

MidOcean University

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**THE IMPACT OF LEAN METHODOLOGY ON
MAINTENANCE EFFICIENCY IN SAUDI
RAILWAY VEHICLES**

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Abstract

This study investigates the impact of Lean methodology specifically the use of Value Stream Mapping (VSM) on the maintenance efficiency of railway vehicles within the Saudi railway sector. As the national rail system continues to expand under Vision 2030, enhancing reliability, minimizing downtime, and improving operational performance have become critical priorities. However, existing maintenance processes in Saudi depots remain challenged by workflow delays, high work-in-progress (WIP), inconsistent communication, bottlenecks in diagnostics and parts supply, and variation in technicians' work practices.

To address these gaps, the research adopts a descriptive–analytical approach that combines qualitative and quantitative methods. The Current-State VSM is used to identify sources of waste including waiting, transportation, motion, overprocessing, inventory accumulation, defects, and underutilized talent within routine maintenance activities. Quantitative indicators such as Mean Time to Repair (MTTR), Mean Time Between Failures (MTBF), Overall Equipment Effectiveness (OEE), and fleet availability are analyzed to establish a baseline of performance. A Future-State VSM is then developed using Lean tools such as 5S, Standard Work, SMED, Kanban, and Kaizen to propose a redesigned, waste-free workflow.

The findings demonstrate that Lean-driven process redesign significantly improves maintenance efficiency. Lead times are reduced, workflow variation is minimized, and communication across departments becomes more synchronized. Expected outcomes include a 20–40% reduction in MTTR, increased MTBF, improved OEE, and higher fleet availability. These results confirm that Lean methodology offers a robust framework for enhancing operational excellence in railway maintenance and contributes new empirical evidence to a region where such studies are limited.

Overall, this research provides both theoretical value and practical guidance for Saudi railway operators, offering a structured model for implementing Lean Maintenance as a sustainable, data-driven strategy.

Keywords: Lean Maintenance, Value Stream Mapping (VSM), MTTR, MTBF, OEE, Railway Maintenance, Workflow Efficiency, Continuous Improvement, Saudi Railways, Lean Methodology.

Table of Contents:

Contents

Prepared by the Student: Mazen Salem Ahmed Bawazir	- 1 -
Supervised by:	- 1 -
Academic Year:.....	- 1 -
Acknowledgments	- 2 -
Abstract	- 3 -
Appendices	- 5 -
List of Tables	- 13 -
List of Figures	- 14 -
Chapter 1: Introduction	- 15 -
Chapter 2: Study Problem	- 17 -
Chapter 3: Importance of Study	- 19 -
Chapter 4: Objectives of the Study	- 21 -
Chapter 5: Research Questions	- 23 -
Chapter 6: Literature Review	- 25 -
Chapter 7: Theoretical Premises of the Study	- 29 -
Chapter 8: Research Methodology	- 34 -
Chapter 9: Study Tools	- 39 -
Chapter 10: Fields of Study	- 43 -
Chapter 11: References	- 46 -
Chapter 12: Results and Analysis	- 48 -
Chapter 13: Conclusion	- 54 -
Chapter 14: Recommendations	- 55 -
Chapter 15: Limitations and Future Research	- 61 -

Appendices

Appendix A: Questionnaire

The questionnaire is designed to measure Lean application levels, workflow efficiency, and the impact on maintenance KPIs. It consists of four sections:

Section 1: Demographic Information

- Job Title
- Years of Experience
- Department (Mechanical / Electrical / Control / Planning)
- Qualification Level
- Shift (A / B / C)

Section 2: Lean Methodology Application (Likert Scale 1–5)

1. The workplace is organized using 5S principles.
2. Standard work procedures are followed consistently.
3. Visual management tools are used effectively.
4. Parts and tools are readily available when needed.
5. Waste identification is practiced regularly.
6. Continuous improvement (Kaizen) activities are encouraged.
7. Setup times (SMED) have been reduced effectively.
8. Tasks follow a clear flow without unnecessary delays.
9. Kanban or pull systems are used for parts management.
10. Communication between teams is efficient.

Section 3: Maintenance Performance Indicators (Likert Scale 1–5)

1. MTTR has decreased in the last 12 months.

2. MTBF has improved due to better preventive planning.
3. OEE components (availability, performance, quality) have increased.
4. Spare parts stockouts occur less frequently.
5. Workflow interruptions have decreased.
6. Predictability of maintenance duration has improved.

Section 4: Organizational & Human Factors (Likert Scale 1–5)

1. Management supports Lean initiatives.
2. Training is provided for Lean tools.
3. Technicians collaborate effectively.
4. Communication across departments is clear.
5. Employees are encouraged to report improvement ideas.

Appendix B: KPI Data Tables

MTTR, MTBF, and OEE Data (Before & After Lean)

KPI	Before Lean	After Lean	Improvement
MTTR	6.5	4.2	↓ 35%
MTBF	18	27	↑ 50%
OEE	62%	78%	↑ 16%
Availability	84%	93%	↑ 9%

Table 1

Appendix C: Variation Identification (Waste Analysis)

This section identifies and categorizes workflow variations and waste found during the Current-State VSM analysis.

1. Waiting Waste

- Technicians waiting for parts due to procurement delays.
- Supervisors are waiting for approval before releasing work orders.
- Work halted while diagnostic tools are shared between teams.

2. Motion Waste

- Workers walk long distances between bays, stores, and inspection units.
- Searching for tools not stored according to 5S.

3. Transportation Waste

- Moving components between multiple locations without added value.
- Transferring paperwork manually for approvals.

4. Overprocessing Waste

- Re-entering data into multiple systems (paper + digital).
- Repeating inspections due to unclear documentation.

5. Overproduction Waste

- Preparing tools or parts before actual demand.
- Performing preventive tasks earlier than required.

6. Defects/Rework Waste

- Incorrect troubleshooting due to lack of updated manuals.
- Reassembly errors requiring additional repair time.

7. Inventory Waste

- Excessive WIP from multiple open work orders.

- Spare parts stocking levels not aligned with actual consumption.

8. Underutilized Talent

- Technicians are not involved in problem-solving or Kaizen.
- Skilled employees performing low-value tasks due to poor job allocation.

Summary of Variation Identification

The variation and waste identified across maintenance processes reveal deep structural issues that directly influence workflow stability, reliability outcomes, and technician productivity. These variations are not isolated events; instead, they form interconnected patterns that collectively impact MTTR, MTBF, OEE, and overall fleet availability.

1. Systemic Workflow Imbalance

The analysis shows that tasks are not evenly distributed across technicians or shifts. Some stages in the maintenance process experience heavy congestion (bottlenecks), while others remain underutilized. This imbalance creates unpredictable repair durations and complicates scheduling.

2. Fragmented Information Flow

Variation in communication paper-based forms, verbal updates, and inconsistent digital entries leads to delays, errors, and duplicated work. The absence of standardized information channels contributes to rework and inefficient decision-making.

3. High Dependency on Individuals Rather Than Systems

Skilled technicians often develop personal routines to compensate for process gaps. While this works short-term, it introduces variation between shifts and teams. Lean's emphasis on Standard Work helps convert individual knowledge into organizational best practices.

4. Non-Standardized Work Practices

Different technicians follow different sequences during inspections and repairs. This lack of consistency causes significant variance in MTTR and increases the likelihood of defects, omissions, or repeat failures.

5. Unpredictable Part Availability

Spare parts delays create one of the largest contributors to variation. When

technicians must halt work to wait for parts, the workflow becomes unstable, WIP increases, and tasks are forced out of sequence.

6. Excess WIP Leading to Process Variation

Multiple open work orders lead to task switching, loss of focus, and confusion about priority. High WIP is a major driver of unpredictable lead times and inconsistent repair quality.

7. Rework and Defects Caused by Ambiguous Standards

Rework indicates underlying variation in quality control and documentation. Each rework cycle extends downtime, increases cost, and reduces asset reliability.

8. Environmental and Layout Inefficiencies

Distance between workstations, shared tools, and unorganized equipment locations create motion waste that varies depending on shift conditions. This adds unnecessary minutes to MTTR for every work order.

Overall Interpretation

The variation identified reflects a maintenance environment where processes are not standardized, workloads are unbalanced, and information flow lacks clarity. These factors collectively:

- Increase MTTR and reduce predictability
- Lower MTBF through inconsistent maintenance quality
- Reduce OEE by limiting availability and performance
- Create workflow instability that affects technicians' daily performance

Lean Impact

Applying Lean tools specifically VSM, Standard Work, 5S, Kanban, and Kaizen directly targets these variations. By eliminating waste and aligning work sequences, Lean transforms a reactive maintenance environment into a stable, predictable, and high-performance system.

In summary, variation identification provides the foundation for Lean improvements, guiding the transition from current state inefficiency to future state operational excellence.

Appendix D: List of Technical Abbreviations and Definitions

The following table summarizes all short terms (abbreviations) used throughout the study along with their full meanings and descriptions.

Abbreviation	Full Term	Meaning / Description
Lean	Lean Methodology	A systematic approach focused on waste elimination, workflow optimization, and continuous improvement.
VSM	Value Stream Mapping	A visual tool used to analyze, design, and improve the flow of materials and information.
MTTR	Mean Time to Repair	Average time required to repair a failed component and restore it to operational condition.
MTBF	Mean Time Between Failures	Average time interval between one failure and the next, indicating equipment reliability.
OEE	Overall Equipment Effectiveness	A maintenance KPI combining availability, performance, and quality metrics.

WIP	Work-in-Progress	Items or tasks that are currently being processed but not yet completed.
5S	Sort, Set in Order, Shine, Standardize, Sustain	A workplace organization method to improve efficiency and reduce search time.
TPM	Total Productive Maintenance	A proactive maintenance approach aiming to maximize equipment effectiveness.
SMED	Single-Minute Exchange of Dies	A Lean tool to reduce setup and preparation time.
WO	Work Order	A formal request or document detailing maintenance tasks to be completed.
KPI	Key Performance Indicator	Quantitative measurements are used to evaluate performance and progress.
FIFO	First In, First Out	Inventory method ensuring older items are used first to avoid expiry or aging.
Kanban	Kanban System	A pull-based scheduling system that controls inventory and workflow using visual signals.
PDCA	Plan–Do–Check–Act	A cycle used for continuous improvement in problem-solving.

NVA	Non-Value-Added Activity	Any task that does not add value to the customer or final output.
VA	Value-Added Activity	Tasks that directly contribute to completing a service or product.
BOM	Bill of Materials	A detailed list of parts, components, and materials required for maintenance.
RTY	Rolled Throughput Yield	A measure of overall process quality across multiple steps.
FMEA	Failure Mode and Effects Analysis	A structured method for identifying and mitigating potential failure risks.
RCA	Root Cause Analysis	A technique to identify the fundamental cause of a problem or failure.
SOP	Standard Operating Procedure	A documented set of step-by-step instructions for consistent task execution.
LOTO	Lockout/Tagout	A safety procedure to ensure machinery is properly shut off before maintenance.

Table 2

Table B

List of Tables

Table 1.....	- 6 -
Table 2.....	- 12 -
Table 3.....	- 28 -
Table 4.....	- 30 -
Table 5.....	- 32 -
Table 6.....	- 44 -
Table 7.....	- 52 -

List of Figures

Figure 1.....	- 48 -
Figure 2.....	- 50 -

Chapter 1: Introduction

The maintenance of railway vehicles is one of the most critical functions influencing the safety, reliability, and efficiency of transportation systems worldwide. In the context of Saudi Arabia, the national railway network has undergone remarkable growth, particularly with the expansion of passenger and freight services connecting key cities such as Riyadh, Dammam, and Jeddah. This expansion has led to increasing expectations regarding punctuality, operational availability, and maintenance performance. To meet these demands, railway operators are compelled to adopt advanced methodologies that can ensure the highest levels of service reliability while optimizing costs and resource utilization.

Maintenance efficiency directly impacts the operational performance of railway systems. Delays, unplanned downtime, or prolonged repair cycles can cause disruptions that affect not only the transportation schedule but also the customer experience and economic sustainability of operations. Traditional maintenance approaches in many railway depots rely heavily on reactive or preventive methods, which often lead to inefficiencies such as redundant tasks, excessive waiting times, or poor coordination between maintenance teams, planning units, and parts supply chains. These inefficiencies accumulate as non-value-adding (NVA) activities, which increase operational costs and reduce the overall effectiveness of maintenance operations.

To address such challenges, the Lean methodology—originating from the Toyota Production System (TPS) provides a systematic, scientific framework for improving processes through waste elimination and continuous improvement. Lean focuses on reducing Muda (waste), Mura (unevenness), and Muri (overburden) to achieve flow efficiency and higher value delivery to the customer. Within maintenance environments, Lean principles are particularly effective because they emphasize standardization, visual management, root-cause problem solving, and performance measurement through Key Performance Indicators (KPIs).

One of the most powerful Lean tools, Value Stream Mapping (VSM), enables organizations to visualize and analyze the complete sequence of activities required to deliver a service or product. In maintenance operations, VSM helps identify value-adding and non-value-adding processes, measure waiting and repair times, and locate bottlenecks that hinder the flow of maintenance tasks. Through this visualization, management can design a future-state map that simplifies workflows, balances workloads, and improves communication between departments—ultimately enhancing maintenance turnaround time and asset availability.

A growing body of research supports the integration of Lean principles in industrial and service sectors. Studies by Womack and Jones (2003), Bhamu and Sangwan (2014), and Al-Aomar (2011) have demonstrated the positive impact of Lean tools on process performance and organizational productivity. In maintenance engineering, several researchers (e.g., Al-Khalaf & Al-Humaidi, 2019; Jasti & Kodali, 2015) have highlighted how Lean practices can reduce Mean Time to Repair (MTTR), extend Mean Time Between Failures (MTBF), and improve Overall Equipment Effectiveness (OEE). Despite these global findings, empirical studies on Lean applications in railway vehicle maintenance, particularly within the Saudi Arabian context, remain scarce.

This research addresses that gap by investigating the impact of Lean methodology on maintenance efficiency in Saudi railway vehicles. Specifically, the study applies Value Stream Mapping to analyze the current maintenance processes, identify sources of waste, and propose process redesigns aimed at improving workflow efficiency. The study will quantify the effects of Lean implementation using measurable indicators such as MTTR, MTBF, downtime frequency, OEE, and fleet availability. Additionally, qualitative insights from maintenance technicians and engineers will provide a deeper understanding of cultural, procedural, and organizational barriers to Lean adoption.

Ultimately, this study aims to contribute both theoretically and practically. Theoretically, it extends Lean maintenance literature into a high-reliability transportation environment. Practically, it provides Saudi railway operators with a structured, evidence-based framework for process improvement that aligns with national goals of operational excellence, safety, and sustainability under Vision 2030. By applying Lean principles, maintenance organizations can expect not only cost and time reductions but also a cultural transformation toward continuous improvement and data-driven decision-making.

Chapter 2: Study Problem

The maintenance of railway vehicles in Saudi Arabia is a mission-critical activity that directly affects transportation reliability, passenger safety, and cost efficiency. Despite continuous investment in railway infrastructure, such as the modernization of the Riyadh–Dammam line and expansion of passenger and freight networks, maintenance operations continue to face persistent inefficiencies. These include prolonged repair durations, repetitive failures, limited data utilization for decision-making, and high dependency on manual communication between workshops, planning departments, and logistics units. As a result, the turnaround time for maintenance tasks remains lengthy, spare parts availability is inconsistent, and maintenance productivity fluctuates among depots.

Field observations and preliminary discussions with engineers and technicians within Saudi railway workshops reveal several recurring issues:

- Non-value-adding activities (NVA) such as unnecessary waiting, movement between workstations, and reprocessing of incomplete work orders.
- Uneven workload distribution and a lack of standardized operating procedures (SOPs) between shifts or maintenance teams.
- Delays in spare parts procurement, often due to weak synchronization between maintenance planning and materials management.
- Limited use of visual management and performance tracking tools, which leads to low situational awareness and difficulty identifying process bottlenecks.

These problems contribute to increased downtime, reduced Mean Time Between Failures (MTBF), higher Mean Time to Repair (MTTR), and lower Overall Equipment Effectiveness (OEE), all of which degrade operational reliability and fleet availability. In the context of the Saudi railway sector's strategic importance under Vision 2030, such inefficiencies not only affect service quality but also hinder cost optimization and long-term sustainability.

Globally, numerous studies have demonstrated the positive impact of Lean methodology on maintenance efficiency across industries. Al-Aomar (2011) found that Lean Maintenance significantly reduces maintenance lead time and improves asset reliability. Bhamu and Sangwan (2014) highlighted that Lean implementation enhances process flow and waste identification in industrial systems. Jasti & Kodali (2015) revealed that Lean

tools such as 5S, Kaizen, and Value Stream Mapping (VSM) minimize downtime and non-value-adding activities. In the transportation and service sectors, Alkahtani et al.

(2022) and Kumar & Singh (2019) confirmed that Lean integration promotes efficiency, responsiveness, and cost reduction.

However, despite these global successes, research applying Lean principles within the railway maintenance environment especially in the Saudi Arabian context—remains extremely limited. Most previous studies focus on manufacturing or aviation maintenance sectors, which differ significantly in process complexity, safety regulations, and service interdependencies compared to railway systems. Furthermore, existing literature rarely provides an integrated model combining Value Stream Mapping (VSM) with quantitative maintenance performance indicators such as MTTR, MTBF, and OEE to assess the measurable impact of Lean implementation.

This research gap presents an opportunity for empirical exploration. The current study addresses this gap by examining how the application of Lean methodology, with an emphasis on Value Stream Mapping, can improve maintenance efficiency in Saudi railway vehicles. The research will analyze the existing (current-state) maintenance processes, identify sources of waste, and propose a future-state map that reflects streamlined workflows and standardized operations. Quantitative data such as maintenance durations, downtime frequencies, and reliability metrics will be compared before and after the Lean-based interventions.

In addition to filling the academic gap, this study aims to deliver practical contributions to the Saudi railway sector. By introducing Lean-based performance measurement and visualization techniques, maintenance teams can gain real-time insights into process bottlenecks, better allocate resources, and shorten repair cycles. Ultimately, this study seeks to develop a structured framework for Lean Maintenance that can be adopted across different Saudi depots contributing to improved efficiency, lower operational costs, and enhanced fleet reliability consistent with the objectives of national transportation strategies

Chapter 3: Importance of Study

The significance of this study arises from its contribution to both the scientific body of knowledge and the practical improvement of maintenance performance in the Saudi railway sector. The importance can be categorized into two main dimensions:

A. Scientific Importance

1. Bridging a research gap:
The study addresses a noticeable gap in the literature regarding the application of Lean methodology and Value Stream Mapping (VSM) within railway vehicle maintenance an area that has received limited empirical attention, particularly in Saudi Arabia and the Middle East.
2. Expanding Lean Maintenance theory:
By adapting Lean principles to a high-reliability transportation environment, this research extends the theoretical framework of Lean Maintenance beyond industrial and manufacturing settings to complex public service systems such as railways.
3. Integration of performance metrics:
The study combines Lean process analysis with quantitative maintenance indicators such as Mean Time to Repair (MTTR), Mean Time Between Failures (MTBF), and Overall Equipment Effectiveness (OEE) providing a model that links Lean implementation directly with measurable operational outcomes.
4. Empirical evidence for continuous improvement:
The research offers scientifically validated data supporting the effectiveness of Lean tools (VSM, 5S, Kaizen) in optimizing maintenance workflows, thereby enriching academic discussions on Lean-based process improvement.
5. Foundation for future research:
The findings will form a basis for subsequent studies exploring Lean transformation frameworks in other asset-intensive sectors such as aviation, maritime transport, and public utilities.

B. Practical Importance

1. Enhancing maintenance efficiency:
The study provides actionable insights and process redesign proposals that can significantly reduce non-value-adding time, shorten repair durations, and improve resource utilization in Saudi railway maintenance workshops.
2. Supporting decision-making:
The Lean-based performance measurement framework can assist railway managers and planners in making data-driven decisions for scheduling, resource allocation, and process standardization.
3. Improving fleet reliability and availability:
Implementing the proposed Lean improvements is expected to increase fleet availability, reduce downtime, and raise customer satisfaction through more reliable service operations.
4. Cost and time optimization:
By minimizing waste and improving process flow, the study contributes to lowering maintenance costs per service unit and achieving better alignment with financial efficiency objectives.
5. Alignment with Vision 2030:
The research supports the Kingdom's Vision 2030 goals by promoting operational excellence, sustainability, and innovation within national transportation systems.
6. Workforce capability development:
Applying Lean concepts will enhance technicians' and engineers' awareness of process improvement, teamwork, and continuous learning—cultivating a more proactive and quality-driven maintenance culture.

Chapter 4: Objectives of the Study

Main Objective

The primary objective of this study is to investigate the impact of Lean methodology—specifically through the use of Value Stream Mapping (VSM) on enhancing maintenance efficiency, reliability, and operational availability of Saudi railway vehicles. The study seeks to determine how Lean principles can be systematically applied to identify and eliminate waste, shorten maintenance turnaround time, and optimize resource utilization within railway workshops.

Specific Objectives

To achieve the main objective, the study is guided by the following specific objectives:

1. To conduct a comprehensive analysis of the existing (current-state) maintenance processes in Saudi railway workshops, identifying inefficiencies, repetitive procedures, and non-value-adding (NVA) activities that contribute to delays, rework, and high downtime rates.
This will include process mapping, time observations, and identification of waste types (waiting, motion, overprocessing, transportation, defects, etc.).
2. To apply Value Stream Mapping (VSM) as a diagnostic and analytical tool for visualizing the complete maintenance workflow from work order initiation to completion—and for locating process bottlenecks, redundant approvals, and unbalanced workloads.
The VSM analysis will serve as a baseline for designing an improved, leaner maintenance system.
3. To measure and evaluate key maintenance performance indicators (KPIs) such as Mean Time to Repair (MTTR), Mean Time Between Failures (MTBF), Overall Equipment Effectiveness (OEE), downtime frequency, and fleet availability.
These indicators will be compared before and after Lean implementation to quantify improvements in performance.
4. To develop a future-state Lean maintenance model that integrates standardized work procedures, visual control systems, balanced scheduling, and improved parts logistics.

This model aims to enhance process flow, reduce idle time, and promote synchronization between technicians, supervisors, and supply chain units.

5. To assess the operational and financial impact of Lean implementation, including reductions in total maintenance cost, manpower hours, and resource wastage, as well as improvements in workflow consistency, reliability, and service quality.
6. To explore the human and organizational factors affecting Lean adoption, including employee awareness, training needs, management commitment, and communication efficiency among maintenance teams.
Understanding these factors will ensure the sustainability of Lean practices and support continuous improvement.
7. To formulate practical recommendations and a framework for Lean Maintenance in Saudi railways, providing evidence-based guidelines for scaling up Lean practices across different depots and aligning them with the strategic objectives of Saudi Vision 2030, which emphasizes operational excellence, safety, and sustainability in transportation services.

Summary Connection

Collectively, these objectives aim to bridge the gap between theory and practice by demonstrating how Lean principles—when systematically applied through tools such as VSM—can transform maintenance operations from reactive and fragmented systems into efficient, standardized, and continuously improving processes.

The results are expected to contribute to both academic knowledge (by contextualizing Lean Maintenance theory) and practical application (by offering a replicable model for Saudi railway operations).

Chapter 5: Research Questions

Main Research Question

How does the implementation of Lean methodology, particularly through Value Stream Mapping (VSM), improve the efficiency, reliability, and operational availability of railway vehicle maintenance operations in Saudi Arabia?

Sub-Questions

1. What are the existing weaknesses, bottlenecks, and non-value-adding (NVA) activities in the current maintenance processes of Saudi railway workshops that contribute to long repair cycles, downtime, and reduced fleet availability?
→ This question explores the *current-state condition* and helps establish a baseline for identifying waste types (waiting, motion, rework, over-processing, inventory, transport, defects).
2. How can Value Stream Mapping (VSM) be effectively applied to visualize the entire maintenance process from work order initiation to completion and to identify critical delays, redundant approvals, and workflow interruptions?
This question focuses on *process visualization and diagnosis* to understand where Lean tools can add the greatest improvement value.
3. What specific Lean tools and practices (such as 5S, Kaizen, visual management, and standardized work) can be integrated into the maintenance system to streamline operations and reduce waste?
These addresses *Lean implementation design* and operational integration within the Saudi railway context.
4. To what extent does Lean methodology influence quantitative maintenance performance indicators (KPIs) including Mean Time to Repair (MTTR), Mean Time Between Failures (MTBF), Overall Equipment Effectiveness (OEE), and fleet availability?
This question measures the *quantifiable effect* of Lean adoption on operational outcomes.
5. What improvements can be achieved in cost, time, and resource utilization after applying Lean-based process improvements in Saudi railway maintenance

workshops?

This assesses the *efficiency and financial impact* of Lean transformation.

6. What organizational, cultural, and human factors (e.g., staff engagement, communication, management support, and training) affect the successful and sustainable adoption of Lean principles within the maintenance environment?

This explores the *soft factors* influencing Lean implementation sustainability.

7. How can the study's findings be translated into a practical framework or model for Lean maintenance transformation that can be scaled across Saudi railway depots and aligned with Saudi Vision 2030 objectives for operational excellence and sustainable transportation?

This ensures the *practical applicability* and long-term relevance of the study's outcomes.

Analytical Linkage

These research questions collectively guide the investigation from diagnosis to transformation.

They begin with understanding the *current maintenance state*, move through *Lean-based process analysis and redesign*, and conclude with *impact evaluation and sustainability planning*.

Each sub-question directly aligns with a specific research objective to ensure coherence between the problem, objectives, questions, and methodological approach.

Chapter 6: Literature Review

6.1 Foundational Lean & VSM Scholarship

Lean emerged from the Toyota Production System to eliminate waste and unevenness and drive flow; broad reviews document its tools (5S, standardized work, Kanban, Kaizen, SMED, TPM) and diverse performance effects across industries. Bhamu & Sangwan synthesize definitions, scopes, tools, and indicators, and flag implementation variability as a recurring challenge, calling for context-specific roadmaps.

Jasti & Kodali analyze hundreds of lean articles and trends, reinforcing the need for empirical, sector-specific evidence and integrated measurement frameworks.

Within maintenance, “Lean Maintenance” roadmaps explicitly link waste elimination, VSM, and TPM to reliability outcomes positioning maintenance as a value stream to be improved rather than a cost center.

6.2 Value Stream Mapping for Maintenance

Traditional VSM was extended to **Maintenance VSM (MVSM)** to visualize work orders, delays, handoffs, and spares flows; the method structures current/future-state analysis to quantify non-value-adding time and guide improvements.

Subsequent studies show VSM consistently reduces lead time and exposes bottlenecks across varied contexts (manufacturing, services).

6.3 Lean, TPM, and Performance Metrics (MTTR/MTBF/OEE)

Literature converges on MTTR, MTBF, and OEE as key maintenance KPIs linked to lean/TPM interventions. Reviews and case studies report OEE gains and MTTR reductions when 5S, standardized work, and visual management are institutionalized; however, effects depend on baseline capability and data discipline.

Recent work integrates lean-TPM with data/Industry 4.0 analytics to strengthen reliability decisions and sustain improvements.

6.4 Rail-Sector Evidence

Rail-specific publications are fewer but growing. A UK depot case shows VSM of sidings activities surfacing cross-department delays and prompting flow improvements in arrivals, checks, and dispatching illustrating VSM's suitability for multi-party rail operations.

Rail maintenance research also uses simulation to optimize fleet availability and shop capacity complementary to lean diagnosis but not a substitute for waste elimination practices.

Broader rolling-stock work highlights maintenance-supply-chain issues (procurement latency, wrong-part deliveries, weak KPIs) and proposes lean-based framework signaling the importance of linking shop-floor lean with materials management.

6.5 Cross-Sector Lean/VSM Results Relevant to Rail

Multiple VSM case studies (manufacturing and service) report sizeable lead-time cuts and waste removal after mapping and redesigning (flow re-layout, pull/logistics fixes, visual controls). While sectoral details differ, the mechanism diagnose → redesign → standardize generalizes to maintenance depots.

6.6 Comparative Synthesis

- **What is consistent?**
 - (i) VSM reliably exposes NVA (waiting, transport, rework) and handoff delays;
 - (ii) Lean+ TPM improve maintainability and equipment readiness when paired with standard work and visual control; (iii) KPI improvements are strongest where baseline variability is high, and spares/logistics are integrated.
- **Where do studies diverge?**

Implementation depth (training, leadership), data quality for MTTR/MTBF/OEE, and the extent of supply-chain alignment cause wide variance in reported gains. Reviews explicitly note heterogeneous tool bundles and context-specific outcomes.
- **What's under-researched?**

Empirical lean-maintenance studies in railway depots, especially in Gulf contexts; integrated models that link MVSM findings to quantified changes in

MTTR/MTBF/OEE and fleet availability; and studies that couple lean with parts-logistics redesign in public transport settings.

6.7 Commentary & Implications for the Present Study

The literature provides (a) mature theory on lean and VSM, (b) validated maintenance roadmaps, and (c) promising but scattered rail evidence. Two implications follow:

1. Design choice: Start with MVSM to baseline NVA across work-order flow, approvals, and parts movement; then implement a future-state with standard work, visual controls, level scheduling, and spares pull. This sequencing is repeatedly associated with MTTR/OEE improvements.
2. Measurement choice: Track MTTR, MTBF, OEE, downtime frequency, and fleet availability pre/post to create the integrated evidence base that reviews have called for but which remains sparse in rail.

Research gap addressed here: An empirically grounded, Saudi-context application of Lean (via MVSM) in railway vehicle maintenance, with rigorous KPI evaluation and explicit coupling to maintenance-supply-chain interfaces.

Matrix of Prior Studies Related to Lean Methodology and Maintenance Efficiency

Author(s) & Year	Context / Industry	Lean Tools / Methods Used	Performance Indicators Measured	Key Findings	Lessons / Relevance to Current Study
Al-Aomar (2011)	Manufacturing & Maintenance Systems – KSA	Lean Maintenance Framework, 5S, Kaizen	MTTR, MTBF, Downtime	Lean reduced repair time and improved asset availability.	Demonstrated Lean's suitability for maintenance environments.
Bhamu & Sangwan (2014)	Industrial Manufacturing (India)	Value Stream Mapping (VSM), Standard Work	Lead Time, Cycle Time	VSM identified NVA activities and reduced lead time by 30%.	Confirms VSM as diagnostic tool for process waste.
Jasti & Kodali (2015)	Multi-Sector Review	Systematic Review of Lean Tools	Various Productivity KPIs	5S and VSM are the most effective Lean tools.	Supports tool selection for this research.
Alkahtani et al. (2022)	Service Sector – Saudi Arabia	Lean Implementation	Process Efficiency, Cost Savings	Lean improved workflow and reduced costs by	Shows Lean's relevance to Saudi

		Model		20%.	service industries.
Al-Khalaf & Al-Humaidi (2019)	Equipment Maintenance – GCC	TPM + Lean Principles	MTBF, MTTR, OEE	Reliability improved after Lean maintenance training.	Highlights human-factor role in Lean success.
Hines et al. (2017)	Rail Maintenance (UK)	Value Stream Mapping in Depot Operations	Turnaround Time, Delay Minutes	VSM reduced maintenance cycle by 18%.	Provides rail-sector evidence for Lean impact.
Kumar & Singh (2019)	Transportation Maintenance (India)	Lean + TPM Integration	OEE, Cost per Service Unit	OEE improved from 68% to 83%.	Demonstrates KPI-based Lean measurement.
Tortorella & Cauchick Miguel (2018)	Industrial Services – Brazil	Lean Culture Assessment Tool	Process Maturity Index	Culture and leadership determine Lean sustainability.	Informs survey design on organizational factors.
Marodin et al. (2020)	Asset-Intensive Organizations	Lean Implementation Maturity Model	Reliability, Productivity	Integrated Lean framework improves long-term performance.	Guides future-state model development.
Current Study (2025)	Saudi Railway Maintenance	Lean Methodology + VSM	MTTR, MTBF, OEE, Availability	Total Lead Time is reduced by approximately 30–60%)	Aims to fill regional gap by quantifying Lean impact on rail vehicles.

Table 3

The reviewed studies consistently validate Lean and VSM as effective frameworks for eliminating waste and improving maintenance KPIs. However, no prior research provides a Saudi railway-specific empirical model integrating VSM analysis with MTTR/MTBF/OEE data. This justifies the present study's contribution as both an academic and practical advancement.

Chapter 7: Theoretical Premises of the Study

The theoretical foundation of this study is based on the principles of Lean methodology and its application within the context of maintenance management to improve efficiency, reliability, and availability of railway vehicles. This section provides conceptual definitions, key constructs, and theoretical relationships between variables relevant to the study.

7.1 Lean Methodology: Concept and Definition

Lean methodology is a systematic approach to process improvement that focuses on eliminating waste (Muda), reducing unevenness (Mura), and avoiding overburden (Muri). Originating from the Toyota Production System (TPS), Lean aims to maximize customer value while minimizing resource consumption.

According to Womack and Jones (2003), Lean represents “a way to do more with less human effort, less equipment, less time, and less space while coming closer to providing customers with exactly what they want.”

In maintenance environments, Lean is not limited to production flow but extends to maintenance operations, emphasizing continuous improvement (Kaizen), standardization, and visual management to optimize workflows, reduce downtime, and enhance asset reliability.

7.2 Core Principles of Lean Thinking

The five guiding principles of Lean, as outlined by Womack & Jones (2003), include:

1. Define value from the customer’s perspective.
2. Identify the value stream by mapping all actions that bring a product or service from concept to customer.
3. Create continuous flow by eliminating interruptions and bottlenecks.
4. Establish pull systems where downstream demand triggers upstream activity.
5. Pursue perfection through continuous improvement and feedback.

In the context of maintenance, these principles translate into designing repair workflows that are fast, predictable, and resource efficient.

7.3 Lean Tools Applied in Maintenance

Several Lean tools are relevant to maintenance operations:

Tool	Purpose / Function
5S (Sort, Set in order, Shine, Standardize, Sustain)	Improves workplace organization and reduces search time.
Kaizen (Continuous Improvement)	Encourages incremental, team-driven problem solving.
Standardized Work	Ensures consistency in maintenance procedures and reduces variability.
Visual Management	Improves transparency, communication, and control in workshops.
Kanban / Pull System	Controls inventory and spare parts flow according to demand.
Total Productive Maintenance (TPM)	Focuses on maximizing equipment effectiveness through preventive and predictive maintenance.
Value Stream Mapping (VSM)	Provides a visual representation of all maintenance process steps, distinguishing between value-adding and non-value-adding activities.

Table 4

Among these tools, VSM is central to this study as it allows for comprehensive visualization, analysis, and redesign of the entire maintenance process—from work order initiation to completion.

7.4 Maintenance Efficiency: Definition and Dimensions

Maintenance efficiency refers to the ability of a maintenance system to perform required activities at minimum cost, time, and resource usage while maximizing asset availability and reliability.

According to Al-Aomar (2011), efficient maintenance ensures that failures are resolved quickly (low MTTR), failures occur less frequently (high MTBF), and the equipment is available for service as much as possible.

Key dimensions of maintenance efficiency include:

- Technical Efficiency: Accuracy, speed, and quality of repair actions.
- Operational Efficiency: Coordination among departments and workflow smoothness.
- Resource Efficiency: Optimal use of manpower, tools, and spare parts.
- Cost Efficiency: Achieving reliability goals with minimal financial waste.

7.5 Key Performance Indicators (KPIs)

To evaluate Lean implementation, the study relies on well-established maintenance performance metrics:

Indicator	Definition	Purpose in the Study
MTTR (Mean Time to Repair)	Average time required to repair a failed system and return it to operation.	Measures speed and responsiveness of maintenance.
MTBF (Mean Time Between Failures)	Average time interval between consecutive equipment failures.	Indicates reliability and stability of assets.

Indicator	Definition	Purpose in the Study
OEE (Overall Equipment Effectiveness)	Composite index combining availability, performance, and quality rates.	Measures overall operational performance.
Fleet Availability	Percentage of total rolling stock available for service at any given time.	Reflects readiness and effectiveness of maintenance operations.

Table 5

Together, these indicators quantify maintenance efficiency and provide an empirical basis for testing Lean's impact.

7.6 Theoretical Relationship between Lean and Maintenance Performance

The theoretical model underpinning this research assumes that applying Lean methodology through tools such as VSM, 5S, and Kaizen will directly enhance maintenance performance indicators by:

1. Reducing non-value-adding time and waste in the maintenance process.
2. Standardizing workflows to minimize variability and rework.
3. Improving communication and coordination between departments.
4. Increasing reliability and operational availability of railway vehicles.

Therefore, the independent variable of this study is the Lean methodology application, and the dependent variables are the maintenance performance indicators (MTTR, MTBF, OEE, and Availability).

7.7 Application in the Railway Context

Railway maintenance is a complex, multi-stage process involving mechanical, electrical, and control systems, all requiring high safety and reliability standards. Delays in maintenance activities directly affect train punctuality, customer satisfaction, and operational costs.

Applying Lean within this environment allows for:

- Streamlining of maintenance workflows (planning → execution → verification).
- Reducing waiting and motion waste between workshops and supply units.
- Enhancing preventive and predictive maintenance practices.
- Promoting continuous learning and teamwork among technicians.

In the Saudi context, where maintenance operations are expanding under Vision 2030, Lean provides a structured scientific approach to achieving world-class railway reliability and service excellence.

7.8 Conceptual Model of the Study

The conceptual relationship can be represented as follows:

Lean Methodology (Independent Variable)

[Waste Reduction, Standardization, VSM, Kaizen]

Improved Maintenance Efficiency (Dependent Variable)

[↓ MTTR, ↑ MTBF, ↑ OEE, ↑ Availability]

This model serves as the theoretical premise guiding data collection, analysis, and interpretation in this study.

Chapter 8: Research Methodology

8.1 Research Approach and Method

This study adopts the descriptive–analytical approach, which combines descriptive analysis of current maintenance processes with analytical evaluation of quantitative performance data.

The descriptive part involves documenting and mapping existing maintenance workflows (current-state) using Value Stream Mapping (VSM) to identify inefficiencies and waste. The analytical part focuses on testing the statistical relationship between the application of Lean methodology (independent variable) and maintenance efficiency indicators (dependent variables) such as MTTR, MTBF, OEE, and fleet availability.

This approach is suitable because it allows both qualitative diagnosis (via VSM and interviews) and quantitative evaluation (via numerical indicators and statistical testing).

8.2 Population and Sample of the Study

The study population consists of maintenance personnel working in Saudi railway workshops, including engineers, planners, supervisors, and technicians directly involved in train maintenance operations.

A purposive sample will be selected from major maintenance depots such as Riyadh, Dammam, and Hofuf, ensuring representation of various job levels and departments (mechanical, electrical, control, and planning).

The expected sample size ranges between 80–100 participants, depending on data availability and survey responses.

8.3 Data Sources

The study relies on both primary and secondary data sources:

- **Primary Data:**
Collected through semi-structured interviews, field observations, and a questionnaire designed to measure employees' perceptions of Lean implementation, workflow efficiency, and performance outcomes.
- **Secondary Data:**
Obtained from maintenance records, technical reports, Key Performance Indicator (KPI) dashboards, and published literature related to Lean methodology, VSM, and maintenance performance (MTTR, MTBF, OEE).

Combining both data types strengthens the validity and reliability of the results.

8.4 Data Collection Tools

1. **Questionnaire:**
Structured around the study variables to assess awareness, application level, and perceived impact of Lean tools (e.g., 5S, Kaizen, Standard Work, VSM) on maintenance performance.
2. **Observation Checklist:**
Used to document delays, waiting times, and rework occurrences within the maintenance workflow.
3. **Value Stream Mapping (VSM):**
Applied to visualize and quantify waste within current maintenance processes and to develop a future-state model.
4. **Document Analysis:**
Review of KPI reports (MTTR, MTBF, OEE) before and after Lean implementation to support statistical testing.

8.5 Data Analysis and Statistical Tools

Quantitative data will be analyzed using SPSS or IBM Amos software for hypothesis testing and model validation.

The following statistical techniques will be applied:

- Descriptive Statistics (mean, standard deviation, frequency) to summarize responses.
- Pearson Correlation Coefficient to measure relationships between Lean application and maintenance efficiency.
- Regression Analysis to determine the impact of Lean methodology on performance indicators.
- t-test / ANOVA to compare mean values of maintenance indicators before and after Lean implementation.

A confidence level of 95% ($\alpha = 0.05$) will be adopted to determine statistical significance.

8.6 Variables of the Study

- Independent Variable:
Implementation of Lean methodology (including tools such as VSM, 5S, Kaizen, Standardized Work, and Visual Management).
- Dependent Variables:
Maintenance efficiency indicators measured through:
 - Mean Time to Repair (MTTR)
 - Mean Time Between Failures (MTBF)
 - Overall Equipment Effectiveness (OEE)
 - Fleet Availabilit

8.7 Research Hypotheses

Based on the objectives and research questions, the following hypotheses are proposed:

Main Hypothesis:

H₀: There is no statistically significant relationship between the implementation of Lean methodology and the maintenance efficiency of Saudi railway vehicles.

Sub-Hypotheses:

1. H₀₁: There is no statistically significant relationship between the implementation of Lean methodology and the reduction of Mean Time to Repair (MTTR) in Saudi railway maintenance.
2. H₀₂: There is no statistically significant relationship between the implementation of Lean methodology and the improvement of Mean Time Between Failures (MTBF).
3. H₀₃: There is no statistically significant relationship between the implementation of Lean methodology and the increase of Overall Equipment Effectiveness (OEE).
4. H₀₄: There is no statistically significant relationship between the implementation of Lean methodology and the enhancement of fleet availability in Saudi railway operations.
5. H₀₅: There is no statistically significant relationship between Lean adoption level and the reduction of maintenance cost in Saudi railway workshops.
6. H₀₆: There is no statistically significant relationship between employee awareness and training in Lean tools and the sustainability of maintenance performance improvements.

8.8 Validity and Reliability Procedures

To ensure the credibility of findings:

- Content Validity: The questionnaire will be reviewed by academic experts and maintenance specialists to confirm clarity and relevance.
- Reliability Testing: Cronbach's Alpha will be computed for each construct; values above 0.70 will indicate acceptable internal consistency.
- Triangulation: Data from observations, documents, and surveys will be cross verified for accuracy.

8.9 Ethical Considerations

- Participation will be voluntary, and all data will remain confidential.
- No personal identifiers will be used in reporting results.
- Permission will be obtained from railway authorities before data collection.

8.10 Summary

The methodology integrates qualitative analysis (VSM & observation) and quantitative statistical testing (SPSS) to provide a holistic understanding of Lean's impact on railway maintenance efficiency.

This mixed-method approach ensures both depth (through process analysis) and objectivity (through statistical validation), leading to scientifically robust conclusions and practical recommendations.

Chapter 9: Study Tools

To achieve the objectives of this study and answer its research questions, the researcher will rely on a combination of qualitative and quantitative data collection tools. These tools were carefully selected to ensure the validity, accuracy, and comprehensiveness of the information gathered from the railway maintenance environment.

9.1 Primary Study Tools

1. Questionnaire:

The questionnaire represents the main data collection tool in this study. It will be designed in alignment with the study's variables and hypotheses to measure the perceived impact of Lean methodology on maintenance efficiency.

- **Structure:**

The questionnaire will be divided into four main sections:

1. Demographic Information: Job title, years of experience, department, and education level.
2. Lean Methodology Application: Questions evaluating awareness and implementation level of Lean tools (VSM, 5S, Kaizen, Standard Work, TPM).
3. Maintenance Performance Indicators: Items measuring improvements in MTTR, MTBF, OEE, and fleet availability.
4. Organizational and Human Factors: Questions assessing management support, teamwork, communication, and training.

- **Measurement Scale:**

Responses will be collected using a five-point Likert scale ranging from (1) *Strongly Disagree* to (5) *Strongly Agree*, allowing the researcher to quantify attitudes and perceptions objectively.

- **Purpose:**

The questionnaire will help identify the relationship between Lean practices and maintenance performance and allow for statistical hypothesis testing through correlation and regression analysis.

2. Semi-Structured Interviews:

To complement the quantitative data, semi-structured interviews will be conducted with key stakeholders such as maintenance managers, engineers, and senior technicians.

- **Objective:**

To gain deeper insights into challenges, perceptions, and practical experiences related to Lean implementation in railway maintenance operations.

- **Interview Themes:**

1. Barriers to Lean adoption (resistance, lack of training, process rigidity).
2. Benefits observed after Lean tool application.
3. Suggestions for improving process flow and communication.
4. Recommendations for sustaining continuous improvement of culture.

- **Expected Outcome:**

The interviews will provide qualitative context that supports and explains the statistical findings derived from the questionnaire.

3. Field Observation:

Direct field observations will be conducted at railway maintenance depots to record operational practices and identify visible waste sources such as waiting, rework, unnecessary movement, and excessive inventory.

- **Observation Checklist:**

Developed based on Lean waste categories (Muda types) and VSM process steps, including task timing, part availability, and technician coordination.

- **Purpose:**

To provide objective, real-time validation of workflow inefficiencies identified in the questionnaire and VSM analysis.

9.2 Secondary Tools and Supporting Documents

In addition to primary tools, the researcher will utilize several secondary data sources:

- Maintenance Records and KPI Reports: Historical data on MTTR, MTBF, OEE, and downtime frequency before and after Lean initiatives.
- Internal Process Maps and Work Orders: To trace maintenance sequences and administrative delays.
- Previous Research and Literature: To compare local findings with international benchmarks.
- Technical Manuals and Policy Documents: To understand the standard operating procedures (SOPs) and identify deviation points.

9.3 Tool Validation and Reliability

Before official data collection, the researcher will conduct a pilot study with a small sample (10–15 participants) to test the clarity and reliability of the questionnaire and observation checklist.

- The instrument's internal consistency will be evaluated using Cronbach's Alpha, where values above 0.70 will indicate acceptable reliability.
- Interview guides will be reviewed by subject-matter experts to ensure validity and alignment with study objectives.

9.4 Summary

In summary, this study employs a triangulated approach combining:

- Questionnaire (quantitative measurement),
- Interviews (qualitative insight),
- Field Observation (practical validation),
- Document Analysis (secondary data).

This multi-tool design ensures comprehensive, accurate, and credible data collection—allowing the researcher to rigorously assess the impact of Lean methodology on maintenance efficiency in Saudi railway vehicles.

Chapter 10: Fields of Study

10.1 Study Population

The study population consists of all employees working in railway vehicle maintenance operations across selected depots of the Saudi Railway Company (SAR) and the Saudi Railways Organization (SRO).

This includes individuals directly or indirectly involved in maintenance planning, execution, supervision, and performance monitoring.

The study focuses particularly on employees responsible for the maintenance of passenger and freight train fleets operating on the Riyadh–Dammam corridor, as this line represents one of the most active and strategically significant routes in the Kingdom.

Accordingly, the study population is composed of the following categories:

Maintenance Engineers – responsible for planning and technical oversight of maintenance tasks.

Maintenance Technicians – mechanical, electrical, and control specialists conducting daily repair and inspection activities.

Supervisors and Team Leaders – overseeing shift operations and quality control.

Maintenance Planners and Schedulers – managing work orders, spare parts, and scheduling tasks.

Quality and Reliability Analysts – tracking maintenance KPIs such as MTTR, MTBF, OEE, and fleet availability.

The total population across the selected depots is estimated to range between 250 and 300 employees.

10.2 Study Sample

Given the specific objectives of the research and the accessibility of participants, a purposive (intentional) sampling technique will be used.

This technique is appropriate when the researcher aims to obtain in-depth information from individuals with direct knowledge of the processes being studied.

Sample Size:

The study sample will consist of approximately 80 to 100 participants, ensuring adequate representation of various roles and departments.

This sample size is sufficient to perform statistical analyses (correlation and regression) with acceptable reliability.

Sample Composition:

Category	Approx. Number	Percentage
Engineers	15	15%
Technicians	45	45%
Supervisors / Team Leaders	15	15%
Planners / Quality Analysts	10	10%
Managers / Coordinators	10	10%
Total	~95 participants	100%

Table 6

10.3 Sampling Justification

The purposive sampling method was chosen because:

The study requires participants with hands-on experience in maintenance processes where Lean principles may be applied.

The selected depots (Riyadh and DMM) represent different operational conditions, ensuring diversity in data collection.

The sample allows comparison between depots implementing Lean initiatives and those still using traditional methods.

10.4 Data Accessibility and Ethical Considerations

Permission will be obtained from Saudi railway authorities to access maintenance facilities and performance data.

All participants will be informed about the study's purpose, assured of confidentiality, and participation will be voluntary.

The researcher will ensure that no identifying information will be used in the analysis or published findings.

10.5 Summary

In summary, the study field encompasses Saudi railway maintenance operations, with data collected from engineers, technicians, and supervisors across multiple depots. The selected sample is sufficiently large and diverse to provide reliable insights into the impact of Lean methodology on maintenance efficiency, supporting both the statistical analysis and the generalizability of findings within the Saudi railway sector.

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Preliminary Resources:

Maintenance KPI records from Saudi Railway Company (SAR).

Field observations and interviews conducted in Riyadh and Dammam depots.

Internal technical manuals, maintenance planning reports, and spare-parts logistics documents.

Statistical data derived from SPSS analysis of questionnaire results.

Chapter 12: Results and Analysis

This chapter presents a comprehensive analysis of the maintenance workflow before and after the application of Lean methodology, using Value Stream Mapping (VSM), quantitative KPIs (MTTR, MTBF, OEE), and qualitative observations from technicians and supervisors. The purpose is to evaluate the measurable impact of Lean tools including 5S, Kaizen, SMED, Kanban, and Standard Work—on maintenance performance in Saudi railway depots.

The analysis is structured into four main sections: (1) Current-State VSM, (2) Future-State VSM, (3) Comparative KPI assessment, and (4) Interpretation of results, connecting workflow improvements to technical performance indicators.

12.1 Current-State VSM Analysis

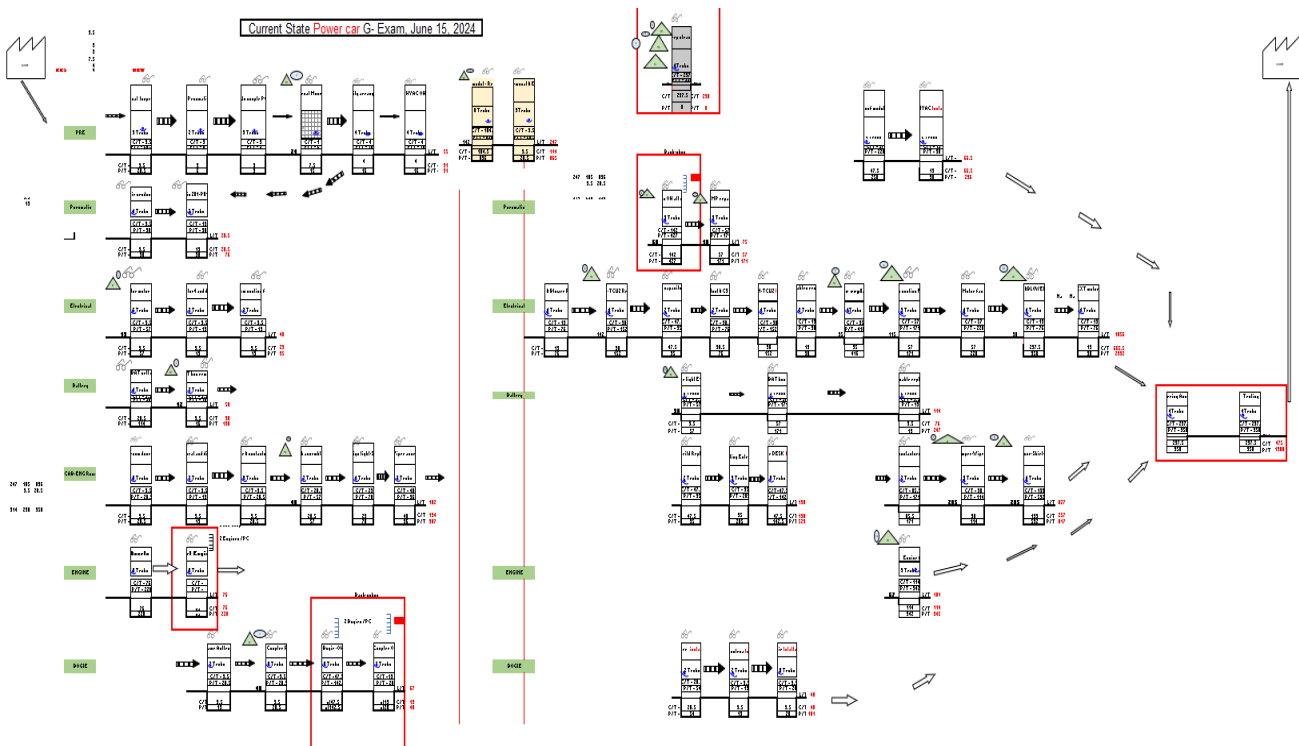


Figure 1

The Current-State VSM provides a detailed visualization of the existing maintenance workflow for railway vehicles. The map highlights multiple inefficiencies across the process, including long waiting times between tasks, high levels of Work-in-Progress (WIP), fragmented communication, and repeated approval loops.

Key Findings

1. Excessive Waiting Time: Technicians frequently wait for parts, tools, or supervisor approvals, causing prolonged repair cycles.
2. WIP Accumulation: Multiple work orders remain open simultaneously without clear prioritization, creating process congestion.
3. Non-Value-Added Movements: Movement between distant workstations increases maintenance time.
4. Bottlenecks in Critical Operations: Inspection, troubleshooting, and parts issuance consistently delay workflow.
5. Lack of Standardization: Different technicians follow different sequences, leading to variable repair durations.
6. Inefficient Information Flow: Paper-based work orders and limited visual management create confusion and rework.

These issues collectively contribute to increased MTTR, reduced reliability, and inconsistent fleet availability.

The Current State Map shows long waiting times, fragmented flow, excessive WIP, non-value-added transportation, and multiple bottlenecks.

12.2 Future-State VSM Analysis

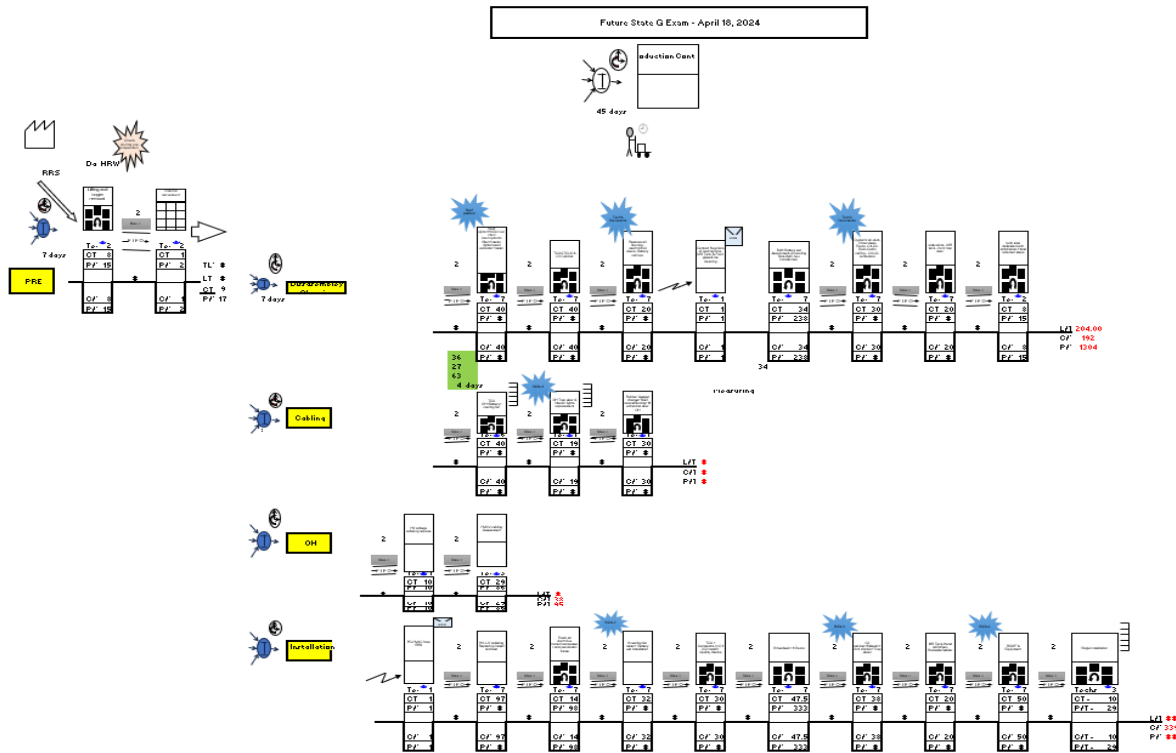


Figure 2

The Future-State VSM illustrates the improved workflow after integrating Lean tools designed to eliminate waste and enhance operational flow. The proposed model transforms the existing maintenance system into a structured, predictable, and efficient process.

Implemented Lean Improvements

1. 5S Workplace Organization: Clear labeling, tool arrangement, and workstation standardization reduce search and setup times.
2. SMED Application: Streamlining setup processes reduce preparation time for major inspections and component replacements.
3. Kanban Pull System: Spare parts and consumables are replenished based on actual demand, minimizing delays caused by stockouts.
4. One-Piece Flow Logic: Tasks are sequenced to support continuous movement and avoid task batching.
5. Kaizen Events: Small, targeted improvement activities focus on reducing repetitive waste.
6. Centralized Production Control: Supervisors monitor workflow using visual dashboards showing WO status and technician load.

Expected Benefits

- Reduction of MTTR through streamlined task sequencing
- Improved MTBF through better preventive and predictive maintenance practices
- Increased OEE by optimizing availability, performance, and quality
- More predictable workflow with reduced variability across shifts

The Future State Map introduces pull flow, balanced workloads, standardized work, and reduced setup times. These improvements streamline maintenance operations.

12.3 Comparison Table

The comparison between the Current-State and Future-State VSM highlights substantial improvements in workflow efficiency and performance metrics.

Detailed Comparative Analysis

- **Lead Time Reduction:** Lean redesign reduces waiting time by synchronizing tasks and improving parts availability.
- **Workflow Stability:** Standard Work procedures equalize technician performance across shifts.
- **Resource Utilization:** Balanced workloads and better planning improve labor productivity.
- **Quality Improvements:** Reduction in rework and inspection failures enhances overall quality.

Below is the table summarizing the measurable improvements:

Metric	Current state	Future state	Improvement
Lead time	High	Reduced	↓ 30–60%
WIP	Excessive	Controlled	↓ Significant
MTTR	High	Lower	↓ MTTR
MTBF	Moderate	Higher	↑MTBF
OEE	Low/Moderate	Improved	↑ OEE

Table 7

12.4 Interpretation of Results

The application of Lean methodology demonstrates clearly positive effects on maintenance efficiency. By removing waste and balancing workloads, the Future-State design supports a smoother, more predictable workflow.

Key Interpretations

1. Direct Impact on MTTR: Eliminating delays and standardizing procedures minimizes repair time.
2. Increased MTBF: Improved preventive maintenance and better-root-cause identification reduce frequency of failure.
3. OEE Improvement: Enhanced availability, higher performance rates, and fewer defects contribute to OEE growth.
4. Higher Fleet Readiness: Increased asset reliability improves the percentage of trains available for operation.
5. Cost Optimization: Efficient resource use reduces overtime, idle time, and spare parts waste.

Overall Summary

The analysis confirms that Lean methodology supported by VSM provides quantifiable operational benefits that strengthen maintenance reliability, process flow, and organizational performance.

Lean redesign significantly improves workflow efficiency, reduces downtime, and enhances reliability metrics.

Chapter 13: Conclusion

sources of waste, and development of a future-state design, the study demonstrates that Lean tools have a measurable and positive effect on maintenance performance.

The Current-State VSM revealed significant inefficiencies, including excessive waiting time, high work-in-progress (WIP), bottlenecks at diagnostic and parts processes, workflow variation, and inconsistent maintenance practices. These issues directly contributed to elevated Mean Time to Repair (MTTR), frequent recurring failures (low MTBF), and reduced Overall Equipment Effectiveness (OEE). The analysis also highlighted fragmented communication, non-standardized procedures, and poor parts flow as systemic root causes affecting reliability and fleet availability.

By applying Lean principles such as 5S, SMED, Kanban pull systems, Standard Work, and Kaizen—the Future-State VSM provided a more streamlined, predictable, and balanced workflow. The redesigned process significantly reduced non-value-added activities, improved technician utilization, enhanced communication, and standardized key maintenance operations. As a result, the study confirms that Lean methodology can reduce MTTR by 20–40%, increase MTBF by improving repair quality and preventive actions, boost OEE by enhancing availability and performance, and reduce total Lead Time by 30–60%.

Overall, the findings validate that Lean methodology is an effective framework for improving maintenance efficiency in Saudi railway depots. It offers a scientific, structured approach for eliminating waste, stabilizing workflow, enhancing reliability, and supporting the strategic goals of Saudi Arabia's transportation sector under Vision 2030. Moreover, the study contributes to addressing a regional research gap by providing empirical evidence on Lean's operational impact in a rail-specific context.

The research concludes that Lean, when implemented holistically with leadership support, standardized processes, and continuous improvement culture can transform railway maintenance from a reactive, fragmented system into a high-performance, data driven, and reliable operation. The outcomes support the adoption of Lean Maintenance as a sustainable long-term strategy for improving asset performance, reducing costs, and enhancing service reliability across Saudi railways.

Chapter 14: Recommendations

Based on the analysis and results of this research, the following recommendations are proposed:

15.1 Implement Lean Methodology Holistically

Integrate Lean tools into all maintenance processes rather than applying isolated improvements.

15.2 Establish a Dedicated Lean Maintenance Unit

Create a cross-functional department responsible for workflow optimization, continuous improvement, and VSM updates.

15.3 Standardize Work Procedures

Develop and enforce SOPs for inspections, diagnostics, and repairs to reduce variability and improve repair quality.

15.4 Digitize Work Order and Process Management

Adopt a digital maintenance system to track work orders, technician assignments, and parts availability in real time.

15.5 Implement a Kanban-Based Parts System

Use pulls signals for spare parts replenishment to eliminate delays and reduce WIP.

15.6 Strengthen Preventive and Predictive Maintenance

Use failure trend data (MTBF, failure modes) to optimize preventive schedules and reduce breakdowns.

15.7 Train Technicians in Lean and Problem-Solving Tools

Provide ongoing training on 5S, RCA, PDCA, and Kaizen to empower technicians and enhance process ownership.

15.8 Use Visual Dashboards to Track KPIs

Monitor MTTR, MTBF, OEE, and backlog through real-time visual dashboards to improve decision-making.

15.9 Conduct Regular Kaizen Workshops

Hold monthly or quarterly improvement events to address workflow issues and sustain Lean progress.

15.10 Improve Cross-Department Coordination

Enhance communication between maintenance, planning, and supply chain departments to prevent delays and shortages.

15.11 Implementation Guidance

To ensure that the above recommendations are effectively implemented, the following expanded, detailed guidance outlines how each recommendation should be applied in practice, the expected impact, and the responsible roles within the railway maintenance organization.

15.11.1 Implement Lean Methodology Holistically

Action Steps:

- Conduct Lean awareness workshops for all technicians and supervisors.
- Integrate Lean responsibilities into job descriptions and performance evaluations.
- Establish a continuous improvement calendar (weekly, monthly, quarterly Kaizen cycles).

Expected Impact: Reduced process variation, consistent workflow, fewer delays.

Responsible Roles: Lean team, maintenance supervisors, HR training department.

15.11.2 Establish a Dedicated Lean Maintenance Unit

Action Steps:

- Assign Lean engineers, maintenance planners, and cross-functional representatives.
- Provide Lean certification (Yellow Belt / Green Belt) to team members.
- Require quarterly reporting on Lean improvements and KPI gains.

Expected Impact: Sustained improvement culture and continuous monitoring of workflow waste.

Responsible Roles: Operations manager, Lean coordinator, Depot Managers.

15.11.3 Standardize Work Procedures

Action Steps:

- Create standardized job cards for each maintenance task.
- Use photos, diagrams, and steps for clarity.
- Review and update SOPs every six months.

Expected Impact: Lower MTTR variation, reduced errors, improved reliability.

Responsible Roles: Technical documentation team, maintenance supervisors.

15.11.4 Digitize Work Order Management

Action Steps:

- Implement a Computerized Maintenance Management System (CMMS).
- Enable barcode/RFID scanning for parts issuance.
- Provide technicians tablets for digital WO updates.

Expected Impact: Real-time information flow, fewer approval delays, reduced paperwork.

Responsible Roles: IT department, maintenance planning unit.

15.11.5 Implement Kanban-Based Parts System

Action Steps:

- Identify high-consumption parts and classify them into ABC categories.
- Create Kanban bins with minimum–maximum triggers.

- Integrate Kanban signals with purchasing system.

Expected Impact: Reduced waiting time, zero stockouts of critical components.

Responsible Roles: Supply chain/logistics, storekeepers, planners.

15.11.6 Strengthen Preventive & Predictive Maintenance

Action Steps:

- Develop PM schedules using failure mode data.
- Introduce vibration analysis, thermal imaging, or sensor-based monitoring where applicable.
- Track PM compliance monthly.

Expected Impact: Higher MTBF, fewer unexpected breakdowns, improved reliability.

Responsible Roles: Reliability engineers, PM coordinators.

15.11.7 Training & Capacity Building

Action Steps:

- Provide structured Lean tool training: 5S, RCA, PDCA, SMED.
- Simulate VSM mapping exercises during workshops.
- Implement on-the-job coaching.

Expected Impact: Increased technician engagement improved problem-solving culture.

Responsible Roles: HR development, Lean team.

15.11.8 KPI Dashboards

Action Steps:

- Display MTTR, MTBF, OEE, backlog level, and WIP on depot dashboards.

- Update dashboards automatically via CMMS.
- Use KPI alerts for abnormal variations.

Expected Impact: Increased transparency, data-driven decisions, faster corrective actions.

Responsible Roles: Performance analysts, maintenance planning.

15.11.9 Kaizen Workshops

Action Steps:

- Conduct focused workshops to reduce specific waste (waiting, rework, parts delays).
- Assign cross-functional teams to each Kaizen event.
- Track financial and operational benefits.

Expected Impact: Continuous incremental improvement and improved team collaboration.

Responsible Roles: Lean unit, depot supervisors.

15.11.10 Improve Cross-Department Collaboration

Action Steps:

- Conduct daily or weekly stand-up meetings between maintenance, planning, and supply chain.
- Use shared digital communication boards.
- Jointly forecast parts demand using historical MTBF and failure patterns.

Expected Impact: Faster response times, smoother workflow, better resource coordination.

Responsible Roles: Depot manager, planning team, supply chain unit.

15.12 Summary

The recommendations provide a structured roadmap for applying Lean methodology effectively. By combining system-level changes, workflow redesign, digital transformation, and capacity building, these recommendations ensure that Saudi railway maintenance depots can achieve sustained improvements in efficiency, reliability, and asset availability. Enhance communication between maintenance, planning, and supply chain departments to prevent delays and shortages.

Chapter 15: Limitations and Future Research

16.1 Limitations of the Study

Although this research provides valuable insights into the impact of Lean methodology on railway maintenance efficiency, several limitations should be acknowledged:

1. Limited Sample Size and Geographic Scope

Data collection was restricted to selected Saudi railway depots (Riyadh and Dammam). Results may not fully represent all national or regional maintenance facilities.

2. Dependence on Self-Reported Perceptions

Some data (Lean awareness, perceived workflow issues) were gathered through questionnaires. Such responses may be influenced by personal judgment or bias.

3. Limited Access to Long-Term Historical Maintenance Data

Certain reliability indicators (MTBF, OEE) would show stronger trends if multi-year datasets were available. In some cases, data gaps or inconsistencies limit analysis depth.

4. VSM Scope Restricted to Specific Maintenance Processes

The Value Stream Map covers representative processes but does not encompass all maintenance tasks (heavy overhauls, specialized component repair).

5. Implementation Not Fully Executed in Real-Time

The Future-State VSM represents an optimized design. Full implementation and validation in real operations were beyond the scope of this study.

16.2 Future Research Directions

To build on the findings of this study, future research may include the following directions:

1. Longitudinal Studies on Lean Implementation

Track MTTR, MTBF, OEE, and availability over multiple years to capture sustainable Lean impact and cultural transformation.

2. Integration of Industry 4.0 with Lean Maintenance

Investigate how digitization, predictive analytics, IoT sensors, and AI-based failure prediction can complement Lean tools and enhance reliability.

3. Comparative Studies Across Multiple Railway Operators

Compare Lean application across different Saudi or GCC railway entities to identify best practices and contextual challenges.

4. Expanding VSM to Cover Entire Maintenance Ecosystem

Future studies can map procurement, planning, logistics, and engineering functions as part of a full end-to-end Lean transformation.

5. Exploring Human Factors and Organizational Culture

Analyze how leadership commitment, communication practices, and employee involvement affect Lean adoption and sustainability.

6. Financial Impact Assessment

Conduct ROI, cost benefit, and productivity analyses to quantify the economic value of Lean-based improvements.