Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/AN16.20260290
Published: June 23, 2026

A Lean Production Approach to Optimize Chassis Repair Lead Times in Heavy-Machinery Workshops

Bryan Cristobal Polino Palacios and Johan Antonio Williard Hoyos Granada
Universidad de Lima, Perú
20201643@aloe.ulima.edu.pe, 20163180@aloe.ulima.edu.pe

Juan Carlos Quiroz Flores
Research Professor
Universidad de Lima, Perú
jcquiroz@ulima.edu.pe

José Antonio Taquía Gutiérrez
Research Professor
Universidad de Lima, Perú
jtaquia@ulima.edu.pe

Abstract

Studies on heavy-machinery maintenance show that long repair cycles, operational variability, and load imbalances reduce service reliability, especially in workshops with limited resources. In this context, chassis repair presents frequent delays that affect customers' operational continuity. This research proposes an integrated operational model based on Job Design, Standard Work, and Heijunka to improve process stability and delivery service performance. The validation was carried out through a hybrid approach that combined pilot implementation tests with discrete-event simulation in Arena and statistical distribution fitting using Input Analyzer with a 95% confidence level. The results show significant improvements: the simulated average total time in the system decreased from 134.46 to 114.47 days (−14.87%) , and operational capacity increased from 35 to 44 repaired vehicles (+25.71%) within the same time horizon. Likewise, average waiting time in dismantling decreased from 93.68 to 76.72 days, representing an improvement of approximately 18.1%, while workspace utilization increased from 70.75% to 86.72%, reflecting better use of available resources. These findings confirm the effectiveness of the proposed model and provide practical implications for maintenance organizations seeking to improve operational reliability, reduce internal congestion, and optimize resource use in highly uncertain environments. The study suggests exploring advanced Lean integrations and data-based approaches to expand the impact of future optimization initiatives.

Keywords
Lean Production; Job Design; Standard Work; Heijunka; Corrective Maintenance.

1. Introduction

Chassis repair in heavy machinery is a key activity for sectors such as construction and mining, which represent approximately 17% of Peru's GDP. Worldwide, proper maintenance of heavy machinery is fundamental for operational efficiency, since between 35% and 45% of operating costs in mining are related to the efficient use of machinery (EY Mining & Metals, 2023). In Peru, the heavy-machinery fleet exceeds 120,000 active units, of which more than 60% operate under intensive conditions due to mining activities and infrastructure projects (SUNAT, 2023). This increases the demand for repair services, especially chassis repair, due to its high immobilization times. In addition, delays in machinery availability can increase overall project costs by between 8% and 12% due to rescheduling and idle times (CAPECO, 2023). However, repair workshops face challenges such as heterogeneous damage, variability in repair times, dependence on operator experience, lack of standardization, unequal workload, and absence of leveled scheduling, factors that reduce process efficiency (Shetty et al., 2010; Cook and Ali, 2012). In the case analyzed, the observed operational repair cycle averaged 28 days, compared to a technical standard of 20 days, and 54.29% of orders were delivered late. This situation increases work in process (WIP), generates internal congestion, and affects the operational availability of equipment. Therefore, optimizing chassis repair times represents a strategic priority to reduce costs, improve machinery availability, and strengthen competitiveness in sectors where delays can reach up to 40% of the scheduled duration of public works (Contraloría General de la República, 2023).

1.1 Objectives

The main objective of this research is to design and validate an improvement model based on Lean Production tools to reduce chassis repair times and improve delivery compliance in a heavy-machinery workshop.

Specifically, the research seeks: first, to diagnose the main causes that generate delays in the chassis repair process; second, to propose an integrated operational model through Job Design, Standard Work, and Heijunka to improve task distribution, standardize work sequences, and level the operational workload; and third, to validate the impact of the proposed model through discrete-event simulation, comparing the current AS-IS scenario with the improved TO-BE scenario. The main contribution of this study is to adapt and integrate Lean tools in a repair service environment characterized by high variability, heterogeneous damage, and limited operational resources, providing an applicable alternative to improve delivery reliability in heavy-machinery workshops.

2. Literature Review

Recent studies in maintenance and repair environments indicate that the main sources of inefficiency are associated with idle times, lack of standardization, operational variability, and unequal distribution of workload. In heavy-machinery workshops, Robai et al. (2023) show that the absence of clear procedures generates unproductive times in critical activities, affecting service continuity. Similarly, Ruiz, Castillo and Paredes (2020), together with Barač et al. (2024), argue that the lack of organized methods and weak coordination between stations increase the accumulation of units waiting and delivery delays. Likewise, Rinaldi et al. (2021) and Keir et al. (2011) indicate that limited staff rotation in demanding tasks increases fatigue, reduces operational flexibility, and affects productivity.

Regarding variability in unit arrivals, Swanson (2008) and Runkler (2011) state that demand fluctuations destabilize internal scheduling and generate bottlenecks. Along the same line, Kuznetsov et al. (2019) highlight that the use of planning models allows repair sequences to be better organized and congestion at critical stations to be reduced. However, Kulsum et al. (2019) and Bautista-Valhondo et al. (2023) warn that leveling techniques may require operational adjustments and implementation costs, so their effectiveness must be quantitatively validated in real contexts.

Based on these contributions, a gap in the literature is identified: although there are studies on idle times, poorly defined sequences, low staff rotation, and random unit arrivals, few works jointly integrate Lean tools in heavy-machinery repair workshops. Therefore, this research proposes an integrated model based on Heijunka, Standard Work, and Job Design, aimed at stabilizing the flow, standardizing operations, and improving work distribution in a highly variable environment.

2.1. Application of Heijunka in the Literature

The literature agrees that demand variability is a critical cause of inefficiency in repair systems. Swanson (2008) argues that flow leveling allows work peaks to be buffered and saturation at critical stations to be avoided. Runkler (2011) complements this idea by pointing out that leveled scheduling improves operational stability by distributing the workload evenly over time. However, Kulsum et al. (2019) warn that the application of Heijunka may involve task rearrangement and adjustments in work configuration, especially in processes with high heterogeneity. More recent studies, such as Zhang et al. (2022), incorporate advanced heuristics to optimize sequencing in systems with random arrivals, demonstrating that leveling methods require adaptations in contexts of extreme variability. Overall, these contributions support the use of Heijunka as a tool to stabilize the operational workload, although its application must be validated in non-repetitive processes, such as chassis repair in heavy machinery.

2.2. Application of Standard Work in the Literature

Several authors argue that the lack of standardization generates inconsistencies in cycle times and accumulation of units waiting. Ruiz, Castillo and Paredes (2020) show that workshop organization and operation standardization contribute to reducing downtime. Barač et al. (2024) point out that poor coordination between stations increases process variability, while Kuznetsov et al. (2019) show that structured sequence planning allows congestion to be reduced and operational flow to be improved. Likewise, Apatenco and Sevryugina (2020) highlight that standardization, combined with a better arrangement of resources, can reduce waiting times within the work sequence. In this sense, Standard Work functions as a mechanism to stabilize the process, reduce variability, and ensure that activities are performed under a defined method. However, its application in chassis repair requires adapting standards to different levels of damage and operational complexity.

2.3. Application of Job Design in the Literature

The literature on Job Design highlights the importance of balancing the physical, cognitive, and temporal workload of operators. Rinaldi et al. (2021) and Keir et al. (2011) demonstrate that the lack of rotation in demanding tasks increases fatigue and ergonomic risks, affecting productivity. Michalos et al. (2010) add that proper task structuring improves overall efficiency by avoiding operator overload in critical activities and facilitating work synchronization. Mishra and Agarwal (2006) point out that work design allows variability in task execution to be reduced, generating more consistent processes. Along the same line, Rerkjirattikarn et al. (2017) highlight that rotation planning contributes to reducing unproductive times and improving operational safety. Finally, Tharmmaphornphilas et al. (2004) indicate that the use of operational information to assign tasks allows process continuity to be improved. These studies support the use of Job Design as a tool to improve flexibility, safety, and operational stability in workshops with high dependence on personnel performance.

3. Methods

The study methodology is structured based on the analysis of existing models aimed at improving operational performance in industrial maintenance workshops. These models address problems such as high repair times, workload imbalance, and lack of standardization; however, they usually apply Lean tools in isolation or in repetitive manufacturing contexts, which limits their applicability in highly variable environments such as chassis repair in heavy machinery. Based on this, a comparative mapping was carried out considering applied tools, type of case study, performance indicators, and validation mechanisms. This analysis evidenced the need for an integral methodological approach that combines workload leveling, operational standardization, and job design, validated through real data and simulation. In response to this gap, the study proposes an integrated operational model applied to a heavy-machinery chassis repair workshop. The methodology is organized into three stages: model foundation, formulation of the proposed model, and development of its components, including diagnosis, implementation of tools, and validation through simulation and operational indicators.

3.1 Model Foundation

The foundation of the model is based on the methodological gap identified between the approaches reported in the literature and the real conditions observed in heavy-machinery repair workshops. Although previous studies have demonstrated improvements through Lean tools, they usually focus on the reduction of specific times or on partial standardization, without jointly addressing demand variability, workload distribution, and dependence on operator performance. In the case analyzed, the operational problems are reflected in high repair times, low compliance with delivery dates, and inefficient use of available resources. Therefore, the model is based on the integration of Heijunka, Standard Work, and Job Design, complementary tools to reduce variability, stabilize processes, and improve task assignment in complex production systems. Likewise, the model incorporates discrete-event simulation, which allows the impact of improvements to be evaluated before their full implementation and reduces the risk associated with operational changes in the workshop.

3.2 Proposed Model

The proposed model aims to reduce the total chassis repair time and improve the operational stability of the workshop through the coordinated intervention of the main causes identified in the diagnosis. Unlike traditional approaches, the model does not focus only on individual activities, but on the integral management of the workflow.

As shown in Figure 1, the model is structured into five stages: system input, problem diagnosis, intervention, implementation and validation, and system output. In the input, critical factors such as the low availability of specialized operators, undefined work sequences, and idle times due to unit changes are identified. Then, the diagnosis uses indicator analysis, Pareto, problem tree, and Ishikawa to prioritize the main causes.

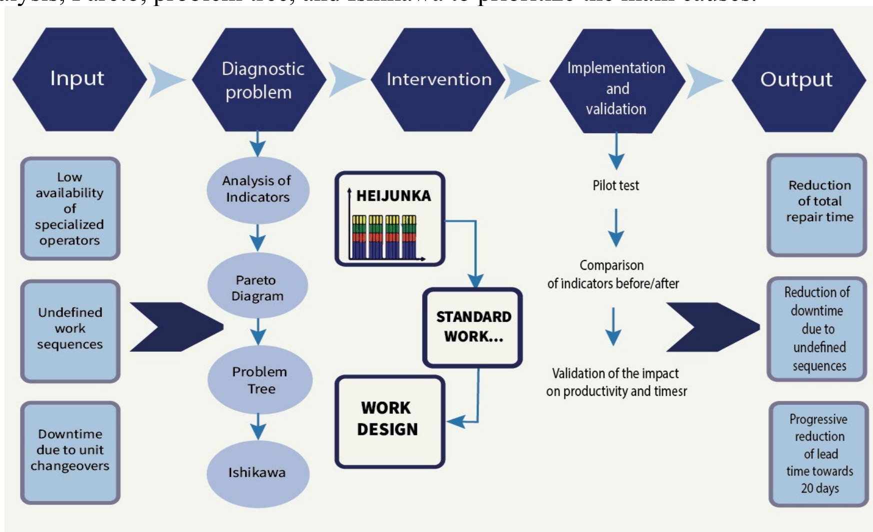

Figure 1. Proposed model

The integration mechanism of the proposed model is based on the sequential and complementary function of the three Lean tools. First, Heijunka levels the arrival and assignment of repair jobs according to damage severity, reducing daily workload fluctuations and preventing overload at critical stations. Based on this leveled workload, Standard Work defines a consistent operational sequence for the repair activities, reducing variability, unnecessary movements, and coordination losses between workstations. Finally, Job Design reorganizes the distribution of tasks among operators and machines, allowing critical activities such as tractioning and welding to be performed with better synchronization and lower idle time. Therefore, the tools do not operate independently; instead, Heijunka stabilizes the workload, Standard Work stabilizes the method, and Job Design stabilizes the use of human and technical resources. This interaction allows the model to address the main root causes simultaneously: unplanned workload variation, undefined repair sequences, and inefficient task allocation.

3.3. Model Components

3.3.1. Problem Diagnosis

The initial diagnosis made it possible to identify that the main problem of the workshop was the high total repair time, which generated delivery delays and a low service level. To understand the associated causes, a structured analysis of the process was carried out using an Ishikawa diagram, identifying three recurring factors: low availability of specialized operators, undefined work sequences, and idle times derived from unit changes. Subsequently, a Pareto diagram was developed to prioritize the causes with the greatest impact. In addition, the problem tree made it possible to visualize the relationship between immediate causes and operational effects, while value stream mapping made it possible to identify bottlenecks, waiting points, and non-value-added activities within the chassis repair process. This diagnosis served as the basis for selecting the tools of the intervention model.

3.3.2. Identification and Implementation of Tools

Based on the identified causes, three Lean tools were selected: Heijunka, Standard Work, and Job Design. The logic of the model focuses on simultaneously intervening in operational variability, the lack of consistent sequences, and the unequal distribution of workload among operators. Heijunka was implemented to level the workload, reduce daily fluctuation, and stabilize the repair flow. Standard Work was applied to define clear sequences, eliminate redundant steps, and reduce idle times due to lack of coordination. Finally, Job Design made it possible to reorganize and redistribute critical tasks, optimizing the physical and cognitive workload of personnel, improving the effective availability of operators, and favoring a better balance between stations. The combination of these tools made it possible to intervene in the central causes of the problem and generate a more stable operational flow, with lower variability and shorter cycle time.

3.3.3. Model Validation

The validation was developed through a hybrid approach that combined the partial implementation of improvements in the real process with discrete-event simulation in Arena. In the first phase, key elements of the model were applied in the workshop, observing changes in station organization, the operational sequence, and workload distribution among operators. In the second phase, a simulation model was built to compare the performance of the system before and after the intervention. As shown in Figure 2, the methodological flow begins with historical records and analysis of the current process, continues with the implementation of Heijunka, Standard Work, and Job Design, and ends with the comparison of the AS-IS and TO-BE scenarios.

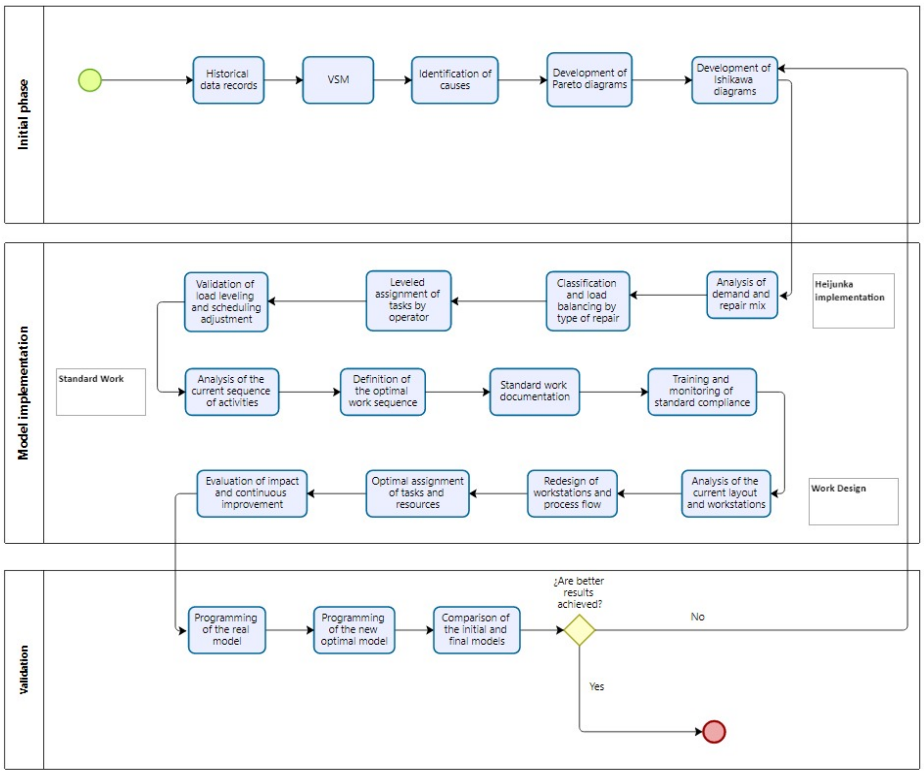

Figure 2. Proposed method flow

The simulation made it possible to quantify the effects of the model on indicators such as average repair time, number of vehicles processed, waiting times at critical stations, and average WIP. This comparison evidenced a reduction in total repair time, greater stability of the operational flow, better workload balance, and a progressive reduction of lead time toward the 20-day objective.

3.4. Model Indicators

The indicators used to evaluate the effectiveness of the implemented tools are presented below, along with the formulas for their calculation:

- **Productivity:** An increase of 20% to 25% in productivity is expected, reflecting a greater number of chassis repaired by operators. This increase is consistent with previous studies showing productivity improvements of up to 25% when optimizing workflows. The formula is:

$$Productivity = \frac{Repaired\ chassis}{Effective\ hours}$$

- **Operational Efficiency:** An improvement of 6% to 9% in efficiency is projected, resulting from the elimination of idle times and the improvement of workflow. Previous research shows improvements of up to 9% with the implementation of Lean tools. The formula is:

$$Operational\ Efficiency = \frac{Productive\ working\ time}{Total\ working\ time} x100$$

- **Deadline Compliance:** An increase of 30% to 35% in delivery deadline compliance is expected, which has been documented in previous studies showing improvements of up to 40% in delivery times through the application of Lean Manufacturing. The formula is:

$$Deadline\ Compliance = \frac{Units\ delivered\ on\ time}{Total\ units\ repaired} x100$$

- **Average Repair Time:** A reduction of 6% to 9% in repair times is anticipated, in line with studies suggesting a reduction of up to 10% in repair times with work standardization. The formula is:

$$A.R.T. = \frac{\sum Repair\ time\ of\ chassis}{Total\ number\ of\ chassis\ repaired}$$

4. Data Collection

4.1. Validation Scenario

This section describes the context in which the proposed model was validated. The validation was carried out in a heavy-machinery chassis repair workshop, characterized by high variability in unit arrivals and different levels of damage severity: minor, moderate, and severe. The process presented an average repair time higher than the sector's technical standard and a low level of on-time delivery compliance, which motivated the application of Lean tools aimed at stabilizing the operational flow, standardizing work sequences, and redistributing the workload among operators.

4.2. Initial Diagnosis

The initial diagnosis made it possible to identify the main causes that explained the low compliance with delivery deadlines in chassis repair. Based on the analysis of historical data and direct observation of the process, high variability in the work sequence, frequent idle times, and imbalance in task assignment among operators were evidenced. The causal analysis was structured through a problem tree, which made it possible to visualize the relationship between root causes and their operational effects, highlighting delays in scheduling, the lack of standardized procedures, and inefficient workload management as predominant factors (Figure 3).

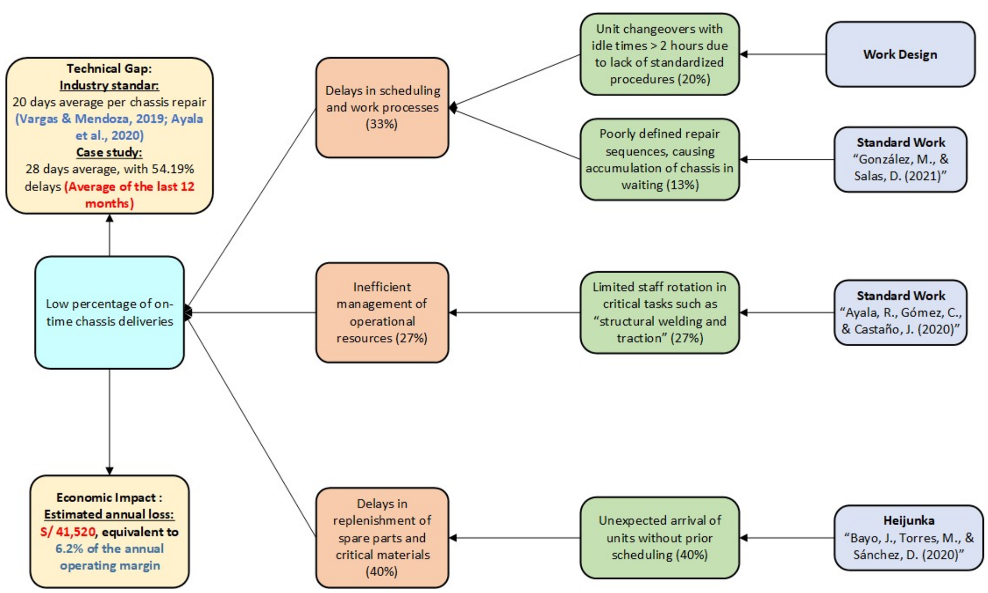

Figure 3 Root Cause Tree

4.3. Validation Design

4.3.1 Sample Size

A preliminary sample was obtained to collect repair-time information by activity and support the subsequent analysis and validation of the simulation model. The preliminary sample size was defined as three observations per activity, based on the classical criteria of the Time Study Manual of Erie Works, General Electric Company, which recommends three observation cycles when the cycle time is 40 minutes or more, as shown in Figure 4. In the case of chassis repair activities, many tasks exceed 40 minutes and may even last several hours or days; therefore, the use of three observations per activity was considered appropriate for the workshop context (Figure 5)**.**

Tiempo de ciclo (minutos)	Número recomendado de ciclos
0.10	200
0.25	100
0.50	60
0.75	40
1.00	30
2.00	20
2.00-5.00	15
5.00-10.00	10
10.00-20.00	8
20.00-40.00	5
40.00 o más	3

Figure 4. Recommended number of observation cycles according to cycle time

											REINFORCEMENT			INTERARRIVAL TIMES				
	1) Inspection	2) Disassembly	3) Cleaning	4) Planning	5) Severe Tractioning	6) Welding	7) Reinforcement	8) Security test	9) Reassembly	10) Final Inspection	11) Reinforcement Inspection	12) Cutting	13) Adjustment	14) Severe Chassis Arrival	15) Moderate Chassis Arrival	16) Minor Chassis Arrival	17) Moderate Tractioning	18) Minor Tractioning
	6.8	17.04	3.44	3.44	81.6	13.6	3.44	6.8	20.4	6.8	3.44	6.8	6.8	188	93.6	374.4	47.6	13.6
	8	20	4	4	96	16	4	8	24	8	4	8	8	208	104	416	56	16
	9.2	23.04	4.64	4.64	110.4	18.4	4.64	9.2	27.6	9.2	4.64	9.2	9.2	228	114.4	457.6	64.4	18.4
Standard Deviation																		
	1.20	3.00	0.60	0.60	14.40	2.40	0.60	1.20	3.60	1.20	0.60	1.20	1.20	20.00	10.40	41.60	8.40	2.40
Absolute Error																		
1) Mean																		
	8.00	20.03	4.03	4.03	96.00	16.00	4.03	8.00	24.00	8.00	4.03	8.00	8.00	208.00	104.00	416.00	56.00	16.00
2) Error = 10%																		
	0.80	2.00	0.40	0.40	9.60	1.60	0.40	0.80	2.40	0.80	0.40	0.80	0.80	20.80	10.40	41.60	5.60	1.60

Figure 5. Pilot Times

The pilot observations provided preliminary values of repair times by activity and served as input for the operational analysis and simulation model. These measurements made it possible to represent the behavior of the workshop, considering the variability of repair activities according to damage severity.

4.3.2 Simulation in Arena

The simulation of the chassis repair process was carried out using Arena software, which made it possible to model the workstations, task flows, and interactions between operators and machines. The modeling included both the current scenario (AS-IS) and the improved scenario (TO-BE), which made it possible to evaluate the impact of Lean tools on the improvement of operational efficiency. The model was validated using the repair times and performance indicators obtained in the measurement phase, comparing the pre- and post-implementation results of the Lean tools. The following metrics were used to evaluate the effectiveness of the implementation: productivity, operational efficiency, and cycle times (Figure 6).

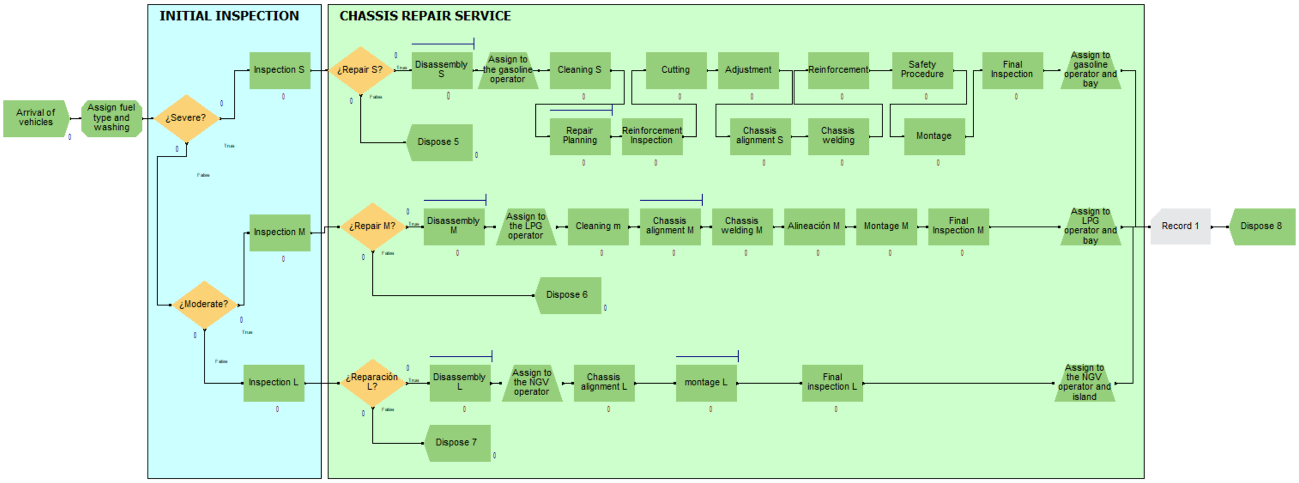

Figure 6. Arena simulation model

5. Results and Discussion

5.1 Results of the Implementation of Standard Work

The implementation of Standard Work aimed to reduce variability in the chassis repair sequence by defining a standardized operating method. This tool allowed the reorganization of movements, establishing a logical sequence of activities, and reducing unproductive times associated with searching for materials, tools, and unnecessary routes within the workshop. In the initial scenario, the analysis of the spaghetti diagram showed repetitive routes, unnecessary crossings between areas, and the absence of a defined sequence. After the implementation, the flow was reorganized into a more direct sequence, grouping complementary operations and reducing unproductive movements. This comparison is shown in Figure 7.

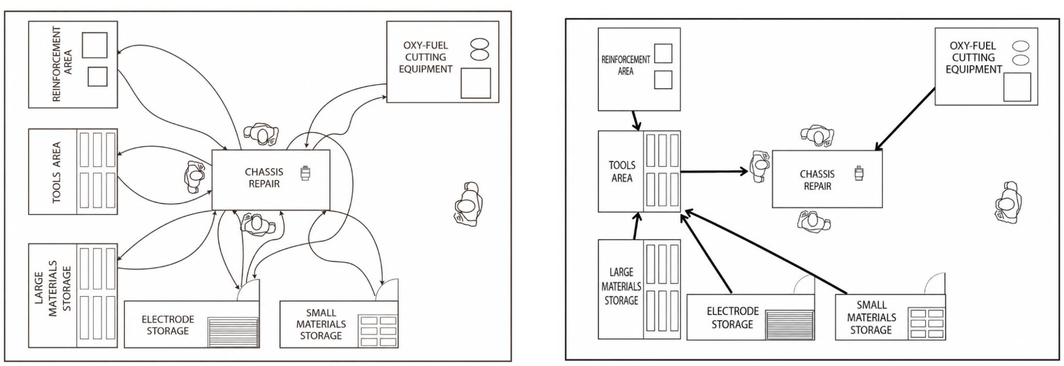

Figure 7. Spaghetti diagram before and after Standard Work implementation

As a result, the total operational cycle time was reduced from 24 minutes to 16.5 minutes, representing a 31% reduction compared to the initial scenario. This improvement reflects better coordination between activities, less operational movement, and a reduction in idle times during chassis repair.

Additionally, a Standard Work Sheet was developed to document the new operational sequence. This visual tool includes thirteen work steps, assigned times, personal protective equipment, required tools, and control responsibilities, ensuring the repeatability of the method and facilitating the monitoring of operational compliance. The standard sheet is presented in Figure 8.

Figure 8. Standard Work sheet for chassis repair operations

The new standard consolidated a documented time of 777 seconds, equivalent to 12.95 minutes, reinforcing the traceability, safety, and uniformity of the process (Table 1).

Table 1. Results of Standard Work implementation

Indicator	Initial scenario	Improved scenario	Improvement
Total operational cycle time	24 min	16.5 min	31% reduction
Work sequence	Not defined	Standardized	Greater operational control
Operational routes	Repetitive and crossed	More direct and orderly	Less movement
Documented standard time	Not available	777 s / 12.95 min	New operational standard

5.2 Results of the Implementation of Heijunka

The implementation of Heijunka aimed to level the daily operational workload in the chassis repair process, in order to reduce variability in task assignment, avoid overload among operators, and stabilize the workflow. For this purpose, repair times by damage type minor, moderate, and severe and by activity were collected, using this information as the basis to build a leveled workload planner. The process was developed in three stages. First, historical repair times by activity were analyzed. Then, the available daily capacity of the operators and the backlog of pending units were defined. Finally, a daily schedule was generated that allowed tasks to be distributed in a balanced manner, considering the repair mix by severity.

The comparison between the initial scenario and the leveled scenario through Heijunka is presented in Figure 9, where the stabilization of the total daily workload is evidenced. Before the intervention, the workload varied according to task assignment, generating overload or inactivity. After the implementation, 24 hours of work were assigned consistently per day, which made it possible to maintain a more uniform distribution of the operational workload.

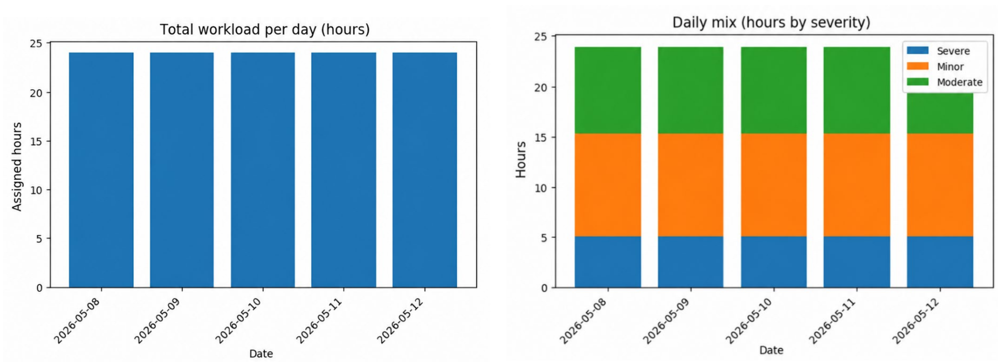

Figure 9. Daily workload before and after Heijunka leveling

Likewise, Figure 10 shows the comparison of scenarios before and after the implementation of Heijunka, evidencing a reduction in variability and a better distribution of activities by repair type.

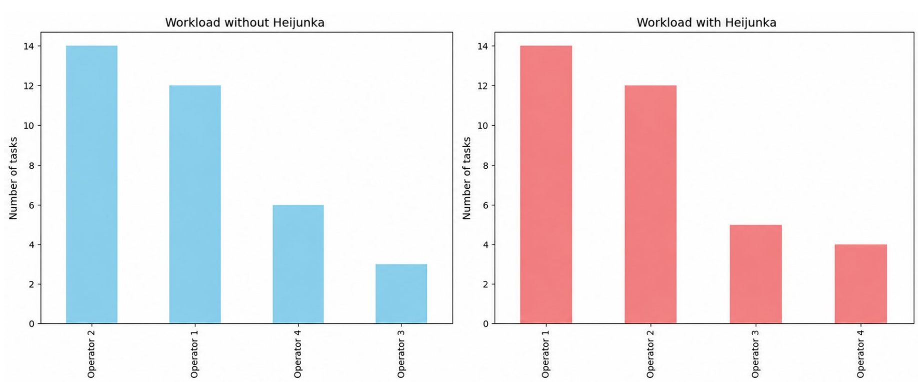

Figure 10. Scenario comparison before and after Heijunka implementation

The quantitative results show that repair times per unit decreased in the three damage types. In minor units, the time was reduced from 56 to 52 hours, equivalent to a 7.1% improvement. In moderate units, the time decreased from 103 to 96.5 hours, with a 6.3% reduction. Finally, in severe units, the time decreased from 135 to 121.9 hours, representing a 9.7% improvement. In addition, the standard deviation of the daily workload went from high variability to 0.00, reflecting a perfectly balanced workload during the planned period (Table 2).

Table 2. Quantitative results before and after Heijunka implementation

Indicator	Before Heijunka	After Heijunka	Improvement
Minor repair time	56 h	52 h	7.1% reduction
Moderate repair time	103 h	96.5 h	6.3% reduction
Severe repair time	135 h	121.9 h	9.7% reduction
Productivity	Low due to overload and idle time	Higher due to balanced workload	20–25% increase
Delivery deadline compliance	Frequent delays	Significant reduction of delays	30–35% improvement

Overall, the implementation of Heijunka made it possible to stabilize the daily workload, reduce repair times by damage type, and improve the workshop's response capacity. These results show that workload leveling directly contributes to reducing delays, avoiding unproductive times, and improving delivery compliance in the chassis repair process.

5.3 Results of the Implementation of Job Design

The implementation of Job Design focused on improving the synchronization between operators and machines in the critical stages of tractioning and structural welding. For this purpose, man-machine interactions, active and inactive times, and task distribution among operators were analyzed. This tool made it possible to redefine roles, execute activities in parallel, and reduce waiting times generated by a disorganized work sequence.

In the tractioning stage, the initial scenario presented low coordination among the four operators and the machines involved, which generated waiting times in activities such as measurement, heating, and anchor preparation. After the intervention, specific roles were defined for each operator: traction leader, anchor assistant, metrology, and thermal support. This redistribution allowed measurement and heating activities to be executed in parallel with tractioning, eliminating idle times and improving resource utilization (Figure 11- Figure 13).

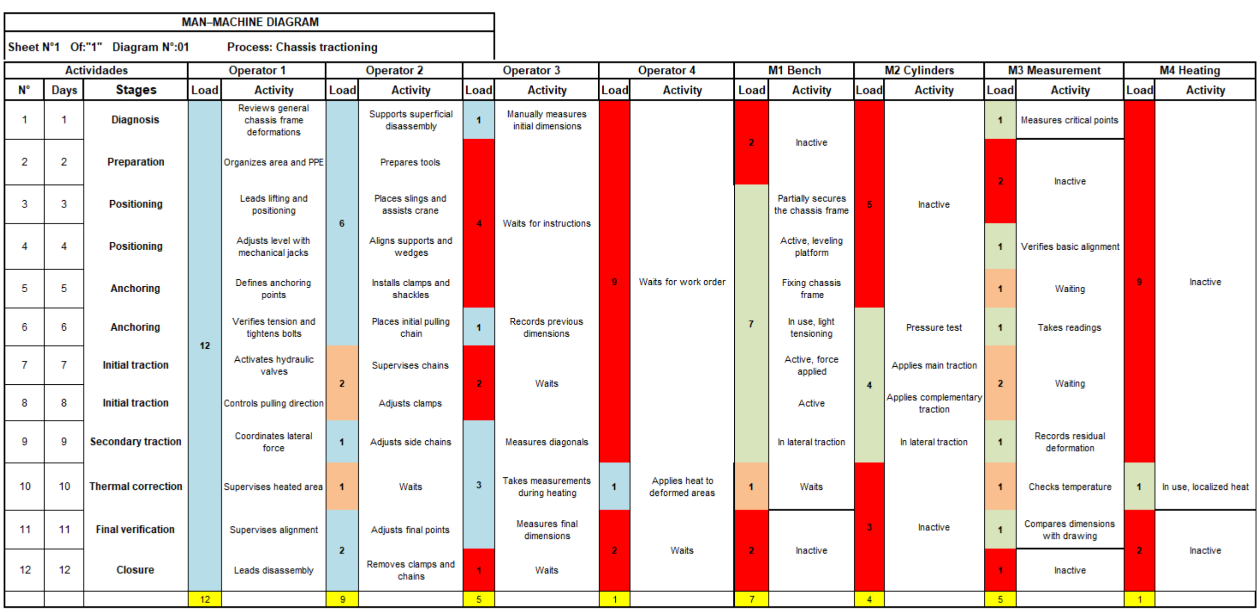

Figure 11. Man-machine diagram of the current traction scenario

MAN–MACHINE DIAGRAM

Sheet N°1 Of:"1" Diagram N°:01 Process: Chassis tractioning

Actividades			Operator 1		Operator 2		Operator 3		Operator 4		M1 Bench		M2 Cylinders		M3 Measurement		M4 Heating	
N°	Days	Stages	Load	Activity	Load	Activity	Load	Activity	Load	Activity	Load	Activity	Load	Activity	Load	Activity	Load	Activity
1	1	Diagnosis		Leads visual inspection and traction plan		Supports cleaning and inspection of impact points		Performs initial measurement with square or laser	1	Organizes tools and prepares the area	2	Inactive		Inactive	1	Verifies initial dimensions with a reference pattern		Inactive
2	2	Preparation		Supervises PPE use and chassis frame locking		Installs mechanical locks and wedges		Checks measuring instruments		Organizes thermal kit and tools		Inactive		Inactive	1	Inactive		Inactive
3	3	Positioning		Coordinates lifting with crane and initial alignment		Places slings and secures primary anchors		Controls longitudinal alignment	1	Prepares next pulling chains		Adjusts platform	5	Inactive	1	Verifies alignment		Inactive
4	4	Positioning		Adjusts supports and chassis frame levelers		Secures clamps and shackles		Measures vertical dimensions		Places side reinforcements		Active in full fixing		Inactive		Controls parallel dimensions		Inactive
5	5	Anchoring		Defines and marks anchoring points according to the drawing		Installs clamps in sequence		Verifies tolerances and dimensions		Secures auxiliary chains		In continuous fixing		Inactive		Measures parallel dimensions	9	Inactive
6	6	Anchoring	12	Supervises and applies hydraulic tension	12	Adjusts shackles and secures traction	12	Measures and records initial deformation		Supports with side locks	7	Maintains active clamping		Applies test tension		Records dimension values		Inactive
7	7	Initial traction		Operates hydraulic traction valves		Controls pulling direction and safety		Measures displacement while pulling		Prepares the next pulling point		Supports structure		Performs controlled traction	8	Measures deformation in parallel		Inactive
8	8	Initial traction		Applies second traction phase according to the plan		Adjusts active clamps		Measures progress along the centerline	9	Repositions chains and locks		Maintains chassis frame load	4	Applies correction force		Measures parallelism		Inactive
9	9	Secondary traction		Leads transverse traction		Secures side chains and controls angle		Takes diagonal readings		Prepares reinforcements or reheats rigid areas		In use, fixed bench		Applies synchronized lateral traction		Controls lateral deviation		Inactive
10	10	Thermal correction		Supervises heat point and steel tension		Prepares and adjusts anchors for the next pull		Measures while the area is heated		Applies controlled direct heat	1	Waiting for thermal release		Inactive		Measures dimension variation	1	Applies controlled heat by zone
11	11	Final verification		Supervises final alignment results		Adjusts remaining anchors		Performs complete final measurement		Supports partial unlocking	2	Inactive	3	Inactive		Validates final alignment	2	Inactive
12	12	Closure		Leads system disassembly		Removes clamps and chains		Cleans the area and records results		Stores tools and PPE		Inactive		Inactive	1	Inactive		Inactive
			12		12		12		10		7		4		9		1	

Figure 12. Man-machine diagram of the improved traction scenario

As a result, the cycle time in tractioning was reduced from 12 to 8 days, equivalent to a 33% improvement. Worker efficiency increased from 75% to 100%, while machine utilization increased from 41.7% to 75%. Likewise, daily production increased from 0.083 to 0.125 units/day, representing a 50% improvement (Table 3).

Table 3. Improvement results in the traction process

Indicator	Current scenario	Improved scenario	Variation
Cycle time	12 days	8 days	33% reduction
Worker labor time	9 days	8 days	11% reduction
Machine work time	5 days	6 days	20% increase
Worker efficiency	75%	100%	+25 p.p.
Machine utilization	41.7%	75%	+33 p.p.
Daily production	0.083 units/day	0.125 units/day	50% increase

In the structural welding stage, Job Design made it possible to reorganize the welding, interpass cleaning, measurement, and fixing tasks. In the initial scenario, the lead welder concentrated most of the activities, while the other operators had waiting times. After the intervention, the tasks were distributed simultaneously: the welding assistant performed cleaning and beveling, the metrology operator verified dimensions in real time, and the thermal support prepared the following positions.

MAN–MACHINE DIAGRAM																		
Sheet N°1 Of:"1" Diagram N°:01 Process: Proceso: Solcadura estructural																		
Activities			Operator 1		Operator 2		Operator 3		Operator 4		M1 Welding Power Source		M2 Grinder		M3 Fume Extractor		M4 Positioner / Bench	
N°	Dias	Stages	Load	Activity	Load	Activity	Load	Activity	Load	Activity	Load	Activity	Load	Activity	Load	Activity	Load	Activity
1	1	Set-up/PPE/work permit	1	Sets welding parameters		Installs ground cables and connectors		Checks bevels with gauges		Prepares ventilation and fastening	1	In setup						
2	2	Marking and beveling	1	Supervises setup		Performs beveling		Checks dimensions and aligns parts		Secures and locks with clamps	2	Inactive	3	In use (beveling)				
3	3	Aligning & securing		Adjusts electrode position and angles		Verifies leveling		Records reference measurements		Tightens clamps and secures chassis								
4	4	General tack welding		Performs main tack welding		Supports secondary tack welds		Verifies dimensions		Controls ventilation and safety			1	Inactive				
5	5	Initial root pass		Performs root weld bead		Immediate interpass cleaning		Measures distortion		Applies air and ventilates								
6	6	Root pass + interpass cleaning		Welding root pass	12	Cleaning	12	Measures tolerances	12	Secures next sections					12	In use	12	In use
7	7	Root closure pass		Closes root weld bead		Cleaning		Final verification		Adjusts next clamps								
8	8	Fill pass 1	10	Welding fill pass		Continuous cleaning		Measures and monitors		Prepares next side	9	In use						
9	9	Fill pass 2		Welding fill pass		Continuous cleaning		Measures parallelism		Prepares next position			8	In use				
10	10	Fill pass 3		Welding fill pass		Intermediate cleaning		Measures		Prepares cover area								
11	11	Fill pass 4		Welding fill pass		Cleaning		Measures		Prepares cover								
12	12	Fill pass 5		Welding final fill pass		Cleaning		Controls measurements		Supports ventilation								
			11		12		12		12		9		11		12		12	

Figure 13. Man-machine diagram of the improved structural welding scenario

Unlike the tractioning process, in structural welding the cycle time remained at 12 days; however, the improvement was reflected in resource utilization. Worker efficiency increased from 41.7% to 100%, while machine utilization increased from 58.3% to 91.7%. This shows that the tool made it possible to eliminate waiting times and make more continuous use of human and technical resources, although without yet reducing the total welding cycle time (Table 4).

T

Table 4. Improvement results in the structural welding process

Indicator	Current scenario	Improved scenario	Variation
Worker labor time	5 days	12 days	+7 days
Machine work time	7 days	11 days	+4 days
Worker efficiency	41.7%	100%	+58.3 p.p.
Machine utilization	58.3%	91.7%	+33.4 p.p.

Overall, the implementation of Job Design made it possible to improve task distribution and synchronization between operators and machines in the critical stages of the process. In tractioning, the improvement was reflected in a direct reduction of cycle time and an increase in daily production. In structural welding, the main benefit was the elimination of idle times and the increase in resource utilization. These results demonstrate that Job Design improved resource synchronization, reduced idle time, and increased the effective use of operators and machines in critical repair activities.

5.4 Results of the Model through Simulation

The simulation results evaluated the impact of the proposed model, integrated by Heijunka, Standard Work, and Job Design, on the chassis repair process. The AS-IS and TO-BE scenarios were compared using indicators related to repair time, repaired vehicles, workspace utilization, waiting time, and work in process. The simulated average total time in the system decreased from 134.46 days in the AS-IS scenario to 114.47 days in the TO-BE scenario, representing a 14.87% reduction. The number of repaired vehicles increased from 35 to 44 units, equivalent to a 25.71% increase in capacity. Workspace utilization also improved from 70.75% to 86.72%, showing better use of available resources. In addition, the average waiting time in dismantling decreased from 93.68 to 76.72 days, representing an 18.10% reduction. Finally, the average WIP decreased from 32.8 to 31.66 units, indicating a lower accumulation of units in process. Figure 14 shows the chassis repair workstation in the real workshop environment, where the improvement model was analyzed and validated (Table 5, Figure 14).

Figure 14. Chassis repair workstation in the real workshop environment

Table 5. AS-IS and TO-BE comparison of simulation indicators

Indicator	AS-IS mean	AS-IS SD	TO-BE mean	TO-BE SD	Improvement
Simulated average total time in system	134.46 days	10.80 days	114.47 days	8.30 days	14.87% reduction
Repaired vehicles	35.00 units	2.60 units	44.00 units	3.20 units	25.71% increase
Workspace utilization	70.75%	6.50%	86.72%	7.10%	+15.97 p.p.
Average waiting time in dismantling	93.68 days	15.50 days	76.72 days	13.20 days	18.10% reduction

To reinforce the validity of the simulation results, the AS-IS and TO-BE scenarios were compared using 50 replications and a 95% confidence level. The main indicators showed consistent improvements across the replications, particularly in average repair time, repaired vehicles, workspace utilization, and waiting time in dismantling. In addition, the lower standard deviation observed in the TO-BE scenario for repair time and waiting time suggests a more stable process after the implementation of the proposed Lean model. Overall, the simulation results support the positive impact of the integrated model on operational performance, showing shorter repair times, higher service capacity, better resource utilization, and lower waiting times at critical stages of the chassis repair process.

5.5 Discussion

In comparison with alternative optimization approaches, the proposed Lean-based model addresses the limitations commonly observed in more complex methodological frameworks applied to maintenance systems. Simulation-optimization and heuristic scheduling models, although effective in structured production environments, require deterministic parameters, stable demand patterns, and high-quality historical data, which are often unavailable in heavy-machinery repair workshops characterized by high variability and uncertainty. Similarly, data-driven approaches such as machine learning-based prediction models and predictive maintenance systems depend on large datasets, sensorization, and digital infrastructure maturity, which are not always feasible in medium-sized industrial contexts. Even when applicable, these approaches tend to focus on failure prediction rather than the operational synchronization of repair activities, which is the main constraint identified in this study.

In contrast, the proposed Lean integration provides a process-centered solution that directly modifies operational behavior through workload leveling, standardized execution, and task redistribution. This allows immediate applicability without requiring advanced technological deployment, making it more suitable for environments where operational discipline and resource optimization are the primary constraints.

5.6 Limitations and Future Research

This study is based on a single-case implementation conducted in a heavy-machinery chassis repair workshop, which limits its direct external generalization. Although the integrated Lean model demonstrated significant improvements in repair time reduction, workload leveling, and operational efficiency, these results are context-dependent and influenced by operational factors such as variability in unit arrivals, availability of specialized operators, and spare parts constraints. Therefore, the proposed model should not be interpreted as universally generalizable without adaptation, but rather as a transferable framework that can be adjusted to similar maintenance environments with high variability. This is consistent with the conceptual nature of Lean-based interventions, where effectiveness depends on contextual implementation conditions.

Future research should focus on validating the model across multiple industrial workshops to assess its scalability and robustness. In addition, the integration of digital technologies such as predictive analytics, real-time scheduling systems, and data-driven decision-making tools could further enhance operational stability and improve decision accuracy in complex repair environments.

5.7 Economic and Risk Evaluation of the Proposed Model

In addition to the operational validation, an economic evaluation was conducted to assess the financial viability of the proposed Lean implementation. The initial investment was estimated at S/ 20,000, covering training, standardization, workplace redesign, and implementation of Lean tools.

The financial results indicate that the project is economically viable. The Net Present Value (NPV) is S/ 88,539.08, demonstrating that the benefits generated by the reduction of non-value-added times and the increase in operational efficiency exceed the initial investment. The Internal Rate of Return (IRR) is 59%, significantly higher than the cost of capital (COK = 13.31%), confirming strong profitability. Additionally, the Benefit-Cost ratio of 5.43 indicates that for every monetary unit invested, the project generates 5.43 units in net benefits. The Payback Period of 2.21 months confirms a rapid recovery of the initial investment.

To complement this analysis, a risk evaluation was performed using Monte Carlo simulation with 1,000 iterations in @Risk software. The results show that the NPV follows an approximately normal distribution with a mean close to S/ 89,887.95 and low dispersion, indicating high financial stability. The 90% confidence interval remains entirely positive, confirming that the project maintains profitability even under unfavorable scenarios. Similarly, the IRR distribution remains consistently above the minimum required return across all simulated scenarios, with values ranging between approximately 52% and 66%. This demonstrates that the financial performance of the model is robust under uncertainty in operational demand and cost variations.

Overall, the economic and risk analysis confirms that the integration of Heijunka, Standard Work, and Job Design not only improves operational performance but also generates stable and sustainable financial benefits, with low exposure to economic risk (Table 6).

Table 6. Economic indicators of profitability

Indicator	Value
NPV	S/ 88,539.08
IRR	59%
B/C	5.43
Payback s	2.21 months

6. Conclusion

The research fulfilled the objective of designing and validating an improvement model based on Lean Production to reduce chassis repair times and improve delivery compliance in a heavy-machinery workshop. First, the diagnosis made it possible to identify that the main delays were associated with non-standardized work sequences, operational workload imbalance, idle times, and limited coordination between operators and critical stations.

Second, an integrated model was proposed through Job Design, Standard Work, and Heijunka, aimed at improving task distribution, standardizing the work method, and leveling the operational workload. The validation through discrete-event simulation confirmed the effectiveness of the model, evidencing a reduction in average repair time from 134.46 to 114.47 days, an increase in repaired vehicles from 35 to 44 units, and an improvement in workspace utilization from 70.75% to 86.72%. Overall, the study demonstrates that the integration of Lean tools can be an applicable alternative to improve efficiency and delivery reliability in heavy-machinery repair workshops with high operational variability.

References

Ahn, H.-I., Leung, Y. T., & Hochstein, A., "Construction of a data-driven vital signs indicator for an economically optimized component replacement policy," PHM 2014 - Proceedings of the Annual Conference of the Prognostics and Health Management Society 2014, pp. 1–10, 2014.

Aivaliotis, P., Arkouli, Z., Georgoulias, K., & Makris, S., "Integration of degradation curves into physics-based models: Towards predictive maintenance of industrial robots," Robotics and Computer-Integrated Manufacturing, vol. 67, pp. 102036, 2021. [https://doi.org/10.1016/j.rcim.2020.102036]

Alfaro-Pozo, R., & Bautista-Valhondo, J., "Heijunka in Mixed-Model Sequences with Minimum Work Overload: Economic Impact," IoT and Data Science in Engineering Management, Lecture Notes on Data Engineering and Communications Technologies, vol. 160, pp. 395–401, 2023. [https://doi.org/10.1007/978-3-031-27915-7_70]

Al-Hussain, A., & Al-Ahmed, H., "The role of Lean principles and 5S programs in increasing maintenance productivity," International Petroleum Technology Conference (IPTC 2022).

Antosz, K., & Ratnayake, R. M. C., "Spare parts' criticality assessment and prioritization for enhancing manufacturing systems' availability and reliability," Journal of Manufacturing Systems, vol. 46, pp. 115–123, 2019.

Apatenco, A. S., & Sevryugina, N. S., "Methods of recruiting of mobile repair services and maintenance of machines performing reclamation works," IOP Conference Series: Materials Science and Engineering, vol. 786, pp. 012037, 2020. [https://doi.org/10.1088/1757-899X/786/1/012037]

Arshad, M. A., Mahmood, A., Shabbir, M. S., & Sleimany, G., "Modelling a multi-objective problem for emergency response in disaster management: Emphasising on mitigating the impact of the delay in the crisis severity," International Journal of Services and Operations Management, vol. 14, no. 2, pp. 200–220, 2022.

Babbs, D., & Gaskins, R., "Effect of reduced equipment downtime variability on cycle time in a conventional 300mm fab," Proceedings of the 2008 IEEE/SEMI Advanced Semiconductor Manufacturing Conference (ASMC), pp. 237–242, 2008. [https://doi.org/10.1109/ASMC.2008.4529045]

Bardyshev, O., Repin, S., Zazykin, A., & Korotkevich, M., "Research on the organization aspects of construction machinery repair in the Arctic," Transportation Research Procedia, vol. 54, pp. 365–373, 2021. [https://doi.org/10.1016/j.trpro.2021.02.039]

Barroeta, C. E., & Modarres, M., "Risk and economic estimation of inspection policy for periodically tested repairable components," Proceedings of the 8th International Conference on Probabilistic Safety Assessment and Management (PSAM 2006).

Benatia, M. A., Ben Abdelaziz, F., & Sahnoun, M., "Energy savings and coverage optimization in edge WiFi sensor deployment for buildings: A multi-objective evolutionary approach," Energy Economics, vol. 2025.

[https://doi.org/10.1016/j.eneco.2024.108096]
Brightling, J., Hawkes, D., & Peters, C., "Lessons Learnt in Emergency Shipments of Catalysts," Ammonia Plant Safety and Related Facilities, vol. 2019.
Butko, A. O., & Kuznetsov, P. M., "Business process management approach to the maintenance and repair of mining equipment," Mining Informational and Analytical Bulletin (Scientific and Technical Journal), vol. 2, pp. 140–149, 2024. [https://doi.org/10.25018/0236-1493-2024-2-0-140-149]
Cakir, H., et al., "Improvement of work design for higher productivity," International Journal of Industrial Engineering, vol. 19, no. 3, pp. 110–121, 2020.
Carrera, G., Espinoza-Andaluz, M., & Santana-Villamar, J., "Evaluation of the impact of COVID-19 on the automotive industry: Analysis of the effects of confinement on a hybrid vehicle," Proceedings of ASME 2023 International Mechanical Engineering Congress and Exposition (IMECE 2023), Vol. 7.
Casa Monta, D. X., & León Valarezo, H. G., "Estandarización de tiempos y métodos de trabajo para el incremento de la productividad en los procesos de operación del taller de enderezada y pintura," Repositorio UTC. Retrieved from [https://repositorio.utc.edu.ec]
EY Minería & Metales, "El impacto del uso eficiente de maquinaria en minería," Informe Anual 2023, p. 45, 2023.
Keir, P. J., Sanei, K., & Holmes, M. W. R., "Task rotation effects on upper extremity and back muscle activity," Applied Ergonomics, vol. 42, no. 6, pp. 814–819, 2011. [https://doi.org/10.1016/j.apergo.2011.01.006]
Koskela, L., & Ballard, G., "Implementing Standard Work in manufacturing," Proceedings of the Lean Manufacturing Conference, pp. 45–59, 2019.
Park, Y., & Kim, D., "Time reduction in repair processes using Lean," Journal of Lean Operations, vol. 31, no. 7, pp. 50–58, 2019.
Ramos, S., et al., "Impact of standardized work on operational efficiency," Journal of Manufacturing Science, vol. 35, no. 7, pp. 101–114, 2017.
Rinaldi, M., Caterino, M., Fera, M., & Macchiaroli, R., "Reducing the physical ergonomic risk by job rotation: A simulation-based approach," IFAC-PapersOnLine, vol. 54, no. 1, pp. 61–66, 2021. [https://doi.org/10.1016/j.ifacol.2021.08.070]
Ruiz, C., Castillo, T., & Paredes, M., "Effects of Implementation of 5S in Heavy Equipment Maintenance Workshops," Proceedings of the 28th Annual Conference of the International Group for Lean Construction (IGLC), pp. 589–600, 2020. [https://doi.org/10.24928/2020/0010]
Runkler, T. A., "Controlling discrete manufacturing processes using Kanban and Heijunka approaches," 2011 9th IEEE International Conference on Industrial Informatics, pp. 181–186, 2011. [https://doi.org/10.1109/INDIN.2011.6034859]
SUNAT, "Flota de maquinaria pesada en Perú," Informe 2023, p. 12, 2023.
Wang, J., & Zhang, H., "Optimizing resource scheduling in heavy machinery repair," International Journal of Production Research, vol. 56, no. 2, pp. 114–127, 2018.
Tharmmaphornphilas, W., & Norman, B. A., "A quantitative method for determining proper job rotation intervals," Annals of Operations Research, vol. 128, pp. 251–266, 2004. [https://doi.org/10.1023/B.0000019108.15750.ae]

Biographies

Bryan Cristobal Polino Palacios is a Bachelor's degree graduate in Industrial Engineering from the University of Lima, Peru. He has experience in logistics organization and operational coordination at CENTRUM PUCP Business School of the Pontifical Catholic University of Peru. His responsibilities included academic scheduling, master's program calendar planning, coordination of operational flows, and administrative support to ensure the proper execution of executive and graduate programs. His professional interests focus on operations management, logistics planning, process optimization, and continuous improvement in educational and corporate environments.

Johan Antonio Williard Hoyos Granada holds a Bachelor's degree in Industrial Engineering from the University of Lima, Peru. He has professional experience in treasury management and customer service operations, performing functions related to payment control, financial reconciliation, administrative support, and client request resolution. His profile integrates financial and operational competencies with interests in process management, business administration, service operations, and data-driven decision-making for organizational improvement.

Juan Carlos Quiroz Flores holds an MBA from ESAN University, a Ph.D. in Business Management from the National University of San Marcos, and is an Industrial Engineer from the University of Lima. He is also a certified Lean Six Sigma Black Belt and currently serves as a research professor in the Industrial Engineering Program at the University of Lima. With over 20 years of experience, he specializes in Lean Supply Chain, operations management, process improvement, and operational excellence, with research interests in logistics, lean manufacturing, Industry 4.0, digital transformation, and continuous improvement.

José Antonio Taquía Gutiérrez holds a Ph.D. in Business Management from the Universidad Nacional Mayor de San Marcos and a Master of Science in Industrial Engineering from the University of Lima, where he also earned his degree in Industrial Engineering. He currently serves as a professor and researcher at the University of Lima. His academic and professional experience focuses on operations management, data analysis, supply chain management, applied analytics, and Industry 4.0, with research interests in predictive analytics, artificial intelligence, machine learning, and supply chain optimization.