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Achieving Maintenance Excellence in Manufacturing Through Integration of Lean Six Sigma and Proactive Approaches: A Case Study

Attia Hussien Gomaa

***Abstract:** Achieving maintenance excellence is essential for enhancing operational efficiency, reducing unplanned downtime, and maintaining the performance of critical manufacturing systems. This study examines the integration of Lean Six Sigma (LSS) with proactive maintenance strategies—Risk-Based Inspection (RBI), Reliability-Centered Maintenance (RCM), and Total Productive Maintenance (TPM)—to improve equipment reliability, extend asset lifespan, and optimize resource utilization. While LSS targets inefficiencies through continuous improvement, RBI, RCM, and TPM offer data-driven, proactive solutions for minimizing downtime and enhancing system performance. Despite their successes, the combined application of these methodologies in asset management remains largely unexplored. This paper introduces a novel framework that integrates LSS, RBI, RCM, and TPM to optimize asset performance by improving reliability, availability, maintainability, and safety (RAMS), while reducing risks and costs. The framework includes well-defined objectives and key performance indicators (KPIs) to facilitate data-driven decision-making and encourage ongoing improvements. Validated through a case study of a major shutdown maintenance project at a feedwater pumping station in a petrochemical company in Egypt, the framework demonstrated significant outcomes, including a 60% reduction in non-value-added time, a 43% decrease in downtime, and a 22% improvement in shutdown efficiency (from 27% to 49%). These results underscore the synergistic potential of integrating LSS, RBI, RCM, and TPM to optimize maintenance practices and enhance operational performance. This study provides valuable insights for both academics and industry professionals seeking to align maintenance strategies with organizational objectives and drive sustainable, long-term improvements.*

***Keywords:** Maintenance Excellence, Proactive Maintenance, Lean Six Sigma, Risk-Based Inspection, Reliability-Centered Maintenance, Total Productive Maintenance*

Abbreviations:

AIM: Asset Integrity Management
ATM: Turnaround maintenance
CMFD: Condition monitoring and fault diagnosis
CoF: Consequences of failure
DT: Digital twins
FMEA: Failure mode effect analysis
KPIs: Key Performance Indicators
LSS: Lean Six Sigma
ML: Machine Learning
OEE: Overall Equipment Effectiveness
PoF: Probability of failure
RAMS: Reliability, availability, maintainability, and safety
RBI: Risk-based inspection
RBM: Risk-Based Maintenance
RCM: Reliability-Centered Maintenance
TPM: Total Productive Maintenance
AHP: Analytical hierarchy process

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I. INTRODUCTION

Achieving maintenance excellence is crucial for optimizing operational efficiency, reducing downtime, and ensuring the long-term sustainability of critical assets. Proactive maintenance is central to improving asset performance by enhancing reliability, preventing unexpected breakdowns, and maximizing resource utilization. Maintenance strategies are typically tailored to the criticality of assets, as illustrated in Figure 1. Reactive maintenance addresses unplanned failures, preventive maintenance mitigates potential breakdowns, predictive maintenance anticipates future issues, and proactive maintenance targets root causes to ensure consistent reliability. These strategies collectively enable organizations to allocate resources more efficiently, extend asset lifecycles, and minimize operational costs. As shown in Figure 2, proactive maintenance significantly impacts key performance indicators (KPIs) such as reliability, availability, maintainability, and safety (RAMS), reducing downtime and repair costs while improving sustainability and driving profitability, [1].

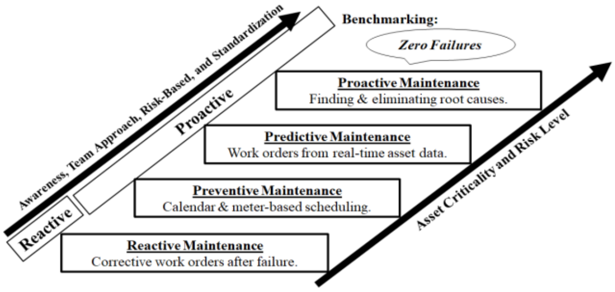
Lean Six Sigma (LSS), combining Lean's waste reduction principles with Six Sigma's focus on minimizing process variation, provides a powerful framework for optimizing maintenance activities, improving asset reliability, and achieving operational excellence, [2]. LSS uses tools such as value stream mapping, root cause analysis (RCA), statistical process control (SPC), and the DMAIC framework to identify inefficiencies, streamline workflows, and predict potential failures, [3]. By addressing issues like excessive inventory, redundant processes, and unnecessary inspections, LSS results in cost savings, optimized scheduling, and extended asset lifecycles. Across industries such as manufacturing, energy, healthcare, and transportation, LSS has led to improvements in Overall Equipment Effectiveness (OEE), reduced downtime, and enhanced reliability, [4]. Figure 3 outlines the key steps for implementing LSS in proactive maintenance: 1) Define: Identify challenges and align goals; 2) Measure: Gather baseline data and map processes; 3) Analyze: Use RCA, Pareto analysis, and FMEA to prioritize issues; 4) Improve: Apply Lean and Six Sigma tools to eliminate waste and reduce variation; 5) Control: Standardize processes and monitor performance with SPC charts; 6) Sustain and Scale: Document best practices, adapt processes, and scale solutions [5].

Risk-Based Inspection (RBI), Reliability-Centered Maintenance (RCM), and Total Productive Maintenance (TPM) are complementary strategies that, when integrated, can significantly enhance operational performance, [6]. RBI focuses inspection efforts on high-risk components by evaluating the probability and consequences of failure, optimizing resource allocation, and minimizing downtime. RCM improves asset reliability by identifying failure modes and selecting the most effective maintenance strategies, [7]. TPM fosters a culture of continuous improvement by involving all employees in maintenance activities, eliminating breakdowns, reducing defects, and increasing productivity. Together, these strategies enhance safety, resilience, and efficiency by focusing on critical assets and high-risk components, [8]. Figure 4 outlines the RBI process: 1) Asset Identification and Data Collection; 2) Risk Assessment; 3) Risk Ranking; 4) Inspection Planning; 5) Inspection Execution; 6) Data Analysis and Decision Making; 7) Review and Continuous Improvement [9].

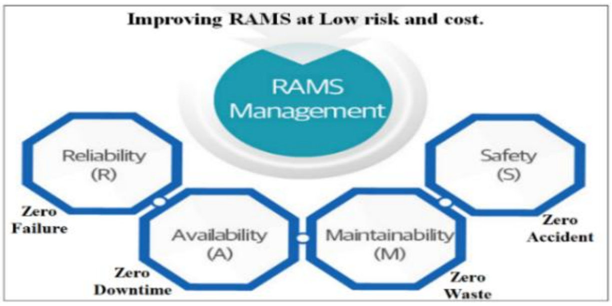
RCM aims to enhance asset reliability by evaluating system functions, identifying failure modes, and determining the most suitable maintenance strategies. It integrates preventive, predictive, and corrective maintenance to reduce unplanned downtime, minimize failures, and optimize resource use, [10]. Figure 5 presents the RCM process, [11]: 1) Define system functions and performance requirements, [12]; 2) Identify failure modes and assess their impact, [13]; 3) Evaluate consequences, [14]; 4) Assess failure probability; 5) Select appropriate maintenance strategies, [15]; 6) Implement maintenance tasks; 7) Monitor performance [16].

TPM is a comprehensive approach designed to maximize equipment effectiveness by involving all employees in maintenance activities, [17]. By emphasizing proactive and preventive maintenance, TPM reduces downtime, [18], eliminates breakdowns, [19], and fosters continuous improvement, [20]. Figure 6 outlines the core steps of TPM, [21]: 1) Autonomous Maintenance; 2) Planned Maintenance; 3) Quality Maintenance; 4) Focused Improvement; 5) Early Equipment Management; 6) Training and Education; 7) Safety, Health, and Environment, [22]; 8) TPM Evaluation and Monitoring [23].

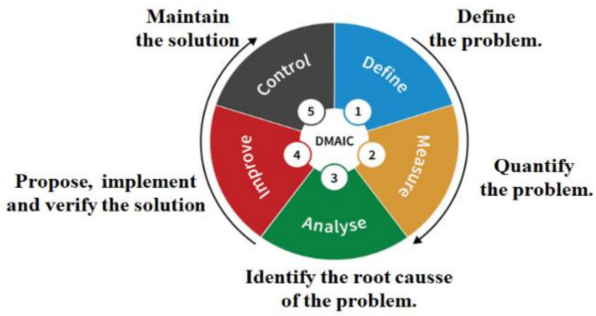
This paper addresses a key gap in the literature by proposing an integrated framework that combines Lean Six Sigma (LSS), Risk-Based Inspection (RBI), Reliability-Centered Maintenance (RCM), and Total Productive Maintenance (TPM). As illustrated in Figure 7, the study explores the effective integration of these methodologies, examines their theoretical foundations, and provides a practical, case-supported approach. The paper highlights the synergistic potential of these strategies in optimizing shutdown maintenance and improving overall operational performance. This work extends the findings presented in Gomaa, 2024 [3]. The paper is organized as follows: Section 2 reviews the relevant literature, Section 3 details the methodology, Section 4 presents the analysis, Section 5 discusses the case study, Section 6 outlines the results and discussion, and Section 7 concludes with key insights and actionable recommendations.



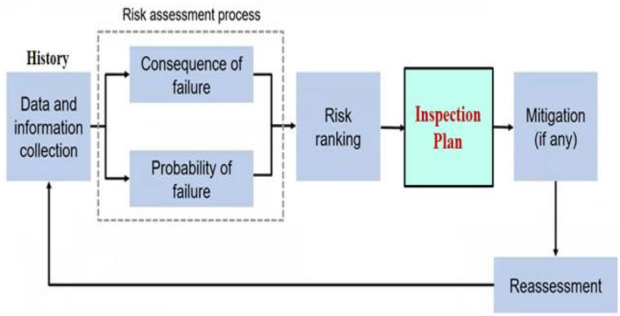
[Fig.1: Maintenance & Inspection Policies]



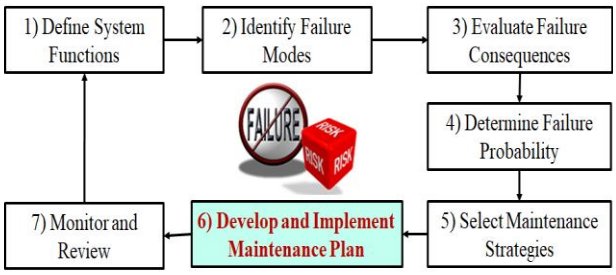
[Fig.2: Main Objectives of Maintenance Management]



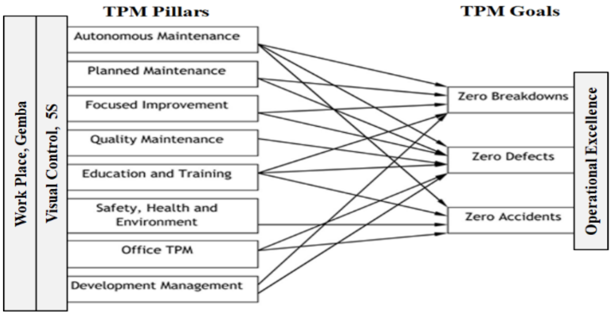
[Fig.3: LSS DMAIC Cycle]



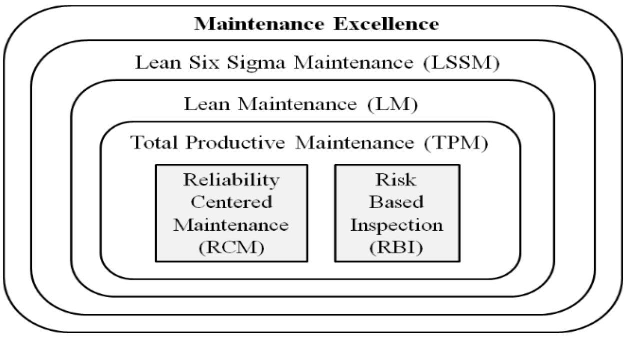
[Fig.4: Planning Process for Risk-Based Inspection (RBI), (API 580, 2016)]



[Fig.5: Planning Process for Reliability-Centered Maintenance (RCM)]



[Fig.6: Total Productive Maintenance (TPM) Pillars and Goals]



[Fig.7: Continuous Improvement Approaches for Maintenance Excellence]

II. LITERATURE REVIEW

This section reviews Lean Six Sigma (LSS) and three proactive maintenance methodologies—Risk-Based Inspection (RBI), Reliability-Centered Maintenance (RCM), and Total Productive Maintenance (TPM)—that enhance asset management. LSS uses data-driven approaches to minimize waste and variation, improving overall operational efficiency. RBI focuses on prioritizing inspections based on risk, which boosts safety and cost-effectiveness. RCM aligns maintenance strategies with asset functions and potential failure modes, thus enhancing reliability and reducing downtime. TPM aims to improve equipment effectiveness through proactive maintenance and employee involvement. Research conducted between 2016 and 2025 highlights the positive impact these methodologies have on performance. While each method has proven effective individually, their integration offers even greater potential. However, the development of a unified framework for their combined application remains a challenge.

Table 1 provides a summary of the key features, applications, and research gaps or future directions for each methodology. LSS is a data-driven approach designed to reduce waste and variation, improving process efficiency. Recent applications of LSS include the automotive industry (Al Farihi et al., 2023, [24]), aviation (Imanov et al., 2021, [25]), and oil and gas (Hassan et al., 2020, [26]). RBI emphasizes the inspection of high-risk components to optimize maintenance efforts and prevent failures, with successful applications in oil and gas (Aditiyawarman et al., 2023, [27]) and offshore platforms (Hameed et al., 2021, [28]). RCM tailors' maintenance strategies to asset functions and failure modes, improving system reliability. RCM has been applied in the rail (Liu et al., 2024, [29]) and water treatment industries (Asghari & Jafari, 2024, [30]). TPM focuses on enhancing equipment effectiveness through proactive maintenance, reducing downtime, and extending asset lifespans. TPM has been successfully implemented in steel manufacturing (Biswas, 2024, [31]) and the pharmaceutical industry (Shannon et al., 2023, [32]).

Table 1: Summary of the Literature Review

Approach	Key Features	Recent Applications (for Examples)
LSS	A data-driven methodology aimed at reducing waste and variation.	- Automotive (Al Farihi et al., 2023, [24]) - Aviation (Imanov et al., 2021, [25]) - Oil & Gas (Hassan et al., 2020, [26])
RBI	Targets high-risk components for inspection to optimize maintenance.	- Oil & Gas (Aditiyawarman et al., 2023, [27]) - Offshore (Hameed et al., 2021, [28])
RCM	Aligns maintenance strategies with asset functions and potential failure modes.	- Rail (Liu et al., 2024, [29]) - Water Treatment (Asghari & Jafari, 2024, [30])
TPM	Aims to maximize equipment effectiveness through proactive maintenance.	- Steel Manufacturing (Biswas, 2024, [30]) - Pharmaceutical (Shannon et al., 2023, [32])

A. Review of Lean Six Sigma in Proactive Maintenance

LSS plays a crucial role in proactive maintenance by improving asset performance, reducing downtime, and enhancing operational efficiency across diverse industries. As summarized in Table 2, LSS has been effectively implemented in sectors such as automotive, aviation, oil and gas, and manufacturing, driving substantial improvements in maintenance practices and outcomes. Several applications illustrate the versatility and effectiveness of LSS in maintenance management. For instance, Al Farihi et al. (2023, [24]) utilized Root Cause Analysis, Total Productive Maintenance (TPM), and Reliability-Centered Maintenance (RCM) to reduce breakdowns in the automotive sector. Trubetskaya et al. (2023), [33] developed an LSS-DMAIC framework that significantly shortened maintenance shutdown durations in dairy plants. Similarly, Arsakulasooriya et al. (2024), [33] identified six major maintenance wastes in high-rise buildings in Sri Lanka and proposed actionable strategies for improvement. Torre and Bonamigo (2024), [35] optimized hydraulic system maintenance in the steel industry using Lean 4.0 principles, resulting in measurable performance gains.

LSS has also given rise to innovative frameworks that integrate modern technologies. For example, Gomaa (2024), [3] combined Digital Twin technology with LSS in Egypt's petrochemical sector, improving overall equipment effectiveness (OEE) and streamlining maintenance processes. Mohammadi et al. (2022), [36] developed a Lean Construction-based decision-making model for road maintenance, which improved cost-effectiveness and resource allocation. Singha Mahapatra and Shenoy (2022), [37] introduced the Lean Maintenance Index (LMI), which assesses the lean-ness of maintenance practices and provides insights for continuous improvement.

Innovations specific to particular industries have also driven progress. Shou et al.

(2021), [38] validated a Lean management framework for turnaround maintenance (TAM) in the oil and gas industry, leveraging 4D building information modeling (BIM) to improve maintenance efficiency. Antosz et al. (2021), [39] applied machine learning techniques to enhance lean maintenance practices in manufacturing, particularly focusing on tool selection and decision-making processes. In Malaysia, Bakri et al. (2021), [40] identified nine critical success factors (CSFs) for lean maintenance management in small and medium enterprises (SMEs), offering a framework for improving maintenance practices and organizational performance.

Despite its successes, LSS faces certain challenges. Research by Karunakaran (2016), [41] and others highlights LSS's success in diverse industries such as aircraft maintenance, textiles, and oil workflows. However, there are still gaps in areas such as predictive maintenance, real-time data integration, and the application of AI and machine learning (ML), which limit its full potential.

To further enhance LSS's effectiveness, dynamic models need to be developed that can respond to real-time changes in production and market conditions. The integration of AI and ML could enable continuous optimization of maintenance practices, while exploring LSS in multi-asset systems may lead to improvements in overall maintenance performance. Addressing these gaps will enable LSS to become more adaptive, data-driven, and capable of meeting the evolving challenges of modern maintenance.

Table 2: Summary of the Review of LSS in Proactive Maintenance

Aspect	Details
Role of LSS	LSS enhances asset performance, reduces downtime, and improves operational efficiency across industries.
Key Applications	- Automotive: Reduced breakdowns using TPM, RCM, and Root Cause Analysis (Al Farihi et al., 2023, [24]). - Dairy Plants: LSS-DMAIC reduced maintenance shutdowns (Trubetskaya et al., 2023, [33]). - High-Rise Buildings: Identified and addressed six maintenance wastes (Arsakulasooriya et al., 2024, [33]). - Steel Industry: Optimized hydraulic systems using Lean 4.0 (Torre and Bonamigo, 2024, [35]).
Innovative Frameworks	- Digital Twin integration with LSS enhanced OEE in the petrochemical sector (Gomaa, 2024, [3]). - Lean Construction principles reduced costs and streamlined road maintenance (Mohammadi et al., 2022, [36]). - The Lean Maintenance Index (LMI) assesses maintenance leanness (Singha Mahapatra & Shenoy, 2022, [37]).
Sector-Specific Advances	- Oil & Gas: Lean framework validated using 4D modeling for turnaround maintenance (Shou et al., 2021, [38]). - Manufacturing: Machine learning enhanced tool selection for lean maintenance (Antosz et al., 2021, [38]). - Malaysian SMEs: Identified nine CSFs for lean maintenance management (Bakri et al., 2021, [40]).
Broader Impact	- Improved workflow efficiency in oil and gas, aviation, and textiles. - Enhanced maintenance strategies and reduced costs in diverse industries.
Remaining Challenges	-Limited integration of predictive maintenance and real-time data. -Need for dynamic LSS models to adapt to production changes. - Gaps in AI/ML adoption for continuous optimization.
Future Directions	-Develop dynamic, real-time LSS models. -Leverage AI/ML for adaptive maintenance strategies. - Explore LSS applications in multi-asset systems for broader performance improvement.

B. Review of Risk-Based Inspection

RBI is a widely adopted methodology that enhances asset integrity, optimizes inspection schedules, and reduces maintenance costs across industries (Yang and Frangopol, 2021, [42]). As outlined in Table 3, numerous studies have demonstrated RBI's critical role in effective risk management and its evolution in application. Recent advancements in RBI have highlighted its growing importance. Javid (2025), [43] introduced a multi-objective RBI framework that uses genetic algorithms to balance risk reduction with inspection costs, automating the process for greater efficiency. Almeida de Rezende et al. (2024), [44] developed a reliability-based approach for offshore mooring chain inspections, incorporating fatigue and corrosion models for more accurate assessments. Huang et al. (2023), [45] proposed an RBI framework for pipeline inspections, optimizing intervals by integrating external corrosion and dents with Dynamic Bayesian Networks (DBNs).

The oil and gas sector has also benefited from RBI innovations. Aditiyawarman et al. (2023), [27] incorporated machine learning into the RBI process, showcasing AI's potential in risk management. Zhang et al. (2023), [46] demonstrated the cost-effectiveness of Condition Monitoring Systems (CMS) in RBI planning, offering dynamic monitoring of asset performance over time. Eskandarzade et al. (2022), [47] proposed an RBI framework for underground pipelines, combining risk assessments with damage progression models. Sözen et al. (2022), [48] further refined pipeline inspections by analyzing internal surface defects under varying pressures.

Offshore industries have also seen advancements through RBI. Hameed et al. (2021), [28] focused on corrosion and fatigue in offshore pipeline inspections, while Agistina et al. (2021), [49] applied API 581-based RBI to separator machines in geothermal power plants. Abubakirov et al. (2020), [50] and Rachman and Ratnayake (2018), [51] used dynamic Bayesian networks and artificial neural networks, respectively, to optimize pipeline inspections and enhance RBI screening in hydrocarbon systems. Early contributions by Arzaghi et al. (2017), [52] and Kamsu-Foguem (2016), [53] refined RBI methodologies for subsea pipelines and petroleum production systems. Additional studies by Febriyana et al. (2019), [54] and Melo et al. (2019), [55] addressed challenges in offshore and unpiggable pipeline inspections, advancing practices in these areas. These studies collectively highlight RBI's versatility in improving asset reliability, extending lifecycles, and optimizing maintenance costs across sectors.

Despite its success, current RBI models often rely on static, historical data, limiting their responsiveness to real-time operational changes. Critical research gaps include developing adaptable RBI frameworks for various industries, integrating real-time environmental and operational data to improve decision-making, and creating user-friendly tools to communicate risks effectively to non-expert stakeholders.

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Future research should focus on developing flexible, real-time RBI models that incorporate advanced technologies such as AI and dynamic data systems. These innovations will enhance the precision and effectiveness of RBI, enabling more adaptive and cost-efficient maintenance strategies that support long-term asset integrity and performance.

Table 3: Summary of the Review of Risk-Based Inspection

Aspect	Details
Role of RBI	RBI enhances asset integrity, optimizes inspection schedules, and reduces maintenance costs across industries.
Key Advancements and Applications	- Genetic Algorithms: Javid (2025), [43] introduced a multi-objective RBI framework to balance risk reduction and inspection costs.
	- Offshore Mooring Chains: Almeida de Rezende et al. (2024), [44] developed a reliability-based approach incorporating fatigue and corrosion models.
	- Pipeline Inspection: Huang et al. (2023), [45] optimized inspection intervals using Dynamic Bayesian Networks (DBNs).
	- Oil & Gas: Aditiyawarman et al. (2023), [27] integrated machine learning for enhanced risk management, and Zhang et al. (2023), [46] showcased the value of Condition Monitoring Systems (CMS).
	- Underground Pipelines: Eskandarzade et al. (2022), [47] proposed an RBI framework combining risk assessments and damage progression models.
	- Offshore and Geothermal: Hameed et al. (2021), [28] and Agistina et al. (2021), [49] applied RBI in pipeline inspections and geothermal separator machines.
Recent Developments	- Use of Dynamic Bayesian Networks (Abubakirov et al., 2020, [50]), Artificial Neural Networks (Rachman & Ratnayake, 2018, [51]) in pipeline inspections.
Challenges	- Reliance on static, historical data, limiting responsiveness to real-time operational changes.
	- Need for user-friendly tools to communicate risks to non-expert stakeholders.
Future Research Directions	- Development of dynamic, real-time RBI models incorporating AI and machine learning.
	- Integration of real-time environmental and operational data to improve decision-making.
	- Focus on the adaptability and flexibility of RBI frameworks to enhance long-term asset integrity and performance.

C. Review of Reliability-Centered Maintenance

RCM is a vital methodology for enhancing asset reliability, optimizing maintenance strategies, and reducing unplanned downtime across various sectors (Rodríguez-Padial et al., 2024). As demonstrated in Table 4, extensive research highlights RCM's effectiveness in aligning maintenance practices with both operational and organizational objectives. Numerous studies showcase the broad applicability and impact of RCM. Liu et al. (2024), [29] applied RCM to high-speed rail facilities, leveraging predictive models to prevent deterioration while reducing maintenance costs. Ali Ahmed Qaid et al. (2024), [56] developed a fuzzy-FMECA-based framework to analyze failure modes in manufacturing machinery, enabling data-driven, criticality-based maintenance strategies. In the utility sector, Asghari and Jafari (2024), [30] employed RCM for water treatment plant pumps, enhancing Mean Time Between Failures (MTBF) and operational efficiency, while Cahyati et al. (2024), [57] achieved a 70% reduction in maintenance costs at a processing plant. Industry-specific adaptations, such as those in boiler engines (Sembiring, 2024, [58]) and cement plants (Al-Farsi and Syafiie, 2023, [59]), further demonstrate RCM's versatility. Additionally, the integration of RCM with Industry 4.0 technologies has optimized performance (Introna and Santolamazza, 2024, [60]) and improved resource allocation.

However, traditional RCM approaches often rely on static maintenance schedules and lack real-time data integration, which limits their adaptability in dynamic environments. Research gaps include the development of adaptive frameworks that incorporate real-time data to assess and prioritize failure modes, exploring how human decision-making impacts RCM effectiveness, and integrating continuous monitoring and predictive analytics to enable proactive maintenance.

Future research should focus on creating dynamic, real-time RCM frameworks that integrate operational data and advanced analytics. Addressing the influence of human factors on decision-making will also enhance RCM implementation. These advancements will optimize asset performance, reduce unplanned downtime, and improve maintenance practices, reinforcing RCM's critical role in modern asset management.

Table 4: Summary of the Review of Reliability-Centered Maintenance

Aspect	Details
Role of RCM	RCM improves asset reliability, optimizes maintenance strategies, and minimizes unplanned downtime across various sectors.
Key Applications and Research	- High-speed Rail Facilities: Liu et al. (2024), [29] used predictive models to prevent deterioration and reduce costs.
	- Manufacturing Machinery: Ali Ahmed Qaid et al. (2024), [56] applied fuzzy-FMECA for criticality-based maintenance strategies.
	- Water Treatment Plants: Asghari and Jafari (2024), [30] improved MTBF and operational efficiency.
	- Processing Plants: Cahyati et al. (2024), [57] achieved a 70% reduction in maintenance costs.
	- Boiler Engines & Cement Plants: Applications in various industries (Sembiring, 2024, [58]; Al-Farsi and Syafiie, 2023, [59]).
	- Industry 4.0 Integration: Introna and Santolamazza (2024), [60] optimized performance and resource allocation.
RCM Effectiveness	Validated by studies like Elijaha (2021), [53] for enhancing asset reliability, reducing downtime, and enabling cost-effective strategies.
Challenges and Research Gaps	- Static schedules in traditional RCM models, lack of real-time data integration.
	- Need for adaptive frameworks that incorporate real-time data and predictive analytics.
	- Exploration of human decision-making's impact on RCM effectiveness.
Future Research Directions	- Focus on flexible, real-time RCM frameworks integrating operational data and advanced analytics.
	- Addressing human factors in RCM decision-making for improved implementation.

III. RESEARCH GAP ANALYSIS

Proactive maintenance, driven by predictive and data-informed strategies, plays a crucial role in improving asset reliability, reducing downtime, and optimizing performance. Key methodologies such as LSS, RBI, RCM, and TPM have significantly advanced maintenance practices. However, these approaches each have inherent

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limitations, presenting opportunities for further research to enhance their integration, adaptability, and overall effectiveness across various industries. Table 5 summarizes the research gaps identified in each methodology. In summary, LSS, RBI, RCM, and TPM have advanced asset management and maintenance practices, yet key challenges remain. The lack of real-time data integration, limited use of AI/ML, and insufficient adaptability across industries hinder their full potential. Overcoming these challenges through the development of dynamic models, predictive maintenance capabilities, and improved cross-functional collaboration will enhance the flexibility and effectiveness of these methodologies. Additionally, integrating LSS with proactive maintenance strategies can further optimize operational efficiency, reduce downtime, and improve asset reliability across diverse sectors. Continued research is essential to refine these approaches and build more resilient, adaptable systems for the future of asset management.

Table 5: Summary of Research Gap Analysis

Approach	Current State	Research Gaps	Proposed Research
LSS	LSS optimizes processes but lacks real-time data integration.	- No real-time adaptability. - Untapped potential of AI/ML. - Limited application in multi-asset systems.	- Develop dynamic models with real-time data. - Explore AI/ML for continuous improvement. - Study applications in multi-asset systems.
RBI	RBI enhances asset integrity using static data.	- Limited adaptability with static data. - Inconsistent industry application. - Ineffective risk communication.	- Develop dynamic, real-time models. - Expand AI/ML integration. - Improve risk communication tools.
RCM	RCM focuses on failure modes with fixed schedules.	- Lack of real-time failure assessments. - Insufficient research on human factors. - Poor asset health integration.	- Develop real-time assessment tools. - Investigate human factors in decision-making. - Integrate asset health monitoring.
TPM	TPM improves reliability but relies on static data.	- Static data limits flexibility. - Underutilization of AI/ML. - Low employee engagement in maintenance.	- Develop IoT-enabled systems. - Integrate AI/ML for predictive maintenance. - Enhance employee involvement in maintenance.
Integration	Limited integration of LSS with proactive methodologies.	- Lack of integration with predictive maintenance. - Underuse of real-time data. - Insufficient cross-functional collaboration.	- Create integrated frameworks for proactive approaches. - Leverage real-time data. - Promote cross-functional collaboration.

IV. RESEARCH METHODOLOGY

The integrated framework combines Lean Six Sigma (LSS), Risk-Based Inspection (RBI), Reliability-Centered Maintenance (RCM), and Total Productive Maintenance (TPM) to optimize maintenance excellence. This approach addresses unplanned downtime, high costs, equipment failures, and inefficiencies by utilizing advanced technologies and data-driven practices. The framework components are as follows:

1. Lean Six Sigma (LSS): Optimizes maintenance processes by eliminating waste, reducing variability, and applying the DMAIC methodology.
2. Risk-Based Inspection (RBI): Prioritizes maintenance efforts by assessing asset risk, ensuring resources are allocated to critical assets based on real-time data.
3. Reliability-Centered Maintenance (RCM): Combines predictive maintenance with Failure Mode and Effects Analysis (FMEA) to address failure modes and enhance asset reliability.
4. Total Productive Maintenance (TPM): Focuses on maximizing Overall Equipment Effectiveness (OEE) through operator involvement in routine maintenance and continuous improvement.
5. Continuous Feedback and Performance Evaluation: Monitors KPIs such as OEE, MTTR, MTBF, and downtime, using Root Cause Analysis (RCA) to refine processes.

As outlined in Table 6, the integration follows key steps to enhance asset reliability and reduce downtime:

1. Asset Identification & Risk Prioritization: LSS identifies critical assets, RBI assesses risk, RCM analyzes failure modes, and TPM aligns with operational goals.
2. FMEA: LSS addresses inefficiencies, RBI focuses on high-risk assets, RCM develops failure mitigation strategies, and TPM empowers operators to handle failure modes.
3. Maintenance & Inspection Plans: LSS reduces delays, RBI creates risk-based schedules, RCM applies condition-based strategies, and TPM emphasizes autonomous maintenance.
4. Execution of Actions: LSS ensures efficient task execution, RBI adapts inspections based on real-time data, RCM prioritizes proactive interventions, and TPM empowers operators.
5. Monitoring & Performance Measurement: LSS tracks KPIs, RBI adjusts inspection strategies, RCM optimizes performance metrics, and TPM assesses OEE to identify gaps.
6. Continuous Improvement: LSS refines strategies through iterative cycles, RBI updates risk models, RCM enhances strategies, and TPM incorporates feedback for ongoing improvement.
7. Training & Collaboration: LSS equips teams with optimization tools, RBI educates on risk assessment, RCM enhances failure analysis, and TPM empowers operators.
8. Data-Driven Decision-Making: LSS refines workflows, RBI uses predictive analytics, RCM integrates big data, and TPM incorporates monitoring systems.
9. Sustainability: LSS reduces waste, RBI considers environmental impact, RCM minimizes ecological effects, and TPM promotes energy efficiency.
10. Long-Term Review: LSS aligns with organizational goals, RBI updates risk profiles, RCM refines strategies, and TPM aligns with priorities.

As illustrated in Table 7, aligning the DMAIC cycle with LSS, RBI, RCM, and TPM drives continuous improvement, asset reliability, and maintenance optimization:

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1. Define: Establish clear maintenance goals, prioritize inspections, and define asset functions.
2. Measure: Collect baseline data on downtime, failure rates, and asset conditions.
3. Analyze: Use tools like Pareto analysis and FMEA to identify inefficiencies and high-risk assets.
4. Improve: Implement improvements, streamline processes, and empower operators for proactive upkeep.
5. Control: Standardize practices, monitor KPIs, adapt strategies, and ensure continuous maintenance practices.

As shown in Table 8, aligning with strategic objectives ensures optimized asset integrity and performance through the following KPIs:

1. Maximizing Asset Performance: MTBF, Availability, MTTR, OEE.
2. Minimizing Operational Risks: RBI Compliance, Incident Rate, Critical Failure Prevention.
3. Optimizing Cost Efficiency: Maintenance Cost per Unit, ROMI, Spare Parts Optimization.
4. Fostering Technological Integration: Predictive Maintenance Accuracy, Digital Twin Utilization, Data Completeness.
5. Enhancing Risk Management: RBI Compliance Rate, Asset Risk Reduction Index.
6. Driving Continuous Improvement: Kaizen Success Rate, Training Effectiveness, Lean Six Sigma Project Completion.

In conclusion, this integrated framework provides a comprehensive and scalable solution for achieving maintenance excellence. By combining LSS, RBI, RCM, and TPM, it addresses critical challenges such as unplanned downtime, high costs, and inefficiencies. Through advanced technologies, real-time data, and continuous improvement, the framework enhances asset reliability, reduces risks, and optimizes performance, ensuring long-term operational success, maximizing asset integrity, and fostering resilience in manufacturing systems.

Table 6: Summary of the Proposed Integrated Framework for Maintenance Excellence

Step	LSS	RBI	RCM	TPM
1. Asset Prioritization	Optimizes critical asset classification.	Prioritizes high-risk assets.	Aligns maintenance with safety needs.	Involves operators in asset identification.
2. FMEA	Tackles root causes using Six Sigma tools.	Targets inspections on high-risk assets.	Mitigates failure modes proactively.	Empowers operators to address failures.
3. Planning	Reduces waste and delays.	Designs risk-based inspection plans.	Adopts predictive maintenance.	Focuses on autonomous maintenance.
4. Execution	Ensures efficient task execution.	Adapts inspections with real-time data.	Prioritizes proactive interventions.	Engages operators for routine tasks.
5. Performance Monitoring	Tracks KPIs for improvement.	Refines schedules with data insights.	Uses metrics to enhance reliability.	Measures OEE for performance gaps.
6. Continuous Improvement	Refines via DMAIC cycles.	Updates risk models with outcomes.	Improves strategies using performance data.	Integrates operator feedback.
7. Training & Collaboration	Optimizes team skills.	Trains on risk assessments.	Builds expertise in failure analysis.	Empowers autonomous maintenance.
8. Data-Driven Decisions	Refines workflows using analytics.	Predicts risks with analytics.	Enhances reliability using big data.	Monitors conditions for proactive actions.
9. Sustainability	Reduces waste, supports eco-goals.	Considers environmental risks.	Minimizes environmental impacts.	Promotes energy efficiency.
10. Strategy Alignment	Aligns with organizational goals.	Adapts to operational changes.	Refines strategies over time.	Aligns with broader priorities.

Table 7: The Proposed DMAIC Framework for Maintenance Excellence

Phase	LSS	RBI	RCM	TPM
Define	Set clear maintenance goals, eliminate waste	Prioritize inspections based on risk assessment	Define asset functions and failure impacts	Set OEE targets for critical assets
Measure	Collect data on downtime, defects, inefficiencies	Assess asset risk probabilities and failure consequences	Gather data on asset conditions and failure rates	Measure OEE, performance, availability
Analyze	Identify inefficiencies using tools like Pareto analysis and control charts	Conduct risk analysis to prioritize high-risk assets	Use FMEA to analyze failure causes	Analyze asset failure patterns and inefficiencies
Improve	Eliminate waste, reduce variation, improve efficiency	Develop risk-based inspection plans for high-risk assets	Implement proactive, predictive, and condition-based strategies	Empower operators for autonomous maintenance
Control	Standardize practices and monitor KPIs (e.g., downtime, costs)	Conduct ongoing risk assessments and adjust strategies	Refine strategies using real-time data	Monitor OEE, and ensure sustainability of improvements

Table 8: The Proposed Objectives and KPIs for Maintenance Excellence

#	Objective	KPIs
1	Maximizing Asset Performance	MTBF, Availability, MTTR, OEE
2	Minimizing Operational Risks	RBI Compliance, Incident Rate, Failure Prevention, Risk Index
3	Optimizing Cost Efficiency	Maintenance Cost per Unit, ROMI, Spare Parts Efficiency, Savings from Proactive Maintenance
4	Fostering Technological Integration	Predictive Maintenance Accuracy, Digital Twin Usage, Data Quality, Integration Rate
5	Enhancing Risk Management	RBI Compliance Rate, Incident Reduction, Failure Prevention, Risk Mitigation
6	Driving Continuous Improvement	Kaizen Success Rate, Training Impact, Defect Elimination, Lean Six Sigma Projects

V. A CASE STUDY

A case study was conducted on a major shutdown maintenance project for the feedwater pumping station at a petrochemical company in Egypt. Scheduled every five years, the shutdown aims to optimize pump performance and extend the lifespan of critical equipment. The maintenance process involves disassembling the pump and motor, inspecting components, and replacing key parts such as seals, impellers, and valves. To minimize downtime and ensure efficient repairs, an on-site inventory of commonly used wear parts is maintained, allowing for quick replacements during the shutdown period.

To evaluate the current maintenance practices and identify areas for improvement, a comprehensive analysis was carried out. This included reviewing operational records, failure logs, shutdown data, and other performance metrics. In addition, brainstorming sessions with operations and maintenance leaders were held to identify recurring issues and potential solutions. Insights gained from this analysis informed the development of the project charter and the adoption of the DMAIC (Define, Measure, Analyze, Improve, Control) framework. The project charter outlines the key problems, scope, objectives, timeline, and team responsibilities, providing a clear roadmap for the project. It ensures alignment and clarity among stakeholders, setting the foundation for successful execution.

The DMAIC framework was chosen as the methodology for driving continuous improvement throughout the project. It offers a structured process for addressing the identified challenges and incorporates a range of analysis and improvement tools. By following the DMAIC approach, the team will focus on identifying root causes, measuring performance, analyzing data, implementing improvements, and ensuring the sustainability of those improvements. The objective is to enhance pump performance, reduce unplanned downtime, extend equipment lifespan, and improve overall operational efficiency.

The DMAIC framework provides a structured and systematic approach for optimizing shutdown maintenance operations, ensuring effective implementation and sustainable results. The following sections outline the tools and techniques applied in each phase of the framework, offering a clear and actionable guide for the project's success.

A. Define Phase

The Define phase sets the stage for the project by establishing its scope, objectives, and challenges, while ensuring stake-holder alignment. Key steps include:

- Step #1: Form the Process Improvement Team with key stakeholders.
- Step #2: Conduct a SWOT analysis to identify strengths, weaknesses, opportunities, and threats.
- Step #3: Select critical systems and components for focused attention.
- Step #4: Define the project scope, timeline, and key performance indicators (KPIs).
- Step #5: Perform Voice of Customer (VOC) analysis to align project goals with customer expectations.
- Step #6: Define Critical to Quality (CTQ) factors and evaluate current performance levels.
- Step #7: Identify key shutdown issues and their root causes.
- Step #8: Map the maintenance process to pinpoint inefficiencies and improvement areas.
- Step #9: Develop a SIPOC diagram to offer a high-level process overview.

B. Measure Phase

The Measure phase assesses the current system's performance and establishes a baseline for improvement. Key steps in-clude:

- Step #10: Design standardized templates to ensure consistent and accurate data collection.
- Step #11: Build a network diagram to map tasks and identify potential bottlenecks.
- Step #12: Create a value stream map to visualize inefficiencies in the process flow.
- Step #13: Apply Pareto analysis to prioritize equipment failures based on frequency and impact.

C. Analyze Phase

The Analyze phase focuses on identifying the root causes of inefficiencies and problems within the system. Key steps in-clude:

- Step #14: Analyze shutdown time to uncover delays and bottlenecks.
- Step #15: Analyze risks and prioritize high-impact assets based on failure likelihood.
- Step #16: Use Fault Tree Analysis to identify failure causes and their consequences.
- Step #17: Conduct FMEA to assess risk levels and prioritize corrective actions.
- Step #18: Identify losses and performance gaps that hinder operational efficiency.
- Step #19: Perform RCA to uncover underlying issues affecting performance.

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- Step #20: Develop Fishbone diagrams to categorize and visualize maintenance problems.

D. Improve Phase

The Improve phase is dedicated to implementing targeted solutions that enhance shutdown maintenance operations. Key steps include:

- Step #21: Develop maintenance and inspection plans to address identified inefficiencies.
- Step #22: Implement maintenance and inspection improvements based on findings.
- Step #23: Establish a standardized shutdown management methodology.
- Step #24: Create a unified documentation system for shutdown procedures.
- Step #25: Develop a communication plan to ensure stakeholder alignment.
- Step #26: Define roles and responsibilities with a RACI matrix.
- Step #27: Revise the project network to accommodate time-crashing scenarios for efficient scheduling.
- Step #28: Construct a Gantt chart to manage scheduling and resource allocation effectively.
- Step #29: Provide advanced training to foster teamwork and enhance continuous improvement efforts.
- Step #30: Implement 5S principles for visual control and better organization on the shop floor.
- Step #31: Empower operators for autonomous maintenance to improve operational efficiency.
- Step #32: Apply Kaizen principles and Lean 8 Wastes to streamline processes and reduce inefficiencies.
- Step #33: Use SMED for quick changeovers (not applied in this case study).
- Step #34: Implement Poka-Yoke for mistake-proofing (not applied in this case study).
- Step #35: Update value stream mapping to reflect improvements made.
- Step #36: Reanalyze shutdown times to evaluate the effectiveness of implemented improvements.

E. Control Phase

The Control phase ensures that the improvements are sustained over time and the system remains effective. Key steps in-clude:

- Step #37: Analyze before/after KPIs to assess the impact of implemented changes.
- Step #38: Promote a culture of continuous improvement within teams.
- Step #39: Document and standardize successful practices for future replication.
- Step #40: Provide ongoing training and support to maintain high-performance standards.
- Step #41: Conduct maintenance audits to ensure compliance and identify improvement opportunities.
- Step #42: Prepare a close-out report with outcomes, lessons, and recommendations.
- Step #43: Share results with stakeholders to improve future initiatives.

In conclusion, the DMAIC framework proved to be highly effective in optimizing shutdown maintenance for a feedwater pumping station. By systematically defining project objectives, measuring current performance, analyzing root causes, and implementing targeted improvements, the project achieved significant gains in operational efficiency, minimized downtime, and extended the lifespan of critical equipment. The Control phase ensured the long-term sustainability of these improvements, fostering a culture of continuous improvement and standardizing best practices. This approach offers a robust and proven model for enhancing maintenance operations, ensuring lasting improvements in both performance and reliability.

VI. RESULTS AND DISCUSSION

This section presents the outcomes of applying the Lean Six Sigma (LSS) framework to optimize shutdown maintenance, demonstrating how various LSS tools were leveraged to identify inefficiencies and implement process improvements.

1. **Current Situation Analysis Before Improvements**: Figure 8 presents the shutdown project network before improvements, establishing a baseline by mapping task sequences and dependencies. This analysis highlights existing inefficiencies and forms the foundation for targeted improvements.

2. **Time and Waste Analysis Before Improvements:** Figure 9 shows the maintenance value stream map, categorizing each shutdown process step as value-added or non-value-added. This tool was instrumental in identifying bottlenecks and wasteful activities, which were then prioritized for elimination. Figure 10 further breaks down shutdown downtime into waiting time, downtime, and unnecessary movements, pinpointing key sources of waste and focusing efforts on addressing critical delays and bottlenecks.

3. **Failure Analysis Before Improvements:** Figure 11 illustrates Fault Tree Analysis (FTA) for motor overheating, uncovering root causes such as inadequate cooling and mechanical failure. Table 10 presents Failure Mode and Effect Analysis (FMEA) for the centrifugal pump, which identified and prioritized failure modes for corrective actions to improve reliability and mitigate risks.

4. **Root Cause Failure Analysis:** Figure 12 shows Root Cause (Why-Why) analysis for bearing failure, revealing issues such as poor lubrication and improper installation. Figures 13 and 14 feature Fishbone (Ishikawa) diagrams that analyze both equipment-related and resource-related inefficiencies, such as inadequate human resources, tools, and training.

5. **Maintenance Process Standardization:** Figure 15 illustrates the standardized shutdown management

methodology developed to streamline operations. This methodology integrates Lean principles to eliminate waste and Six Sigma strategies to reduce variability, ensuring a more efficient and consistent shutdown process.

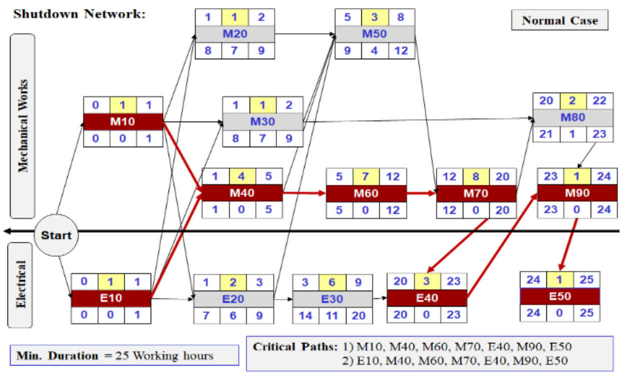
6. **Time-Crashing and Resource Allocation:** Figure 16 displays the shutdown project network under time-crashing conditions, where task priorities were adjusted, non-value-added activities were removed, and resources were reallocated to shorten the shutdown duration without compromising quality or safety. Figure 17 presents an optimized Gantt chart that adjusts shutdown schedules and worker allocation to ensure timely task completion.

7. **Post-Improvement Time and Waste Analysis:** Figure 18 compares pre- and post-improvement maintenance value stream maps, highlighting a reduction in inefficiencies and a more streamlined workflow. Figure 19 demonstrates the reduction in non-value-added time, showcasing Lean Six Sigma's impact on waste reduction and enhanced operational efficiency.

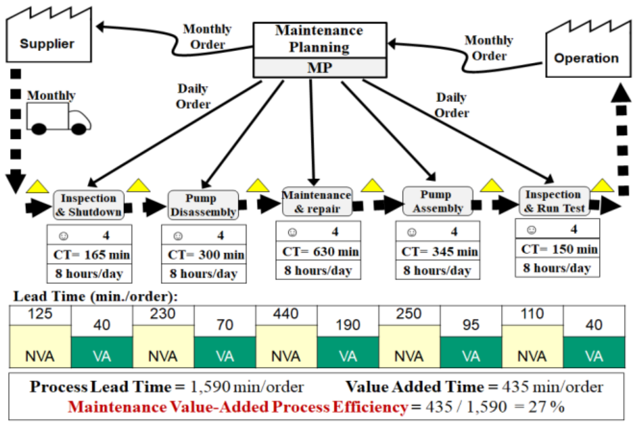
8. **Key Performance Indicators (KPIs):** Figure 20 presents the shutdown maintenance KPIs dashboard, which tracks critical metrics like downtime reduction, efficiency gains, and cost savings. This dashboard provides a clear overview of the improvements achieved through the LSS framework. The application of LSS resulted in significant improvements, including a 60% reduction in non-value-added (NVA) time by eliminating waiting, unnecessary movements, and redundant tasks, leading to increased workforce productivity. Shutdown downtime was reduced by 43%, minimizing operational disruptions and financial losses. Enhanced pre-shutdown planning, standardized processes, and real-time monitoring allowed for a quicker resumption of operations, resulting in higher plant productivity.

9. **Further Insights:** The LSS framework also provided valuable insights that contributed to its success. Tools such as cause-and-effect diagrams and Pareto analysis revealed inefficiencies, including poor task prioritization and communication gaps, which were effectively addressed. Training personnel in Lean Six Sigma fostered a culture of collaboration and continuous improvement. Additionally, real-time tracking enabled dynamic adjustments during the shutdown, enhancing flexibility and alignment with operational goals.

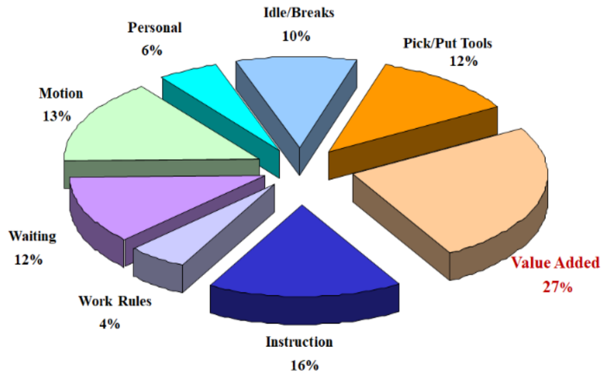
The success of this framework underscores its potential for broader applications in maintenance management. By emphasizing waste reduction and process optimization, Lean Six Sigma can be applied to areas like predictive maintenance, long-term asset management, and wider operational improvements, offering long-term benefits in reliability, productivity, and cost-efficiency.



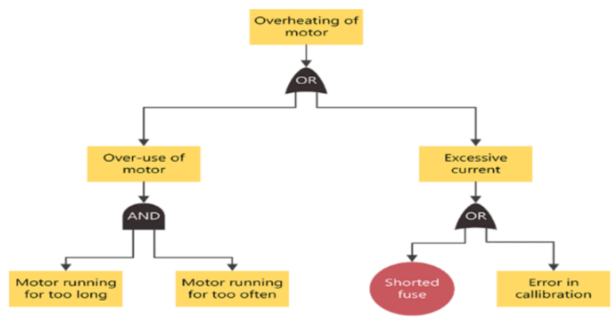
[Fig.8: Shutdown Project Network for Normal Case (Before Improvement)]



[Fig.9: Maintenance Value Stream Mapping (Before Improvement)]



[Fig.10: Shutdown Time Analysis (Before Improvement)]



[Fig.11: Fault Tree Analysis (FTA) for Overheating of the Motor]

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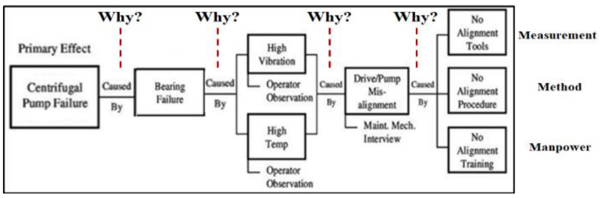
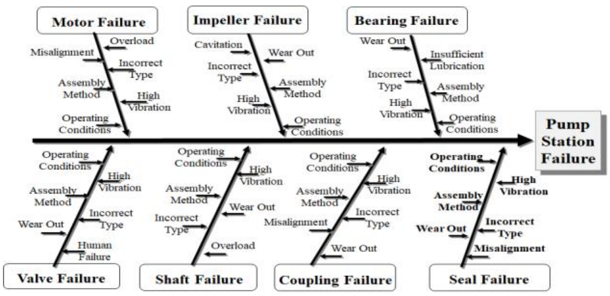
Table 9: FMEA for the Centrifugal Pump

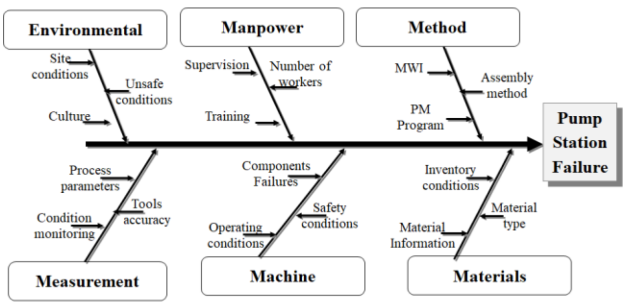
Identify			Analysis			Control	
	Description	Failure Mode	Failure Cause	Failure Effect	Risk Level	Maintenance Task	Frequency
Functions	Fluid Flow	No flow	- Overloaded motor	Motor failure	H	- Check misalignment - Check motor	Quarter
		Insufficient flow	- Cavitation on impeller - Insufficient NPSH	Low pump efficiency	M	- Check impeller - Check NPSH	Quarter
	Fluid Head	Insufficient head	- Cavitation on impeller - Insufficient NPSH	Low pump efficiency	M	- Check impeller - Check NPSH	Quarter
Main Items	Mechanical Seal	Fluid leakage	- Seal fails - Poor maintenance	Leakage Low pump efficiency	M	- Check seal - Material selection	Quarter
	Pump Bearing	Excessive vibration	- Bearing fails - High bearing temp. - Poor maintenance	Bearing failure	M	- Check misalignment - Check bearing temp. - Check bearing vib.	Quarter
	Impeller	Insufficient head	- Cavitation - Insufficient NPSH - Poor maintenance	Low pump efficiency	M	- Check impeller - Check NPSH	Quarter
	Coupling	Excessive vibration	- Coupling damage	Misalignment	M	- Check misalignment	Quarter



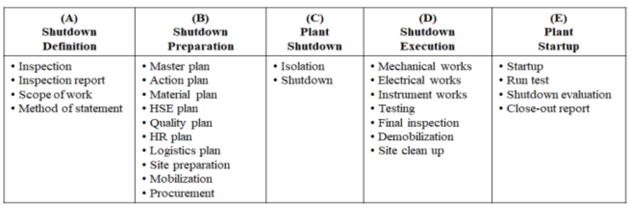
[Fig.12: Root Cause (Why-Why) Analysis for Bearing Failure]



[Fig.13: Fishbone Diagram Based on Equipment items]

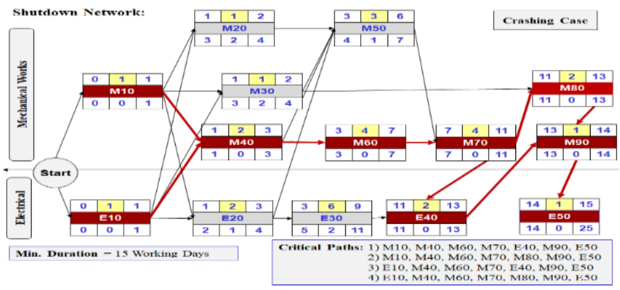


[Fig.14: Fishbone Diagram Based on Maintenance Resources]

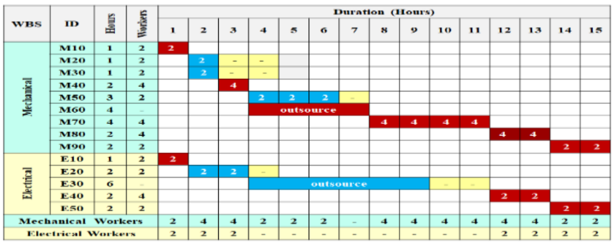


(A) Shutdown Definition	(B) Shutdown Preparation	(C) Plant Shutdown	(D) Shutdown Execution	(E) Plant Startup
• Inspection • Inspection report • Scope of work • Method of statement	• Master plan • Action plan • HSE plan • Material plan • Quality plan • HR plan • Logistics plan • Site preparation • Mobilization • Procurement	• Isolation • Shutdown	• Mechanical works • Electrical works • Instrument works • Testing • Final inspection • Demobilization • Site clean up	• Startup • Run test • Shutdown evaluation • Close-out report

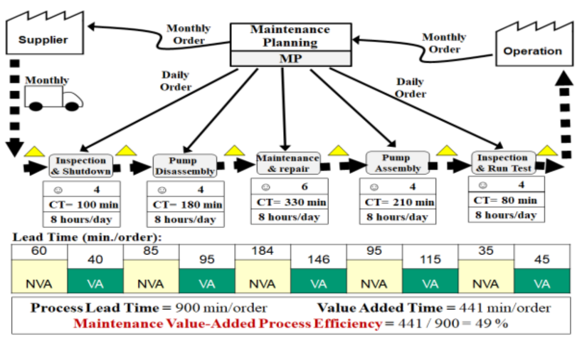
[Fig.15: Standard Shutdown Management Methodology]



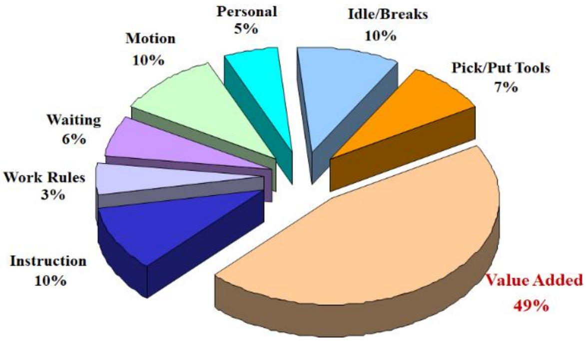
[Fig.16: Shutdown Project Network for time Crashing Case]



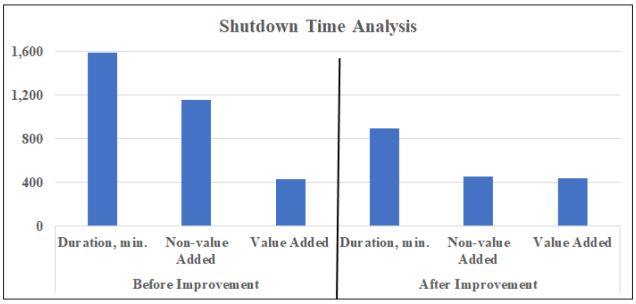
[Fig.17: Shutdown Project Gantt Chart and Workers Allocation]



[Fig.18: Maintenance Value Stream Mapping (after Improvement)]



[Fig.19: Shutdown Waste Time Analysis (after Improvement)]



[Fig.20: Shutdown Maintenance KPIs Dashboard]

VII. CONCLUSION AND FUTURE WORK

This study investigates the integration of Lean Six Sigma (LSS) with proactive maintenance strategies—Risk-Based Inspection (RBI), Reliability-Centered Maintenance (RCM), and Total Productive Maintenance (TPM)—to optimize maintenance practices. The synergy between LSS and these strategies enhances equipment reliability, extends asset lifecycles, and optimizes resource utilization. While LSS drives continuous improvement by eliminating inefficiencies, RBI, RCM, and TPM provide proactive, data-driven solutions to reduce downtime and improve operational performance. Despite the proven success of each methodology, their combined potential in asset management remains underexplored.

A novel framework is proposed that integrates Lean Six Sigma (LSS), Risk-Based Inspection (RBI), Reliability-Centered Maintenance (RCM), and Total Productive Maintenance (TPM) to optimize asset performance by enhancing reliability, availability, maintainability, and safety (RAMS), while minimizing risks and costs. This framework defines clear objectives and key performance indicators (KPIs), enabling data-driven decision-making and promoting continuous improvement. By aligning maintenance strategies with organizational goals, it fosters the development of sustainable, cost-effective maintenance systems. Organizations adopting this integrated approach can improve reliability, optimize resource allocation, and ensure long-term maintenance sustainability. This research offers valuable insights for both academics and industry professionals seeking to leverage LSS tools to enhance maintenance performance.

Validated through a case study of a major shutdown maintenance project at a feedwater pumping station in a petrochemical company in Egypt, the proposed framework led to significant improvements: a 60% reduction in non-value-added time, a 43% reduction in downtime, and a 22% increase in shutdown efficiency (from 27% to 49%). These results demonstrate the effectiveness of combining LSS, TPM, RBI, and RCM in optimizing shutdown maintenance and enhancing operational performance. This study builds on the findings presented in Gomaa (2024a).

Future research should explore the integration of emerging technologies such as Digital Twins, Machine Learning (ML), Artificial Intelligence (AI), and the Internet of Things (IoT) to further advance predictive maintenance and enable real-time asset monitoring. Additionally, refining LSS methodologies for critical assets across industries, alongside the development of industry-specific metrics, implementation roadmaps, and workforce training programs, will address sector-specific challenges and promote continuous improvement. These advancements will enhance asset reliability, optimize maintenance planning, and support the long-term sustainability of critical manufacturing systems.

DECLARATION STATEMENT

I must verify the accuracy of the following information as the article's author.

- **Conflicts of Interest/ Competing Interests:** Based on my understanding, this article has no conflicts of interest.
- **Funding Support:** This article has not been sponsored or funded by any organization or agency. The independence of this research is a crucial factor in affirming its impartiality, as it has been conducted without any external sway.
- **Ethical Approval and Consent to Participate:** The data provided in this article is exempt from the requirement for ethical approval or participant consent.
- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Authors Contributions:** The authorship of this article is contributed solely.

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