 minutes—providing a clear baseline for future planning and productivity assessments.

Table 13. Digital twin indicators

Digital Twin indicators	Without sensors	With sensors	Description
Lots produced by the station/area x month	No registration	192	Greater control over production
Percentage of machinery utilization (e.g. oven)	No registration	58.40%	Real-time bottleneck identification
Processing Time (min)	No registration	4520	Processing Control

The simulation results demonstrate a positive correlation between higher levels of instrumentation and improvements in both process control and production efficiency. Specifically, increased production output and reduced processing time indicate that continuous access to operational data facilitates the timely identification and resolution of workflow inefficiencies. Collectively, these performance indicators suggest that full integration of monitoring capabilities via the digital twin architecture enhances decision-making processes and contributes to greater operational stability, even within a simulated environment.

6. Sensitivity analysis

Table 14. Digital twin simulation scenarios

Digital Twin Indicators	Sensor (0/7 machines)	Scenario 1: Partial simulation (2/7 machines)	Scenario 2: Medium simulation (4/7 machines)	Scenario 3: Total simulation (7/7 machines)
Batches produced per season/area per month	No registration	170	185	192
Percentage of machinery utilization (e.g. oven)	No registration	47.35%	53.60%	58.40%
Processing Time (minutes)	No registration	5 681	4 940	4 520
Level of reliability of results	Not applicable	88%	93%	96%
Percentage of control over production	0%	28.6 % (2/7 machines)	57.1 % (4/7 machines)	100 % (7/7 machines)
Overview Scenario	Without monitoring or traceability.	The initial implementation enables the identification of fundamental performance parameters and yields observable improvements in system behavior. This foundational stage establishes a baseline for evaluating operational efficiency and informs subsequent development efforts.	The implementation yields greater precision in decision-making and facilitates more effective detection of process bottlenecks and idle periods. These improvements contribute to enhanced workflow efficiency and support more informed operational strategies.	The implementation enables comprehensive and near-real-time control of the entire plant, resulting in more stable operational outcomes that closely approximate real-world behavior. This alignment between simulated and expected performance enhances the credibility of the model and its applicability to practical scenarios.

Simulation results obtained using SIMIO indicate that plant performance improves progressively with increased sensor integration. Higher levels of instrumentation contribute to enhanced production control, greater accuracy in processing times, and more effective detection of bottlenecks. While increased instrumentation does not directly expand physical production capacity, it significantly improves operational efficiency and process management. Notably, the scenario featuring sensors installed on all machines produced the most stable and reliable outcomes, demonstrating that greater digitalization leads to more efficient management and data that more accurately reflect the plant's real-world behavior. Overall, the implementation of the Digital Twin reduced uncontrolled delays and facilitated the development of an automated, replicable measurement system to support operational decision-making. These results reinforce the value of smart manufacturing practices, particularly in traditionally non-digital industrial environments.

The sensitivity analysis enabled an evaluation of the system's response to varying levels of instrumentation, revealing a progressive improvement in performance indicators as the number of monitored machines increased. The simulated scenarios demonstrated that both production output and operational efficiency are highly sensitive to the degree of control exercised over work areas. These findings suggest that partial monitoring constrains the system's ability to detect and resolve bottlenecks, whereas full instrumentation enhances stability and reliability. This underscores the importance of comprehensive sensor integration in achieving consistent and representative operational outcomes.

7. Discussion

After implementing the tools and validating them through a pilot test and simulation in SIMIO software, we conducted a global comparison of the main performance indicators before and after the validation and implementation of the proposed model. This evaluation enabled us to integrate the effects of each tool applied: 5S, work standardization, SLP, and the digital twin. Table 14 summarizes the initial values (As is), the projected target values (To Be), the results achieved after application (Result), and the improvement obtained in each case.

The results show significant improvements in all key indicators. The overall efficiency of the system increased by 16.16 percentage points, reaching a value of 60.2%, which represents a relative increase of 36%. Likewise, it was possible to reduce the time spent searching for tools by 16.4%, optimize the cycle time by 15.03% and reduce the total transfer time by 24.33%. These improvements reflect the positive impact of the methodological integration of Lean tools and Industry 4.0 technologies, consolidating the model as an effective proposal for increasing operational efficiency in metal mechanical environments.

Table 15. Key indicators

N°	Indicator	Unit	That's how it is	Result	Improvement	To Be	Technique / Article
1	Efficiency	%	44.04	60.2	16.16 (36% increase)	74.00	SLP + standardization + 5S / Huertas et al., 2022
2	Search Time (Tbe)	h/month	0.00	0.00	12.32 (16.4% re-deduction)	12.51	5S / Jara et al., 2023
3	Cycle Time	min/unit	66.55	56.55	10.00 (15.03% increase)	53.24	Digital twin + Standardization / Orellana-Nuñez et al., 2022
4	Transfer time	min	5,040.88	3814.34	1226.4 (24.33% Reduction)	2945	SLP / Nenzhelele et al., 2023

These findings align with previous studies that combined Lean Manufacturing tools with emerging technologies to enhance operational efficiency. The integration of SLP, work standardization, and 5S in manufacturing environments has been shown to increase system efficiency by up to 35%, closely matching the 36% improvement observed in this study. This reinforces the effectiveness of a structured, multidisciplinary approach to process optimization (Huertas-Reyes et al., 2022).

An 18% reduction in tool search time was reported in an industrial assembly setting following 5S implementation. In this study, a similar decrease of 16.4% was achieved, confirming that disciplined application of Seiri and Seiton yields immediate improvements in workspace organization and input accessibility.

Orellana-Nuñez et al. (2022b) reported a 14% reduction in cycle time through the implementation of standardized procedures combined with IoT technologies in an electronic assembly line. In the present study, a comparable improvement of 15.03% was achieved, highlighting the effectiveness of integrating Digital Twin monitoring with stable, repeatable protocols—particularly in processes where operational variability exerts a significant influence on productivity.

In a comparable study, SLP application reduced transfer times by 23% in an industrial processing plant, closely aligning with the 24.33% improvement achieved in this research. This validates the effectiveness of SLP in optimizing production layouts, particularly in environments with intermittent flows and spatial constraints (Nenzhelele et al., 2023).

8. Conclusion

The proposed model led to a substantial improvement in operational efficiency on the mill bolt production line, increasing performance from 44.04% to 60.2%

The implementation of the 5S methodology, validated through a pilot program, significantly improved workplace organization and visual management, resulting in a 16.4% reduction in tool search time. Compliance levels for Seiri, Seiton, and Seiso exceeded 59%, demonstrating the effectiveness of the intervention in enhancing operational efficiency and safety.

The work standardization tool contributed to reducing variability in critical tasks and eliminating waiting times due to coordination between processes. The average compliance with the procedure was 93.59% and allowed for a reduction of the total process time by 9.26%, demonstrating that operational standards are key to stabilizing production.

The application of the SLP methodology, validated through SIMIO simulation, optimized the system’s physical layout by reducing travel distances by 38.05% and travel time by 24.33%. These results demonstrate that layout redesign based on functional relationship analysis significantly improves material flow and space utilization.

9. Future Research

Future research should explore plant layout redesign using the SLP methodology under varying workload scenarios, with a focus on minimizing transport distances to optimize material flow. Sustaining the 5S methodology through training and periodic audits warrants investigation to assess its long-term impact on search time reduction and industrial safety. Additionally, standardizing critical operations—particularly in forging and threading—should be analyzed for its potential to reduce process variability and support the onboarding of new operators.

The use of Digital Twins with virtual sensors is proposed to enhance material flow traceability, enabling early bottleneck detection and the generation of objective performance metrics integrated into visualization platforms. Future research should also focus on regularly evaluating key efficiency indicators—such as cycle time, delivery compliance, and resource utilization—to validate the effectiveness of these tools across diverse industrial contexts. Furthermore, integrating these technologies into Lean-based continuous improvement strategies, with an emphasis on operator engagement and sustainability of standardized practices and layout configurations, is essential to adapt to evolving demand and technological advancements.

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