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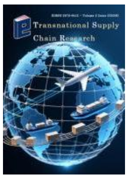

Research Article

Enhancing Manufacturing Excellence Through Lean Six Sigma: A Case Study Approach

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KEYWORDS

manufacturing excellence
lean six sigma
process optimization
operational excellence
continuous improvement

ABSTRACT

Achieving manufacturing excellence requires continuous improvement in operational efficiency, quality, and process performance. Although Lean Six Sigma (LSS) is widely recognized for process optimization, its application in complex manufacturing environments remains constrained by the lack of structured, scalable, and empirically validated frameworks, while existing literature remains fragmented and provides limited guidance for sustainable industrial deployment. This study adopts a case study approach to develop and validate a structured Lean Six Sigma framework for enhancing manufacturing performance. A systematic review of LSS applications in manufacturing (2010–2026), combined with a gap analysis, identified key challenges, including inconsistent implementation practices, limited industrial validation, workforce capability gaps, and high deployment complexity. To address these gaps, a comprehensive framework is proposed that integrates the DMAIC methodology with five functional domains: strategic alignment, process analysis, quality improvement, reliability and maintenance, and continuous improvement, with explicit linkages among DMAIC phases, analytical tools, and performance indicators to support structured and sustainable improvement. The framework was implemented and validated in a car spare parts manufacturing company in Egypt, resulting in significant improvements, including an increase in first-time product quality from 26.7% to 80.0%, achievement of 100% post-rework quality, sigma level improvement up to 6.0, and a reduction in processing lead time by more than 50%, alongside an increase in value-added efficiency from 47% to 79%. The findings demonstrate that the proposed Lean Six Sigma framework bridges the gap between theory and practice and provides a scalable pathway toward sustainable manufacturing excellence.

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1. Introduction

Manufacturing excellence has become a strategic imperative for organizations operating in highly competitive global markets. Achieving high operational efficiency, superior product quality, reduced lead times, and enhanced customer satisfaction is essential for both profitability and long-term resilience. These outcomes require more than incremental improvements; they demand systematic, structured, and data-driven methodologies capable of identifying inefficiencies, reducing variability, and optimizing operational performance. Through rigorous analysis and continuous improvement, organizations can enhance value creation and sustain competitive advantage in complex industrial environments [1,2].

1.1. Lean Six Sigma: Conceptual Foundations and Methodological Structure

Lean Six Sigma (LSS) integrates Lean manufacturing principles with Six Sigma methodologies into a unified approach for operational excellence. It focuses simultaneously on waste elimination and process variation reduction, thereby improving efficiency, quality, cost performance, and customer satisfaction [3-5]. Lean emphasizes flow optimization and elimination of non-value-added activities, while Six Sigma applies statistical techniques to reduce defects and variability. Their integration enables more stable processes, shorter lead times, and improved organizational performance [6,7].

Originating from the Toyota Production System (TPS) and Motorola's Six Sigma initiative, LSS has evolved into a widely adopted methodology across manufacturing and service sectors [8-10]. The DMAIC framework—Define, Measure, Analyze, Improve, and Control—provides a structured cycle for implementation. Define identifies customer requirements and critical-to-quality (CTQ) characteristics; Measure establishes baseline performance; Analyze determines root causes; Improve implements targeted solutions; and Control ensures sustainability through standardization and monitoring [11-16].

LSS has been widely applied beyond manufacturing, including healthcare, finance, and service industries, improving efficiency, transparency, and responsiveness. Its integration with quality management systems such as ISO 9001 further strengthens process standardization, compliance, and strategic alignment [17-22]. Empirical studies consistently report measurable improvements in quality performance, lead time reduction, cost efficiency, and customer satisfaction [23-26].

Lean Six Sigma (LSS) is a data-driven, integrative improvement approach that combines Lean manufacturing principles with Six Sigma methodologies to systematically enhance operational performance. Lean concentrates on eliminating non-value-adding activities and streamlining process flow, whereas Six Sigma seeks to minimize process variability and defects through rigorous statistical analysis. As depicted in the figure, LSS brings together a coherent set of tools, techniques, and cultural enablers—including value stream mapping, DMAIC, and root cause analysis—to enable structured problem-solving, sustain continuous improvement, and deepen employee engagement across organizational levels. Collectively, these elements yield measurable improvements in operational efficiency and product quality, while also supporting innovation and long-term organizational sustainability [27-34].

Lean Six Sigma (LSS) tools provide an integrated, end-to-end framework for enhancing manufacturing performance by aligning customer requirements with data-driven analysis, process optimization, and sustained control across the DMAIC cycle. They support structured problem definition and requirement translation through tools such as SIPOC, VOC, Kano Analysis, and QFD, while measurement and analytical techniques, including value stream mapping, process capability analysis, time studies, Pareto analysis, and root cause analysis, enable systematic identification of inefficiencies, variation, and critical improvement priorities. Improvement methodologies such as Kaizen, Design of Experiments (DOE), SMED, and cellular manufacturing enhance efficiency, flow, and process robustness. These gains are sustained through control mechanisms including Statistical Process Control (SPC), control plans, standardized work, and visual management systems, while cultural enablers such as 5S and Kaizen practices institutionalize continuous improvement and employee engagement, ultimately delivering sustained improvements in productivity, quality, and cost efficiency [35-44].

Sustainability has also become a significant driver of LSS adoption. By combining waste reduction with defect minimization, LSS contributes to reduced resource consumption and environmental impact [45-48]. In addition, tools such as 5S, Kaizen, Kanban, DFSS, and statistical process control support continuous improvement, innovation, and workforce engagement, reinforcing LSS as both a technical and organizational transformation framework [49-51].

1.2. Problem Statement

Despite its widespread adoption, LSS implementation still faces critical challenges. Existing studies often adopt generalized approaches that fail to address industry-specific requirements, particularly in complex manufacturing environments such as machining and discrete production systems. Many contributions focus on isolated tools or individual DMAIC phases rather than providing integrated, end-to-end frameworks that ensure consistency, scalability, and sustainability.

Furthermore, sustainability integration within LSS remains insufficiently developed. Although Lean and Six Sigma independently support efficiency and quality improvement, their combined application is not consistently aligned with environmental performance, energy efficiency, or broader sustainability objectives. Organizational barriers, including limited workforce capability, resistance to change, and insufficient employee engagement, further hinder effective implementation. In addition, there is a lack of comprehensive, empirically validated case studies—particularly in developing economies—that demonstrate full-cycle implementation from problem identification to performance validation.

These limitations highlight the need for a structured, scalable, and empirically validated Lean Six Sigma framework that integrates methodological rigor, sustainability considerations, and industrial applicability.

1.3. Study Objectives and Contributions

This study develops and validates a structured Lean Six Sigma framework for manufacturing operations, addressing gaps in industry-specific applicability, sustainability integration, and practical implementation. Based on a systematic literature review (2010–2026), the proposed framework integrates Lean principles with the DMAIC methodology to enhance process performance and support continuous improvement.

To demonstrate practical applicability, the framework was implemented in a car spare parts manufacturing company in Egypt. Building on Gomaa (2023) [13], this study extends prior research by presenting a more comprehensive and empirically validated framework that bridges theoretical concepts with industrial practice. The study provides a structured, data-driven approach for achieving operational excellence in complex manufacturing environments.

The paper is organized as follows: Section 2 presents the literature review; Section 3 identifies key research gaps; Section 4 outlines the methodology and proposed framework; Section 5 presents the case study; and Section 6 concludes the study with findings and future research directions.

2. Literature Review on Lean Six Sigma in Manufacturing

This review systematically examines literature published between 2010 and 2026, retrieved from Scopus, Web of Science, and ScienceDirect, using keywords including Lean Six Sigma, DMAIC Framework, Manufacturing Excellence, Process Performance, Process Optimization, Operational Excellence, and Continuous Improvement. It synthesizes research on Lean Six Sigma (LSS) applications in manufacturing, highlighting trends, methodologies, implementation practices, and operational outcomes. The review identifies adoption patterns, best practices, and challenges across various industrial contexts, emphasizing LSS's impact on critical performance indicators such as quality, productivity, cycle time, overall equipment effectiveness (OEE), and cost efficiency. Key gaps include inconsistent application of DMAIC phases, limited integration of emerging technologies, and the absence of standardized performance metrics. These insights inform the development of a structured framework to guide future research and practical LSS implementation, providing actionable guidance for both academic and industrial stakeholders.

Lean Six Sigma integrates Lean manufacturing principles with Six Sigma methodologies to enhance operational efficiency, reduce waste, and improve process performance [52-57]. Lean emphasizes the elimination of non-value-added activities, workflow streamlining, process standardization, and optimal resource utilization [54], whereas Six Sigma employs statistical, data-driven methods to minimize variation, improve quality, and strengthen operational outcomes [55]. By combining these approaches, LSS provides a structured framework that drives operational excellence, cost reduction, product quality improvement, and customer satisfaction [56]. Implementation also enhances supply chain coordination, transparency, and responsiveness, while alignment with ISO 9001 quality management systems ensures standardized processes, strategic coherence, and measurable outcomes [57]. LSS originates from the Toyota Production System (TPS) of the 1950s, which emphasizes waste elimination and efficiency, and Motorola's Six Sigma methodology of the 1980s, which targets defect reduction and variation control. Lean principles define customer value, map the value stream, create flow, establish pull, and pursue perfection, while Six Sigma's DMAIC (Define, Measure, Analyze, Improve, Control) framework offers a structured, repeatable approach to problem-solving and process optimization [23-26].

Lean manufacturing, pioneered by Toyota, is a systematic production philosophy focused on waste elimination, workflow stabilization, and process standardization to enhance efficiency, competitiveness, and resilience [58-60]. Lean is often integrated with complementary practices such as Just-in-Time (JIT), Total Quality Management (TQM), Total Preventive Maintenance (TPM), and Human Resource Management (HRM), forming an integrated improvement system that strengthens product quality, reliability, and employee engagement across the value chain [61-63]. Empirical evidence demonstrates that Lean adoption improves operational, financial, and environmental performance by reducing cycle times and production costs, increasing product quality, and minimizing waste and resource consumption [64-67]. Tools such as 5S, SMED, Kanban, Kaizen, and Poka-Yoke operationalize Lean principles, promoting standardization, continuous improvement, flow efficiency, and defect prevention, supporting sustainable manufacturing performance [68-72].

Six Sigma complements Lean by offering a rigorous, data-driven methodology designed to achieve near-perfect process performance, targeting no more than 3.4 defects per million opportunities. It systematically identifies, analyzes, and eliminates root causes of variation, improving process capability, consistency, and reliability [73-76]. Six Sigma has been successfully applied across manufacturing sectors—including automotive, electronics, textiles, and energy—and service industries such as banking, education, and transportation, delivering measurable improvements in productivity, quality, and customer satisfaction [77,78]. Its DMAIC framework guides organizations from problem identification to root-cause analysis, solution implementation, and performance evaluation, fostering evidence-based decision-making and continuous improvement [79-82].

The integration of Lean and Six Sigma consistently enhances operational performance by optimizing production processes, inventory management, and cost efficiency [83,84]. By combining Lean's focus on waste elimination and process standardization with Six Sigma's data-driven reduction of variation, LSS lowers costs in product design, development, and manufacturing while conserving materials, labor, and management resources [85-89]. Embedded transportation and inventory management practices strengthen operational capabilities by improving cash flow, increasing inventory turnover, minimizing stock obsolescence, and ensuring timely material availability, reducing bottlenecks and enhancing responsiveness [90,91]. LSS drives measurable financial improvements through reduced defects and rework, higher productivity, increased profit margins, and improved returns on sales, assets, and investments [92-94]. Beyond operational and financial benefits, LSS fosters a culture of continuous improvement, value-added activities, and employee engagement, promoting proactive problem-solving and sustainable organizational growth [95,96].

LSS also promotes innovation by encouraging continuous improvement, process optimization, customer-focused solutions, and organizational value creation [97,98]. Lean principles facilitate creative problem-solving, enabling organizations to identify internal and external opportunities for innovation. LSS supports innovation through root-cause analysis, employee empowerment, customer value orientation, and cross-functional collaboration [99-101]. Structured methodologies such as DMAIC and Design for Six Sigma (DFSS) provide systematic, replicable approaches for developing, testing, and implementing innovative solutions [102]. By fostering a culture of participation, communication, and collaboration, LSS motivates employees to generate novel processes, products, and solutions, embedding innovation into daily operations and sustaining competitive advantage [103,104].

LSS also enhances environmental sustainability by reducing emissions, minimizing waste, improving resource efficiency, and strengthening corporate reputation while maintaining operational and financial performance [105,106]. Lean's waste-elimination strategies combined with Six Sigma's data-driven variation control enable organizations to optimize energy, water, and material use, reduce emissions, and improve overall resource utilization [47,48]. Sustainable practices such as energy efficiency, recycling, and renewable resource adoption reduce environmental impacts while preserving productivity and cost efficiency [107]. Embedding environmental accountability into organizational culture ensures continuous improvement, operational resilience, and long-term competitiveness in sustainability-focused markets [105].

Finally, LSS has demonstrated success across multiple industries, including manufacturing, healthcare, food processing, laboratories, and financial services. It stabilizes laboratory processes, reduces errors, and improves quality control reliability [108,109]; in food processing, it optimizes production lines, minimizes defects, and streamlines workflows [110,111]; in healthcare, it improves patient care workflows, insulin administration, and hospital service delivery, enhancing safety and efficiency [112,113]; in financial services, it accelerates claims processing, reduces errors, and improves service quality [114,115]. Maximum benefits are achieved when defect reduction and process optimization are pursued concurrently, with outcomes influenced by baseline performance, project scope, team expertise, and implementation strategy. Despite its proven effectiveness, gaps remain in industry-specific frameworks, machining applications, and comprehensive performance assessment. Structured implementation, alignment with ISO 9001, and integration of sustainability objectives further strengthen long-term competitiveness, highlighting avenues for future research and practical application [20,34,47,48].

3. Challenges and Research Gaps Analysis

Lean Six Sigma (LSS) is a well-established methodology for improving operational efficiency, product quality, and overall manufacturing performance. However, its implementation in machining-intensive environments faces multiple technical, organizational, and technological challenges. Machining processes involve highly interdependent variables—including cutting parameters, tool wear, material properties, machine dynamics, thermal effects, and vibrations—where even minor deviations can result in surface defects, dimensional inaccuracies, rework, and premature tool failure. Conventional process improvement approaches often fail to capture these complexities comprehensively, highlighting the need for structured, data-driven frameworks capable of analyzing variability, identifying root causes, and optimizing performance in industrial settings [32,56,117].

Table 1 summarizes the key challenges and research gaps in implementing LSS for machining-intensive manufacturing. These challenges are grouped into three overarching categories: (1) Framework, Validation, and Research Gaps; (2) Workforce, Culture, and Resource Constraints; and (3) Scalability, Sustainability, and Digital Integration, reflecting the multidimensional barriers to effective and sustainable adoption.

1) Framework, Validation, and Research Gaps: A major barrier is the absence of a unified, adaptable LSS framework. Most studies examine Lean and Six Sigma separately, and few integrated frameworks address the specific complexities of machining operations, resulting in fragmented improvements and inconsistent outcomes [55,56,116]. Empirical validation is limited: while Lean or Six Sigma tools are often applied individually, real-world testing in machining environments is scarce, and evaluation of key performance indicators (KPIs)—including OEE, first-pass yield, cycle time, and customer satisfaction—is insufficient [34,108,117]. Standardized benchmarks are lacking, and performance measurement gaps persist when operational, financial, and environmental outcomes are not assessed simultaneously [1,47,48]. Most studies focus on general manufacturing rather than machining-specific contexts, and empirical validation is often confined to laboratory studies, simulations, or small-scale pilots [34,56,116,108].
2) Workforce, Culture, and Resource Constraints: Effective LSS adoption depends on a skilled and engaged workforce, yet gaps in training and expertise frequently hinder implementation [13,118,119] Organizational culture and change management challenges—including resistance to change, limited leadership support, and insufficient cross-functional collaboration—further reduce adoption and the long-term benefits of improvement initiatives [95,96,122]. Even with tools such as DMAIC, 5S, Kaizen, Kanban, and statistical process control, success depends on fostering a culture of continuous improvement, knowledge sharing, and active employee participation [99,122,103]. Alignment with ISO 9001 or similar quality management systems ensures strategic coherence and consistent performance monitoring [20,22]. High resource and cost requirements also present barriers, particularly for smaller organizations [84,123]. Sustainability considerations are often overlooked; few studies systematically measure energy consumption, emissions, or material use, especially in machining-intensive operations [45,47,107]. Integrating environmental metrics into LSS initiatives is essential for aligning operational efficiency with sustainability and long-term competitiveness.
3) Scalability, Sustainability, and Digital Integration: Many LSS applications are limited in scope, focusing on individual processes or production lines, with little guidance for replicating improvements across machines, lines, or facilities [56,116]. Developing scalable frameworks is critical to ensure consistent performance across diverse production contexts. Despite advances in Industry 4.0, LSS frameworks often underutilize real-time data analytics and smart manufacturing technologies. Machining data is frequently underexploited, limiting predictive and proactive decision-making [26,48]. Integration with CNC automation, IoT-enabled sensors, and Industry 4.0 systems is often insufficient, reducing opportunities for dynamic process optimization and sustainable performance improvements [1,119]. Operational capability—critical for mediating innovation and financial performance—is often addressed indirectly

[120,121], and organizational experience is essential, with quality programs generally requiring at least three years to achieve stable results [122,123].

Collectively, these challenges underscore the need for integrated, empirically validated frameworks, a skilled and engaged workforce, cost-efficient and sustainability-focused practices, scalable strategies, and full utilization of digital and advanced manufacturing technologies. Addressing these barriers enables LSS to maximize operational performance, foster innovation, enhance competitiveness, and support sustainable manufacturing in machining-intensive industries [116-119].

Table 1. Key Challenges and Research Gaps in Lean Six Sigma Implementation for Manufacturing

Category	Challenge / Research Gap	Description
1) Framework, Validation, and Research Gaps	Lack of a Unified, Adaptable Framework	Most studies treat Lean and Six Sigma separately; few integrated frameworks address machining-specific complexities, leading to fragmented improvements and inconsistent outcomes.
	Limited Integration and Empirical Validation	Lean and Six Sigma tools are often applied in isolation; real-world validation in machining environments is scarce, and comprehensive evaluation of KPIs (OEE, first-pass yield, cycle time, customer satisfaction) is limited.
	Inadequate Performance Measurement	Few studies assess operational, financial, and environmental metrics simultaneously; lack of standardized benchmarks limits comparability and practical applicability.
2) Workforce, Culture, and Resource Constraints	Skills and Workforce Readiness	Effective LSS implementation requires personnel skilled in Lean, Six Sigma, and machining operations; lack of trained staff hinders adoption and sustainability.
	Organizational Culture and Change Management	Resistance to change, limited leadership support, and insufficient cross-functional collaboration impede LSS adoption and long-term performance gains.
	Cost and Resource Constraints	High initial investment in training, data infrastructure, and process redesign can limit implementation, particularly in resource-constrained organizations.
3) Scalability, Sustainability, and Digital Integration	Scalability and Adaptability	Many LSS applications are process-specific or small-scale, with limited guidance on scaling improvements across machines, production lines, or facilities.
	Sustainability and Environmental Considerations	Traditional LSS focuses on operational efficiency and quality, often overlooking energy consumption, emissions, tool wear, and material waste.
	Underutilization of Digital Technologies and Data Analytics	Real-time machining data is underexploited; predictive and proactive decision-making is limited, reducing process optimization.
	Integration with Advanced Manufacturing Technologies	LSS frameworks are often not fully aligned with CNC automation, IoT sensors, and Industry 4.0 systems, limiting real-time optimization and predictive capabilities.

4. Research Methodology for Developing a LSS Framework for Manufacturing Excellence

Achieving manufacturing excellence in modern production systems requires a systematic, data-driven, and multi-dimensional approach. The increasing complexity, automation, and digital integration of manufacturing processes have rendered traditional improvement methods insufficient to meet the high standards of precision, efficiency, quality, and reliability demanded in competitive industrial environments. Challenges such as variability in machining operations, unplanned equipment downtime, production bottlenecks, and inconsistent product quality necessitate robust, evidence-based frameworks that integrate operational, strategic, and technological perspectives.

To address these challenges, this study proposes a comprehensive Lean Six Sigma (LSS) framework that integrates structured problem-solving, advanced analytics, reliability engineering, and continuous improvement practices. LSS principles systematically identify and eliminate inefficiencies, advanced analytics optimize process performance, reliability engineering enhances equipment availability and operational consistency, and continuous improvement fosters a culture of operational excellence, collaboration, and workforce engagement. Together, these elements deliver measurable, sustainable, and scalable improvements in process capability, product quality, equipment reliability, and operational efficiency, aligned with organizational strategy and customer expectations.

Figure 1 illustrates the integrated Lean Six Sigma framework, which combines the DMAIC methodology—Define, Measure, Analyze, Improve, and Control—with five functional groups of LSS tools: strategic alignment, process analysis, quality optimization, reliability and maintenance, and continuous improvement. Each functional group is linked to its corresponding DMAIC phase, ensuring structured, evidence-based, and measurable improvements across operations. Digital technologies, including IoT sensors, digital twins, predictive analytics, and dashboards, support real-time monitoring, predictive optimization, and data-driven decision-making, further enhancing process capability, product quality, and operational performance while fostering a sustainable culture of continuous improvement.

Table 2 provides a detailed overview of the framework, presenting functional groups, associated DMAIC phases, key tools, and KPIs. Group A emphasizes strategic alignment and project prioritization, ensuring initiatives are aligned with organizational goals, customer requirements, and long-term priorities while focusing on high-impact projects. Group B addresses process definition and analysis, providing clarity of process flows, identification of bottlenecks, and baseline performance measurement. Group C targets process optimization and quality enhancement, applying statistical and experimental techniques to reduce defects, improve yield, and enhance product reliability. Group D focuses on reliability, equipment, and maintenance excellence, ensuring high equipment availability, reduced downtime, and improved operational efficiency. Finally, Group E emphasizes standardization, sustainment, and continuous improvement, embedding best practices, workplace organization, and continuous learning into operations. This structured categorization ensures that strategic, operational, and cultural initiatives are directly linked to measurable outcomes, providing a clear roadmap for achieving Manufacturing Excellence.

The LSS tools are organized into five functional categories, reflecting the progression from strategic alignment and process analysis to optimization, sustainment, and continuous improvement. Group A ensures that initiatives are strategically focused and resource-efficient, utilizing tools such as the Project Selection Matrix, Impact–Effort Matrix, SWOT Analysis, and Hoshin Kanri, with KPIs tracking strategic alignment, project ROI, and initiative impact. Group B clarifies process flow and identifies bottlenecks, employing DMAIC, SIPOC diagrams, Process Mapping, CTQ Analysis, Value Stream Mapping (VSM), SPC, Cp/Cpk, and Gage R&R to maintain process stability and data reliability. Group C achieves high precision, robustness, and defect prevention through DOE, Response Surface Methodology (RSM), Taguchi Method, FMEA, and Root Cause Analysis (RCA). Group D strengthens equipment performance and operational reliability through Total Productive Maintenance (TPM), Overall Equipment Effectiveness (OEE), and Reliability-Centered Maintenance (RCM). Finally, Group E focuses on stabilizing gains and embedding a culture of continuous improvement, using Standardized Work, 5S, Benchmarking, Control Plans, Visual Management, and Kaizen.

The DMAIC methodology anchors the framework, providing a structured roadmap for continuous, evidence-based improvement. In the Define phase, process boundaries, objectives, and strategic alignment are established, supported by digital twins and real-time sensor data, producing clear process definitions and prioritized improvement opportunities. The Measure phase captures baseline performance, quantifies variability, and identifies critical parameters through IoT-enabled monitoring, process capability analysis, and statistical evaluation, providing actionable insights and highlighting performance gaps. During the Analyze phase, root causes of defects, inefficiencies, and variability are identified and validated using predictive analytics, machine learning, and experimental methods, enabling precise optimization of process parameters and improved process robustness. The Improve phase implements validated solutions using DOE, Taguchi Method, TPM, and RCM, with digital twin simulations allowing virtual testing prior to physical implementation, reducing trial-and-error costs and increasing operational confidence. The Control phase sustains improvements by maintaining gains, reinforcing best practices, and driving continuous improvement through dashboards, predictive monitoring, and KPI tracking, ensuring long-term process stability and alignment with strategic objectives.

Integration of Industry 4.0 technologies amplifies Lean Six Sigma effectiveness by enabling adaptive, intelligent, and predictive manufacturing. IoT sensors provide continuous, real-time monitoring; digital twins allow virtual simulation, optimization, and validation of process improvements; predictive analytics and machine learning facilitate early detection of deviations and identification of improvement opportunities; and dashboards provide visualization of KPIs for operational and strategic decision-making. This integration ensures the methodology supports smart, connected, and continuously improving manufacturing systems, bridging Lean Six Sigma principles with digital transformation initiatives.

Ultimately, the framework delivers measurable improvements across four dimensions. Strategically, it aligns initiatives with organizational objectives and customer requirements, prioritizing high-impact projects. Operationally, it reduces process variability, enhances product quality, improves process capability, and increases equipment efficiency. Culturally, it embeds continuous improvement, evidence-based decision-making, and workforce engagement, fostering a resilient, learning-oriented organization. Digitally, it enables predictive, adaptive, and intelligent manufacturing through IoT, analytics, and digital twins. By systematically linking LSS tools, DMAIC phases, KPIs, digital integration, and operational outcomes, the framework provides a robust, evidence-based roadmap for achieving sustainable, scalable, and measurable Manufacturing Excellence in modern production environments.

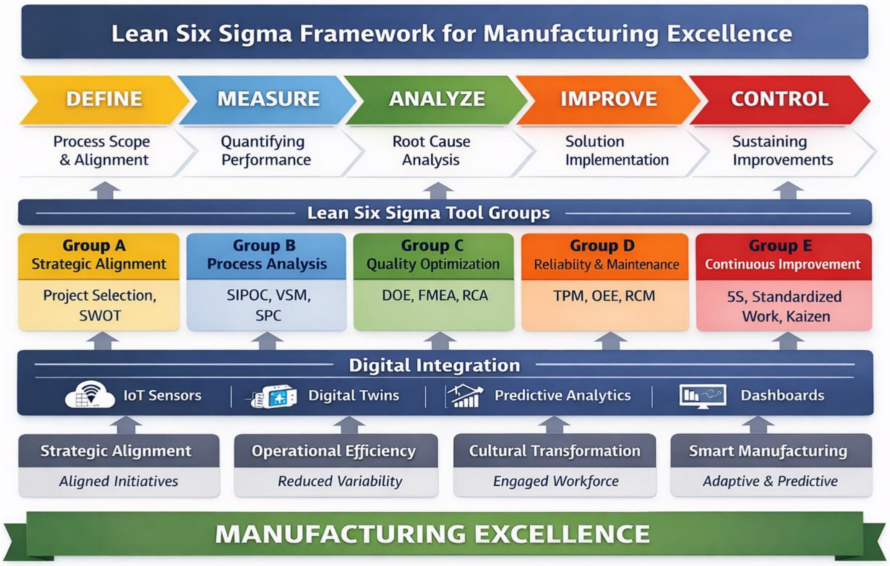


Figure 1. Integrated LSS Framework for Achieving Manufacturing Excellence.

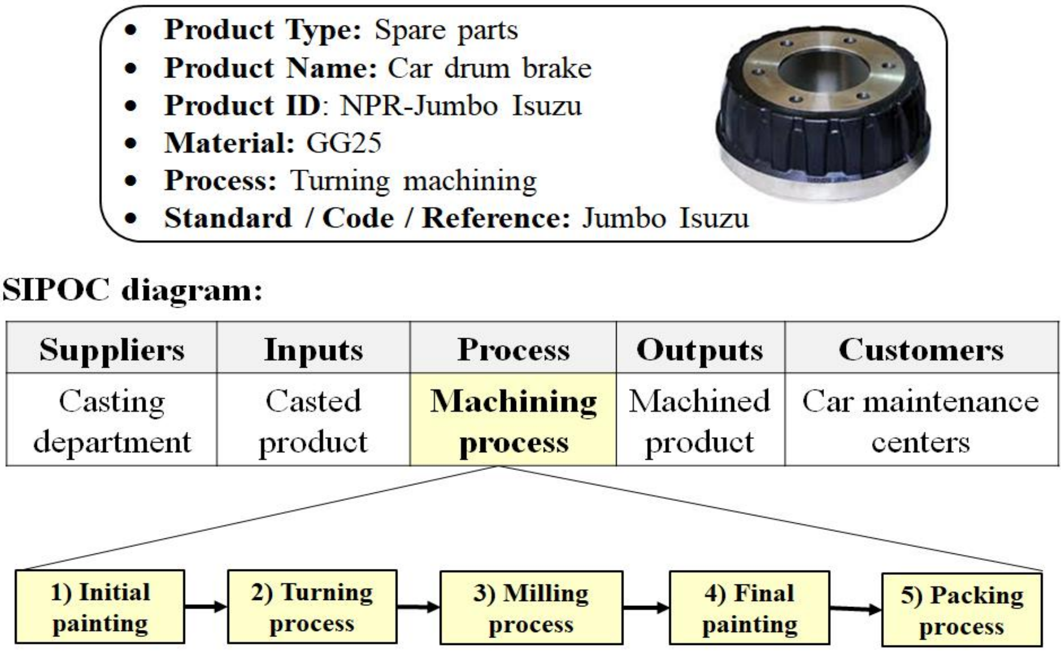
Table 2. Integrated LSS Framework for Achieving Manufacturing Excellence

DMAIC	Functional Group	Key Tools	Key Performance Indicators (KPIs)
Define	Strategic Alignment & Project Prioritization	Project Selection Matrix, Impact–Effort Matrix, SWOT Analysis, Hoshin Kanri	Alignment with organizational strategy, project ROI, and initiative impact
Measure	Process Definition, Mapping & Analysis	DMAIC, SIPOC, Process Mapping, CTQ Analysis, Value Stream Mapping (VSM), SPC, Cp/Cpk, Gage R&R	Baseline performance, variability reduction, and identification of bottlenecks
Analyze	Process Optimization & Quality Enhancement	Design of Experiments (DOE), Response Surface Methodology (RSM), Taguchi Method, FMEA, Root Cause Analysis (RCA)	Defect reduction, yield improvement, enhanced product reliability
Improve	Reliability, Equipment & Maintenance Excellence	Total Productive Maintenance (TPM), Overall Equipment Effectiveness (OEE), Reliability-Centered Maintenance (RCM)	Increased equipment availability, reduced downtime, improved operational efficiency
Control	Standardization, Sustainment & Continuous Improvement	Standardized Work, 5S, Benchmarking, Control Plans, Visual Management, Kaizen	Sustained process stability, continuous improvement adoption, and workforce engagement

5. Case Study

The proposed Lean Six Sigma (LSS) framework was applied in an auto parts manufacturing company in Egypt, specializing in high-quality ductile and gray cast iron components. The company is a leading supplier of spare parts for car maintenance and repair centers nationwide. The study aimed to reduce product defects, eliminate waste, and minimize non-value-added time in the production process, thereby improving operational efficiency, product quality, and overall competitiveness.

The NPR-Jumbo Isuzu drum brake was selected for the study. Figure 2 presents the product and SIPOC diagram for the machining process, while Figure 3 illustrates the detailed process flow. These tools established a baseline for identifying bottlenecks, defect sources, and non-value-added activities.



- **Product Type:** Spare parts
- **Product Name:** Car drum brake
- **Product ID**: NPR-Jumbo Isuzu
- **Material:** GG25
- **Process:** Turning machining
- **Standard / Code / Reference:** Jumbo Isuzu

SIPOC diagram:

Suppliers	Inputs	Process	Outputs	Customers
Casting department	Casted product	**Machining process**	Machined product	Car maintenance centers

Figure 2. Process description and SIPOC diagram.

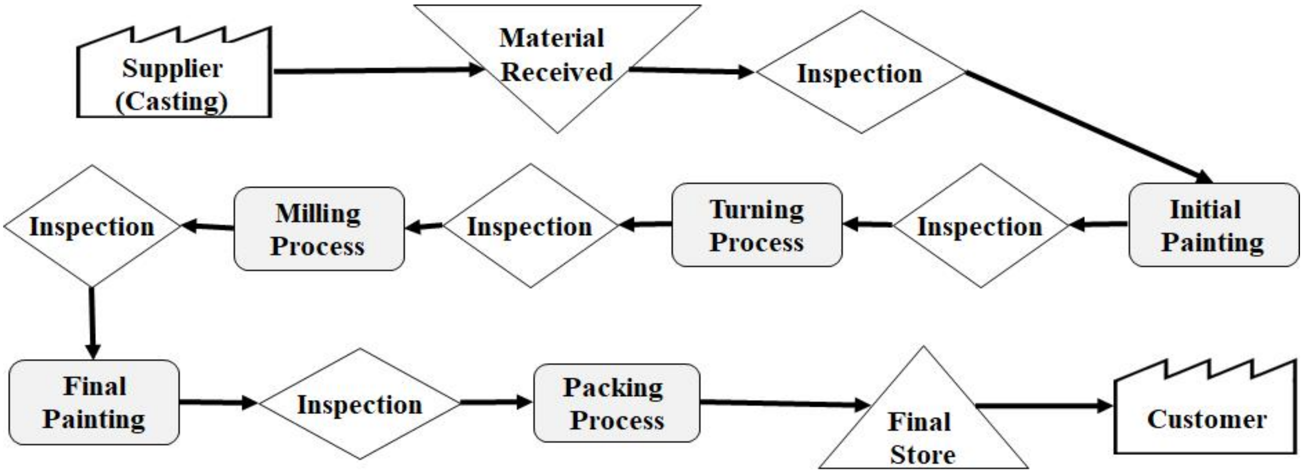


Figure 3. Process flow chart.

5.1. Methodology Implementation

The LSS framework was applied systematically, integrating DMAIC methodology with sigma level analysis, ABC-HML defect classification, cause-and-effect analysis, and Value Stream Mapping (VSM). This combined approach provided a structured, data-driven method for identifying process inefficiencies and implementing targeted improvements.

1) Sigma Level Analysis:

Figure 4 presents the sigma level report, highlighting major contributors to machining defects, including poor surface finish, dimensional deviations, and rework requirements. Corrective actions—such as tool adjustments, process parameter optimization, and operator training—improved first-time quality from 26.7% to 80% and quality after rework to 100%. Sigma levels increased from 2.12 to 2.34 (first-time) and from 2.34 to 6.0 (after rework). Process control charts (Figure 5) and process capability analysis (Figure 6) confirm reduced variability and improved consistency.

2) ABC-HML Defect Classification:

Defects were classified based on frequency and business impact. Table 3 lists primary defects and their associated risks. Figure 7 shows a Pareto chart indicating poor surface finish as the most frequent defect. Table 4 summarizes ABC-HML classification, and Figure 8 presents a cause-and-effect diagram mapping root causes across materials, methods, machinery, manpower, measurements, and environment. This ensured corrective actions targeted the most critical defect drivers.

3) Value Stream Mapping (VSM):

VSM visualized the process and identified non-value-added activities. Figures 9 and 10 show the VSM and value-added time analysis before improvement, highlighting idle time, redundant steps, and excessive handling. Figures 11 and 12 depict the VSM and value-added analysis after improvement. Processing time decreased from 1,847 to 915 seconds per unit, and process efficiency increased from 47% to 79%.

Sigma Level Analysis Report:

- **Product Name:** Car drum brake
- **Product ID**: NPR-Jumbo Isuzu
- **Material:** GG25
- **Process:** Machining Process

Number of Machines: 3 (M1, M2, M3)
Critical To Quality:
- **Inner Diameter:** ϕ 156 ± 0.04 mm
- **Surface Roughness:** Ra 3.2 μm

Before LSS

- **Defect (First-Time)** = Rework + Rejected = 11 / 15 = 73.3%
  - Rework = 8/15 = 53.3 %
  - Rejected = 3/15 = 20.0%
- **Quality (First-Time)** = 26.7%
- **Quality (After Rework)** = 80.0 %

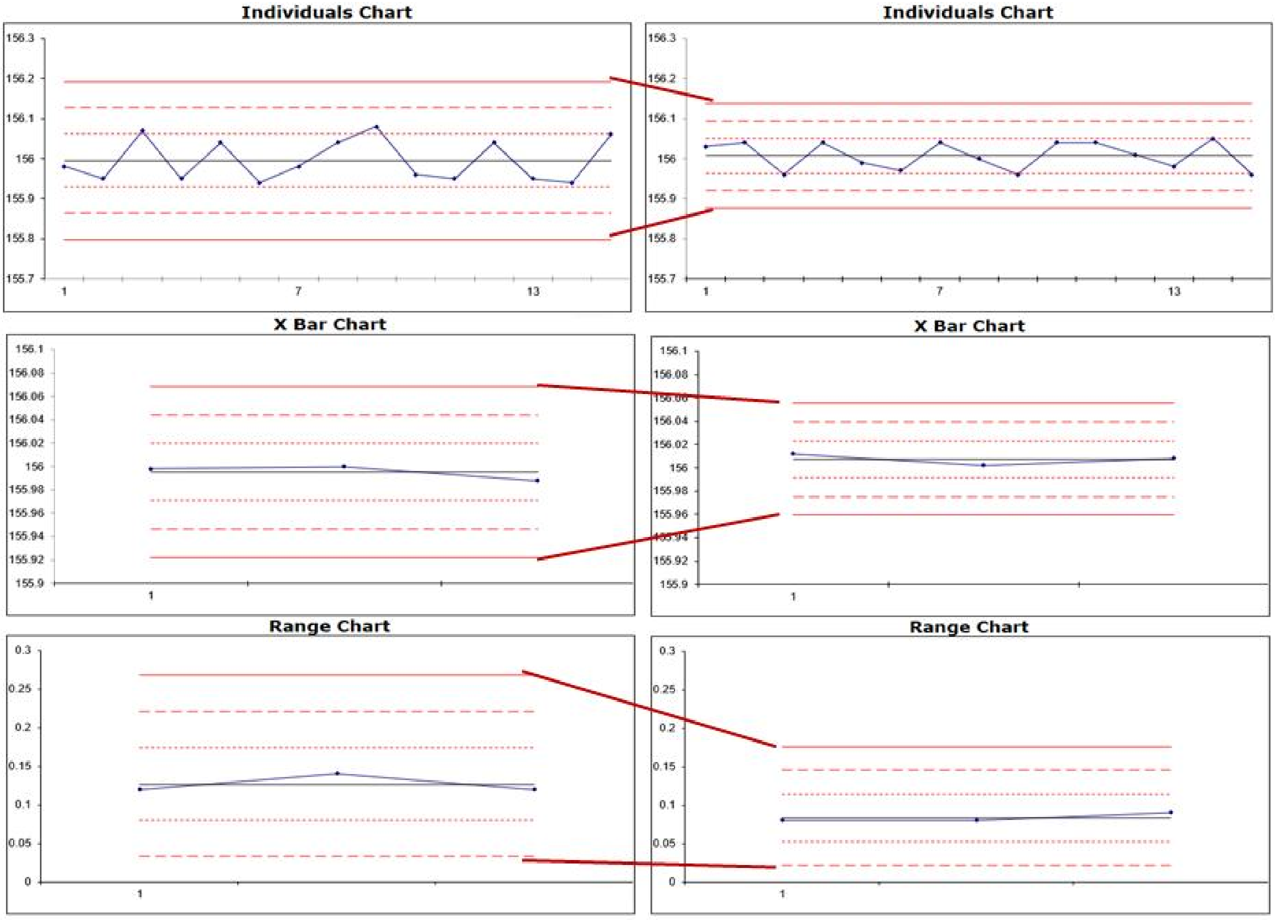
- **Defect (First-Time)** = 733,000 DPPM
- **Sigma Level (First-Time)** = 2.12 (D)
- **Defect (Rejected)** = 200,000 DPPM
- **Sigma Level (After-Rework)** = 2.34 (D)

After LSS

- **Defect (First-Time)** = Rework + Rejected = 3 / 15 = 20.0%
  - Rework = 3/15 = 20.0 %
  - Rejected = 0/15 = 0.0 %
- **Quality (First-Time)** = 80.0 %
- **Quality (After Rework)** = 100 %

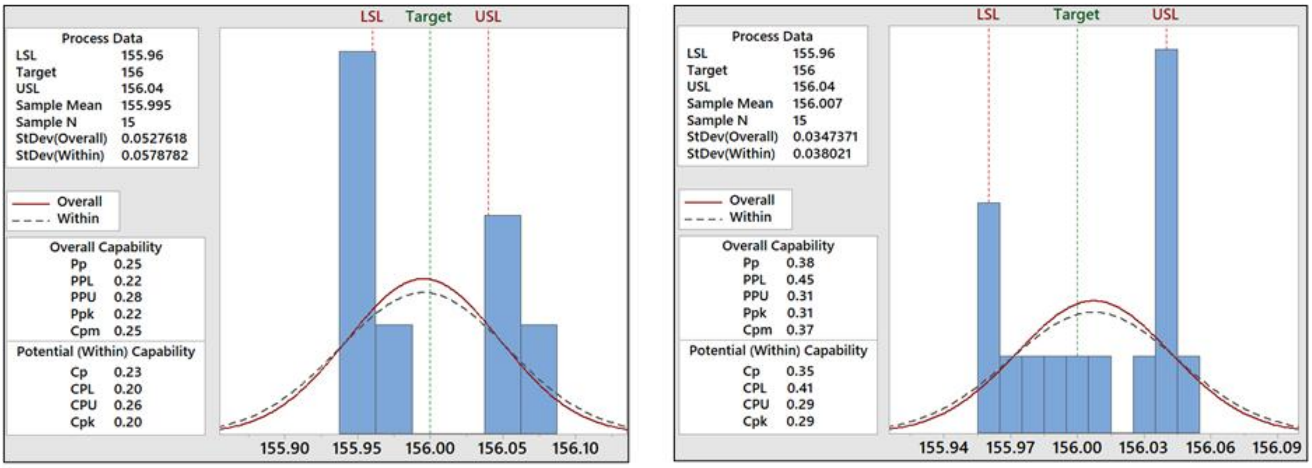
- **Defect (First-Time)** = 200,000 DPPM
- **Sigma Level (First-Time)** = 2.34 (D)
- **Defect (Rejected)** = 67,000 DPPM
- **Sigma Level (After-Rework)** = 6.0 (A+)

Figure 4. Sigma level analysis report (Before / After).



(Before) **(After)**

Figure 5. Process control charts first-time (Before / After).



(Before) **(After)**

Figure 6. Process capability first-time (Before / After).

Table 3. Main defect list for the machining process.

Defect Types		Total Defect #	Defect Risk
D1	Wrong Dimension	4	M
D2	Surface Burn	6	L
D3	Axis is not straight	2	L
D4	Porosity	3	M
D5	Bad Surface Finish	10	H
D6	Out-of-Roundness	2	M
D7	Surface Crack	1	H

Defect Risk (Rework time, Rework cost, … etc.): H:High, M:Medium, L:Low.

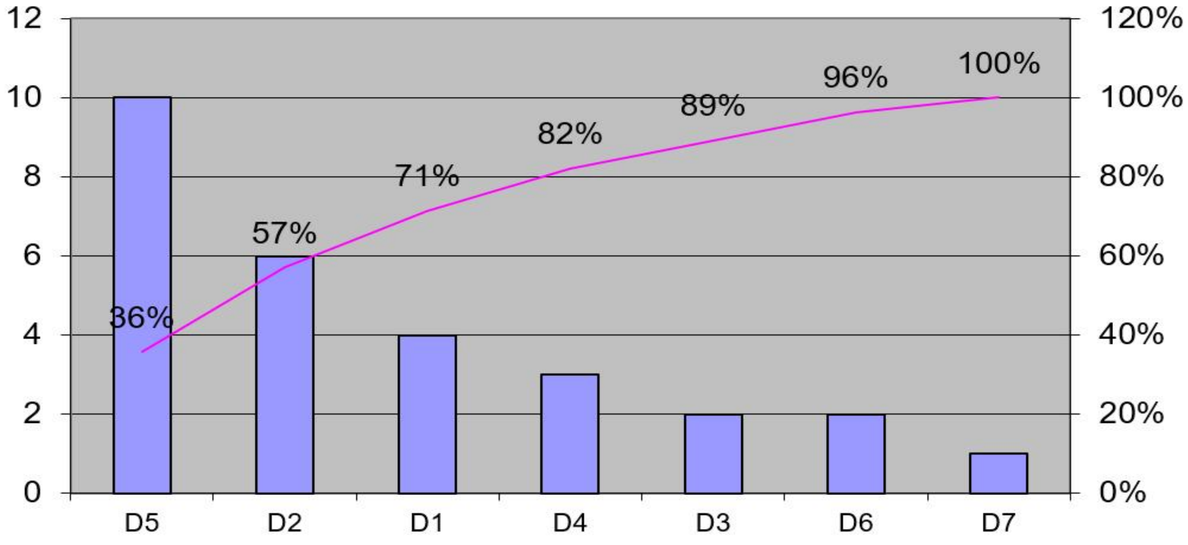


Figure 7. Pareto chart of defect types (Before improvement).

Table 4. ABC-HML classification

Product Defect %	A	D2	D1	D5
	B		D4	
	C	D3	D6	D7
		L	M	H
		Defect Risk (Rework time, Rework cost, … etc.)		

Criticality	VH	H	M	L	VL
Defect ID	D5	D1	D2, D4, D7	D6	D3
Control Level	Close	Max.	Medium	Low	Very Low

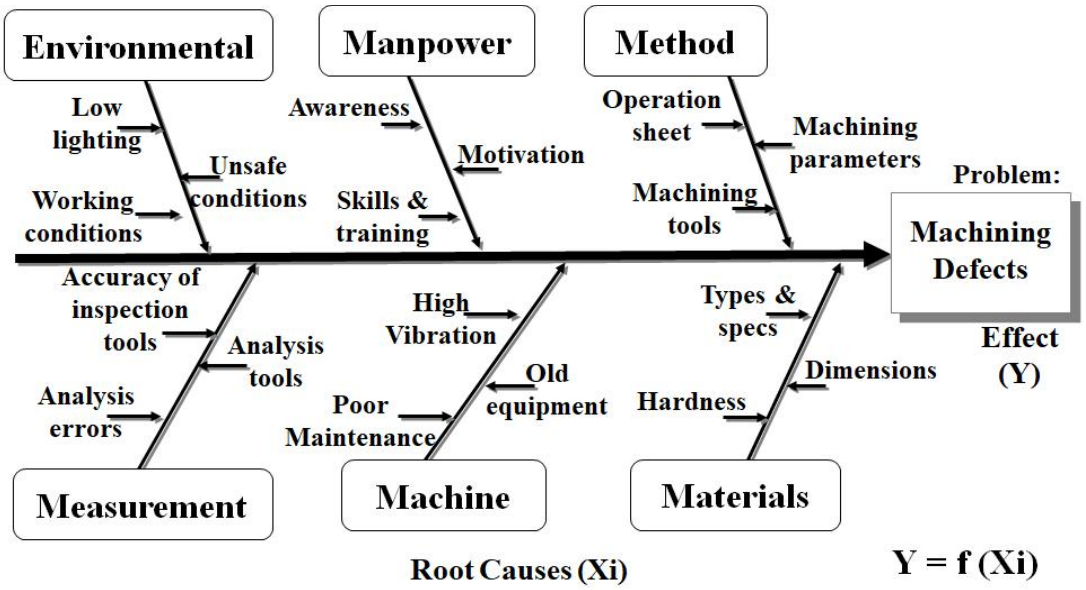


Figure 8. Fishbone diagram for machining defects.

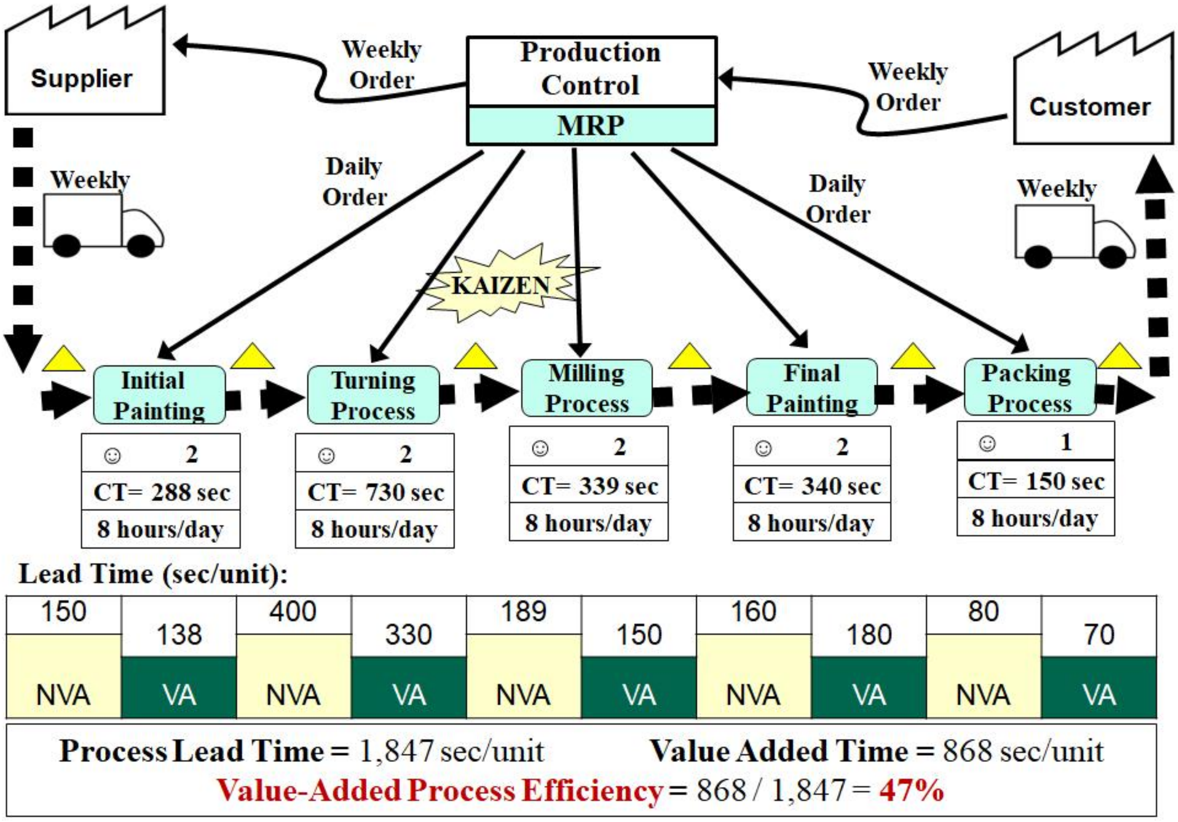


Figure 9. Value stream mapping (before improvement).

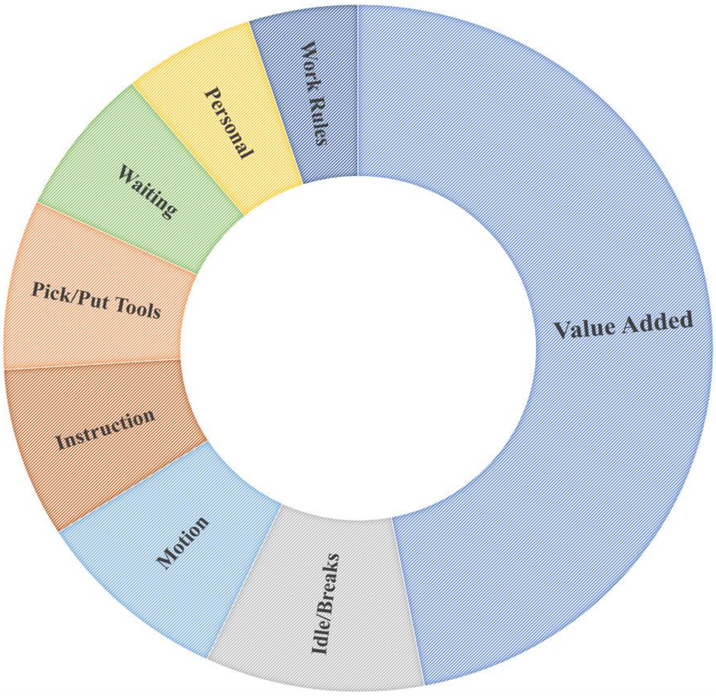


Figure 10. Value-added time analysis (before improvement).

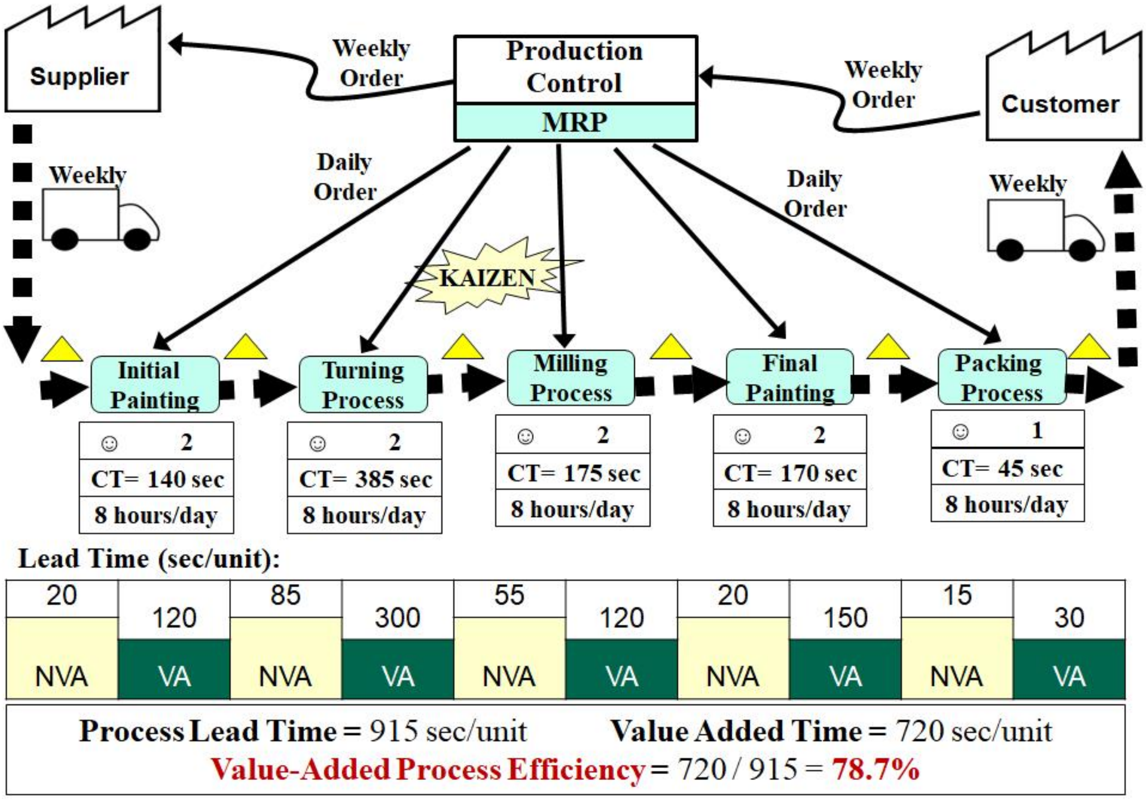


Figure 11. Value Stream Mapping (After 3 months of improvement).

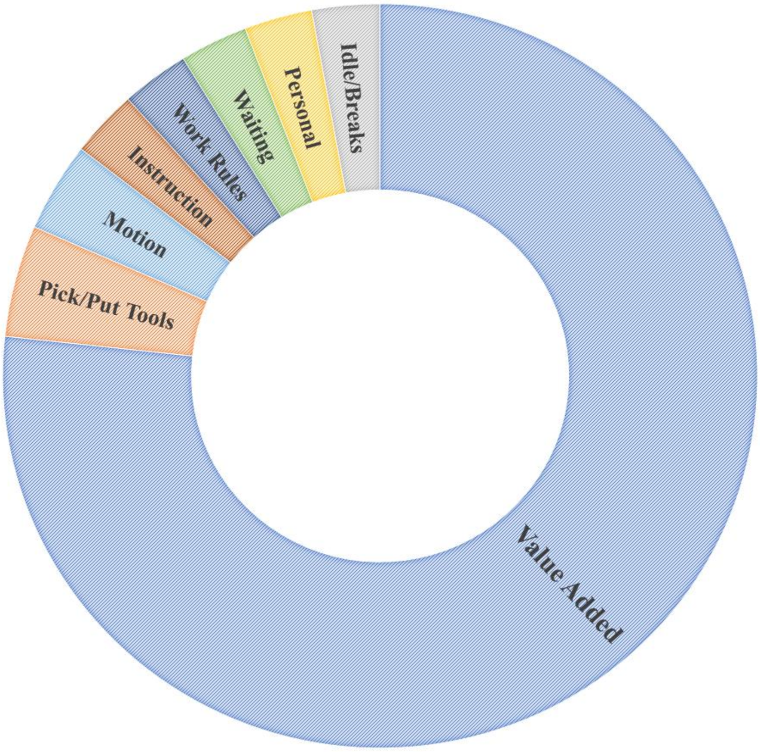


Figure 12. Value-Added Time Analysis (After 3 months of improvement).

5.2. Results and Analysis

Table 5 and Figure 13 summarize the performance improvements achieved over three months. The first-time quality rate rose from 26.7% to 80%, indicating a substantial reduction in initial defects and rework. Quality after rework reached 100%, confirming that all products met specifications following corrective interventions. Sigma levels improved from 2.12 to 2.34 for first-time quality and from 2.34 to 6.0 after rework, demonstrating enhanced process capability, reduced variability, and stronger process control.

Processing lead time was reduced from 1,847 to 915 seconds per unit, nearly halving the cycle time. This reduction highlights the framework's effectiveness in eliminating non-value-added activities, including idle time, redundant steps, and excessive handling. As a result, value-added process efficiency increased from 47% to 79%, indicating that a significantly larger portion of production time contributed directly to product value. These improvements enhanced throughput, optimized resource utilization, and strengthened overall operational performance.

The results validate the integrated Lean Six Sigma framework, which combines DMAIC methodology, ABC -HML defect classification, cause-and-effect analysis, and Value Stream Mapping (VSM). By systematically identifying critical defects, prioritizing improvement actions, and implementing targeted interventions—such as process parameter optimization, tool adjustments, and operator training—the framework achieved measurable and sustainable gains in quality, efficiency, and reliability.

Beyond immediate metrics, the findings highlight broader operational benefits. The structured, data-driven approach improved process stability, reduced variability, and created a foundation for continuous improvement. By linking analytical tools to actionable interventions, the framework offers a practical and scalable roadmap for long-term Manufacturing Excellence, enhancing both operational efficiency and competitive advantage.

The case study demonstrates that integrating multiple LSS tools provides a comprehensive approach to defect identification, prioritization, and waste elimination. By systematically addressing high-impact defects, continuously monitoring performance, and applying targeted interventions, the company achieved sustained improvements in quality, efficiency, and reliability. Furthermore, the study emphasizes the importance of structured data collection, cross-functional collaboration, and process visualization as essential enablers of Manufacturing Excellence.

Overall, these results confirm that Lean Six Sigma is not only a methodology for defect reduction but also a strategic approach for improving competitiveness and operational sustainability, delivering measurable, scalable, and long-term performance improvements.

Table 5. A summary of process performance indicators (Before and after improvement).

KPIs	Unit	Target	Before	After
1) Product quality (first time)	%	90	26.7	80
2) Product quality (after rework)	%	100	80	100
3) Sigma level (first time)	#	2.8	2.12	2.34
4) Sigma level (after rework)	#	6	2.34	6
5) Process lead time	sec. / unit	780	1847	915
6) Value-added process efficiency	%	90	47	79

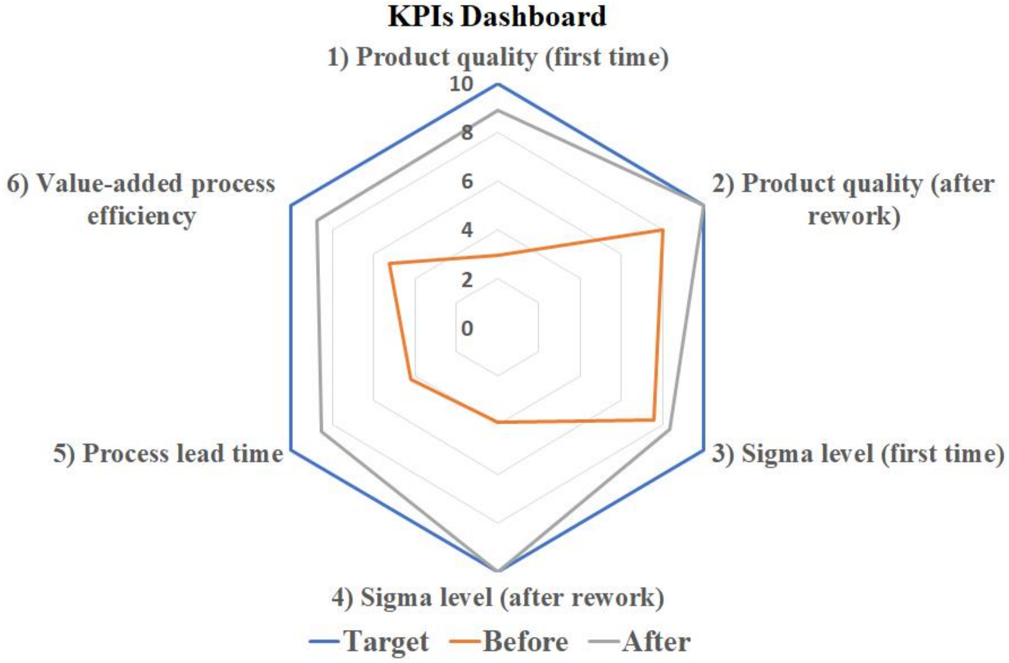


Figure 13. A summary of process performance indicators (Before and after improvement).

6. Conclusion and Future Work

This study highlights the critical role of Lean Six Sigma (LSS) in achieving Manufacturing Excellence, particularly in machining-intensive and automated production environments where variability, process complexity, and equipment sensitivity present major challenges. A systematic literature review from 2010 to 2026 identified persistent gaps in LSS implementation, including the lack of standardized frameworks, limited industrial validation, workforce skill shortages, and high resource requirements. These gaps restrict predictive optimization, hinder scalability, and reduce the sustainability of performance improvements, limiting LSS's potential to enhance operational efficiency, product quality, and competitiveness.

To address these challenges, a comprehensive LSS framework was developed, integrating the DMAIC methodology with five functional tool groups—strategic alignment, process analysis, quality optimization, reliability and maintenance, and continuous improvement. By systematically linking DMAIC phases, tool groups, and key performance indicators, the framework enables structured process optimization, continuous improvement, and data-driven decision-making, delivering measurable, scalable, and sustainable improvements across operational, strategic, cultural, and technological dimensions.

The framework was validated in a car spare parts manufacturer in Egypt, focusing on the NPR-Jumbo Isuzu drum brake. Over three months, first-time product quality increased from 26.7% to 80%, quality after rework reached 100%, sigma levels improved from 2.12 to 2.34 (first-time) and from 2.34 to 6.0 (after rework), and processing lead time decreased from 1,847 to 915 seconds per unit, raising value-added process efficiency from 47% to 79%. These results confirm that a structured LSS framework can substantially enhance process capability, product quality, and operational efficiency, providing a practical, adaptive roadmap for sustainable Manufacturing Excellence.

Theoretical Implications: The study contributes to LSS literature by presenting a structured, integrated framework that addresses gaps in standardization, scalability, and industrial validation, offering a foundation for systematic LSS implementation in complex manufacturing environments.

Practical Implications: The framework provides practitioners with actionable guidance to identify inefficiencies, optimize processes, reduce defects, and achieve measurable performance improvements in highly variable and automated production settings.

Managerial Implications: Managers can use the framework to prioritize improvement initiatives, allocate resources effectively, and foster a culture of continuous improvement, supported by clear, evidence-based performance metrics.

Study Limitations: This study is based on a single case in a car spare parts manufacturer, limiting generalizability. The implementation period was short, and long-term effects were not assessed. Further validation across diverse industries and production contexts is recommended.

Future Research Directions: Future research should test the framework in different manufacturing sectors to assess generalizability and long-term sustainability. Studies could explore workforce training, change management strategies, advanced process monitoring, and broader organizational impacts such as cost reduction, efficiency gains, and supply chain performance. Comparative analyses of different LSS implementations could identify best practices and support scalable, context-specific operational excellence strategies.

Conflicts of Interest

The authors declare no conflicts of interest.

Generative Artificial Intelligence Statement

The authors used the free version of ChatGPT to refine the writing quality of some paragraphs. No generative artificial intelligence (GenAI) was used in creating the manuscript content.

Data Availability Statement

Data supporting this study are included within the article.

Abbreviations

Abbreviation	Full Term	Short Definition
5S	Sort, Set in Order, Shine, Standardize, Sustain	Workplace organization and efficiency
CI	Continuous Improvement	Ongoing process enhancements
CTQ	Critical to Quality	Key quality requirements
DMADV	Define, Measure, Analyze, Design, Verify	Six Sigma design method
DMAIC	Define, Measure, Analyze, Improve, Control	Process improvement framework
DOE	Design of Experiments	Statistical process optimization
FMEA	Failure Mode and Effects Analysis	Identify and prevent failures
Gage R&R	Gage Repeatability and Reproducibility	Measurement system accuracy
JIT	Just-In-Time	Produce only as needed
KPIs	Key Performance Indicators	Performance measurement metrics
LSS	Lean Six Sigma	Lean and Six Sigma methodology
OEE	Overall Equipment Effectiveness	Equipment productivity measure
PDCA	Plan-Do-Check-Act	Iterative improvement cycle
RCA	Root Cause Analysis	Identify underlying causes
RCM	Reliability-Centered Maintenance	Maintenance based on equipment criticality

Abbreviation	Full Term	Short Definition
SIPOC	Suppliers, Inputs, Process, Outputs, Customers	High-level process mapping
SOP	Standard Operating Procedure	Documented standard work instructions
SPC	Statistical Process Control	Monitor and control variation
SWOT	Strengths, Weaknesses, Opportunities, Threats	Strategic analysis tool
Takt	Takt Time	Production rate to meet demand
TPM	Total Productive Maintenance	Maximize equipment performance
TQM	Total Quality Management	Organization-wide quality focus
VOC	Voice of Customer	Capture customer needs and feedback
VSM	Value Stream Mapping	Visualize process flows and waste

References

[1] Gomaa, A.H., 2025. Optimizing Machining Process Performance Using Lean Six Sigma: A Case Study. Transnational Supply Chain Research, 1(1), pp.52-81.

[2] Gayratovna, R.D., 2026. International experience in increasing production efficiency and possibilities of its applicability In London International Monthly Conference on Multidisciplinary Research and Innovation (LIMCMRI) (Vol. 3, No. 2, pp. 141-144).

[3] Antony, J., Setijono, D. and Dahlgaard, J.J., 2016. Lean Six Sigma and Innovation–an exploratory study among UK organisations. Total Quality Management & Business Excellence, 27(1-2), pp.124-140.

[4] Alhuraish, I., Robledo, C. and Kobi, A., 2017. A comparative exploration of lean manufacturing and six sigma in terms of their critical success factors. Journal of cleaner production, 164, pp.325-337.

[5] Adeodu, A., Kanakana-Katumba, M.G. and Rendani, M., 2021. Implementation of Lean Six Sigma for production process optimization in a paper production company. Journal of Industrial Engineering and Management, 14(3), pp.661-680.

[6] Gomaa, A.H., 2022. Improving manufacturing efficiency and effectiveness using lean six sigma approach. International Journal of Technology and Engineering Studies, 8(1), pp. 22-33.

[7] Afandi, M. and Hermansyah, M., 2026. Implementation of Product Quality Improvement Using the Six Sigma Method (DMAIC) to Minimize Defects in the Reusable Diaper Industry. Journal La Sociale, 7(1), pp.149-165.

[8] Heckl, D., Moormann, J. and Rosemann, M., 2010. Uptake and success factors of Six Sigma in the financial services industry. Business process management journal, 16(3), pp.436-472.

[9] Jeyaraman, K. and Kee Teo, L., 2010. A conceptual framework for critical success factors of lean Six Sigma: Implementation on the performance of electronic manufacturing service industry. International Journal of Lean Six Sigma, 1(3), pp.191-215.

[10] Raja Sreedharan, V. and Raju, R.J.I.J., 2016. A systematic literature review of Lean Six Sigma in different industries. International Journal of Lean Six Sigma, 7(4), pp.430-466.

[11] Antony, J., Snee, R. and Hoerl, R., 2017. Lean Six Sigma: yesterday, today and tomorrow. International Journal of Quality & Reliability Management, 34(7), pp.1073-1093.

[12] Omoush, M.M., 2020. Lean six sigma effect on the quality of the products in Jordanian food companies: the moderating role of the manufacturing process. International Review of Management and Marketing, 10(6), p.1.

[13] Gomaa, A.H., 2023b. Operational Excellence for Improving Manufacturing Performance Using Lean Six Sigma. International Journal of Business and Administrative Studies, 9(2), p.1.

[14] Hossain, A., Khan, M.R., Islam, M.T. and Islam, K.S., 2024. Analyzing the impact of combining Lean Six Sigma methodologies with sustainability goals. Journal of Science and Engineering Research, 1(01), pp.123-144.

[15] Ciasullo, M.V., Douglas, A., Romeo, E. and Capolupo, N., 2024. Lean Six Sigma and quality performance in Italian public and private hospitals: a gender perspective. International Journal of Quality & Reliability Management, 41(3), pp.964-989.

[16] Gomaa, A.H., 2023a. A systematic review of lean six sigma in manufacturing domain. Engineering Research Journal (Shoubra), 52(4), pp.139-148.

[17] Karthi, S., Devadasan, S.R. and Murugesh, R., 2011. Integration of Lean Six-Sigma with ISO 9001:2008 standard. International Journal of Lean Six Sigma, 2(4), pp.309-331.

[18] Aramoon, V., Aramoon, E. and Bazrkar, A., 2020. Investigating the effect of implementing the lean six sigma on organizational performance based on the mediating role of strategic knowledge management with structural equation modeling approach. Navus-Revista de Gestão e Tecnologia, 10, pp.01-16.

[19] Omisola, J.O., Shiyanbola, J.O. and Osho, G.O., 2024. A predictive quality assurance model using lean six sigma: Integrating FMEA. SPC, and root cause analysis for zero-defect production systems.

[20] Yang, K., Wu, Q. and Cormican, K., 2025. From the Great Wall to great workflow: lean six sigma in Chinese listed companies. International Journal of Lean Six Sigma, 16(4), pp.946-971.

[21] Gulyaz, E., Venugopal, V., van der Veen, J.A. and van Gorp, D.M., 2013, June. Decision support framework for estimating return on lean six sigma projects. In 20th EurOMA conference, Dublin, Ireland.

[22] Amjad, M.H.H., Shovon, M.S.S. and Hasan, A.S.M.M., 2024. Analyzing Lean Six Sigma practices in engineering project management: A comparative analysis. Innovatech Engineering Journal, 1(01), pp.245-255.

[23] Trakulsunti, Y., Antony, J. and Douglas, J.A., 2020. Lean Six Sigma implementation and sustainability roadmap for reducing medication errors in hospitals. The TQM Journal, 33(1), pp.33-55.

[24] Yaduvanshi, D. and Sharma, A., 2017. Lean six sigma in health operations: challenges and opportunities—'Nirvana for operational efficiency in hospitals in a resource limited settings'. Journal of Health Management, 19(2), pp.203-213.

[25] Vashishth, A., Chakraborty, A. and Antony, J., 2019. Lean Six Sigma in financial services industry: a systematic review and agenda for future research. Total Quality Management & Business Excellence, 30(3-4), pp.447-465.

[26] Gholami, H., Jamil, N., Mat Saman, M.Z., Streimikiene, D., Sharif, S. and Zakuan, N., 2021. The application of green lean six sigma. Business Strategy and the Environment, 30(4), pp.1913-1931.

[27] Timans, W., Antony, J., Ahaus, K. and van Solingen, R., 2012. Implementation of Lean Six Sigma in small-and medium-sized manufacturing enterprises in the Netherlands. Journal of the Operational Research Society, 63(3), pp.339-353.

[28] Timans, W., Ahaus, K., van Solingen, R., Kumar, M. and Antony, J., 2016. Implementation of continuous improvement based on Lean Six Sigma in small-and medium-sized enterprises. Total Quality Management & Business Excellence, 27(3-4), pp.309-324.

[29] Daniyan, I., Adeodu, A., Mpofu, K., Maladzhi, R. and Katumba, M.G.K.K., 2022. Application of lean Six Sigma methodology using DMAIC approach for the improvement of bogie assembly process in the railcar industry. Heliyon, 8(3).

[30] Wu, Q., Zhou, Q. and Cormican, K., 2024. Promoting shared leadership in Lean Six Sigma project teams: toward a three-way interaction model. International Journal of Lean Six Sigma, 15(3), pp.642-663.

[31] Irfan, M.T.H., Rafiquzzaman, M. and Manik, Y.A., 2025. Productivity improvement through lean tools in cement industry–A case study. Heliyon, 11(3).

[32] Adikorley, R.D., Rothenberg, L. and Guillory, A., 2017. Lean Six Sigma applications in the textile industry: a case study. International journal of lean six sigma, 8(2), pp.210-224.

[33] Afandi, M. and Hermansyah, M., 2026. Implementation of Product Quality Improvement Using the Six Sigma Method (DMAIC) to Minimize Defects in the Reusable Diaper Industry. Journal La Sociale, 7(1), pp.149-165.

[34] Condé, G.C.P., Oprime, P.C., Pimenta, M.L., Sordan, J.E. and Bueno, C.R., 2023. Defect reduction using DMAIC and Lean Six Sigma: a case study in a manufacturing car parts supplier. International Journal of Quality & Reliability Management, 40(9), pp.2184-2204.

[35] Habidin, N.F. and Yusof, S.M., 2012. Relationship between lean six sigma, environmental management systems, and organizational performance in the Malaysian automotive industry. International Journal of Automotive Technology, 13(7), pp.1119-1125.

[36] Enoch, O.K., 2013. Lean six sigma methodologies and organizational profitability: a review of manufacturing SMEs in Nigeria. American Journal of Industrial and Business Management, 3(6), pp.573-582.

[37] Fullerton, R.R., Kennedy, F.A. and Widener, S.K., 2014. Lean manufacturing and firm performance: The incremental contribution of lean management accounting practices. Journal of Operations Management, 32(7-8), pp.414-428.

[38] Dora, M. and Gellynck, X., 2015. Lean Six Sigma implementation in a food processing SME: a case study. Quality and Reliability Engineering International, 31(7), pp.1151-1159.

[39] Kumar, R. and Kumar, V., 2016. Effect of lean manufacturing on organisational performance of Indian industry: a survey. International Journal of Productivity and Quality Management, 17(3), pp.380-393.

[40] Habidin, N.F., Mohd Yusof, S.R. and Mohd Fuzi, N., 2016. Lean Six Sigma, strategic control systems, and organizational performance for automotive suppliers. International Journal of Lean Six Sigma, 7(2), pp.110-135.

[41] Olutade, O., Adeyinka, A.M. and Durodola, O., 2023. Exploring lean six sigma: A comprehensive review of methodology and its role in business improvement. International Journal of Multidisciplinary Research and Growth Evaluation, 4(6), pp.939-947.

[42] Sim, C.L., Li, Z., Chuah, F., Lim, Y.J. and Sin, K.Y., 2022. An empirical investigation of the role of lean six sigma practices on quality performance in medical device manufacturing industry. International Journal of Lean Six Sigma, 13(3), pp.671-691.

[43] Sim, C.L., Li, Z., Chuah, F., Lim, Y.J. and Sin, K.Y., 2022. An empirical investigation of the role of lean six sigma practices on quality performance in medical device manufacturing industry. International Journal of Lean Six Sigma, 13(3), pp.671-691.

[44] Dara, H.M., Raut, A., Adamu, M., Ibrahim, Y.E. and Ingle, P.V., 2024. Reducing non-value added (NVA) activities through lean tools for the precast industry. Heliyon, 10(7).

[45] Gomaa, A.H., 2026. Achieving operational excellence in manufacturing supply chains using lean six sigma: a case study approach. International Journal of Lean Six Sigma, 17(2), pp.614-648.

[46] Huang, J., Irfan, M., Fatima, S.S. and Shahid, R.M., 2023. The role of lean six sigma in driving sustainable manufacturing practices: an analysis of the relationship between lean six sigma principles, data-driven decision making, and environmental performance. Frontiers in Environmental Science, 11, p.1184488.

[47] Belhadi, A., Kamble, S.S., Zkik, K., Cherrafi, A. and Touriki, F.E., 2020. The integrated effect of Big Data Analytics, Lean Six Sigma and Green Manufacturing on the environmental performance of manufacturing companies: The case of North Africa. Journal of Cleaner Production, 252, p.119903.

[48] Tucci, H.N.P., de Oliveira Neto, G.C., Rodrigues, F.L., Giannetti, B.F. and de Almeida, C.M.V.B., 2021. Six sigma with the blue economy fundamentals to assess the economic and environmental performance in the aircraft refueling process. Renewable and Sustainable Energy Reviews, 150, p.111424.

[49] Dorval, M., Jobin, M.H. and Benomar, N., 2019. Lean culture: a comprehensive systematic literature review. International Journal of Productivity and Performance Management, 68(5), pp.920-937.

[50] Duggan, J., Cormican, K. and McDermott, O., 2023. Lean implementation: analysis of individual-level factors in a biopharmaceutical organisation. International Journal of Lean Six Sigma, 14(2), pp.309-334.

[51] Hoerl, R.W. and Gardner, M.M., 2010. Lean Six Sigma, creativity, and innovation. International Journal of Lean Six Sigma, 1(1), pp.30-38.

[52] Sreedharan V, R. and Sunder M, V., 2018. A novel approach to lean six sigma project management: a conceptual framework and empirical application. Production Planning & Control, 29(11), pp.895-907.

[53] Raval, S.J., Kant, R. and Shankar, R., 2020. Analyzing the Lean Six Sigma enabled organizational performance to enhance operational efficiency. Benchmarking: An International Journal, 27(8), pp.2401-2434.

[54] Shrafat, F.D. and Ismail, M., 2019. Structural equation modeling of lean manufacturing practices in a developing country context. Journal of Manufacturing Technology Management, 30(1), pp.122-145.

[55] Achibat, F.E., Lebkiri, A., Lougraimzi, H., Berrid, N. and Maqboul, A., 2023. Analysis of the impact of Six Sigma and Lean Manufacturing on the performance of companies. Management Systems in Production Engineering, 31(2), pp.191-196.

[56] Gomaa, A.H., 2024. Improving productivity and quality of a machining process by using lean six sigma approach: A case study. Engineering Research Journal (Shoubra), 53(1), pp.1-16.

[57] Marques, P., Requeijo, J., Saraiva, P. and Frazão-Guerreiro, F., 2013. Integrating six sigma with ISO 9001. International Journal of Lean Six Sigma, 4(1), pp.36-59.

[58] Goshime, Y., Kitaw, D. and Jilcha, K., 2019. Lean manufacturing as a vehicle for improving productivity and customer satisfaction: A literature review on metals and engineering industries. International Journal of Lean Six Sigma, 10(2), pp.691-714.

[59] Singh, J., Singh, H. and Singh, G., 2018. Productivity improvement using lean manufacturing in manufacturing industry of Northern India: A case study. International Journal of Productivity and Performance Management, 67(8), pp.1394-1415.

[60] El-Khalil, R., Leffakis, Z.M. and Hong, P.C., 2020. Impact of improvement tools on standardization and stability goal practices: An empirical examination of US automotive firms. Journal of Manufacturing Technology Management, 31(4), pp.705-723.

[61] Gupta, S. and Jain, S.K., 2013. A literature review of lean manufacturing. International journal of management science and engineering management, 8(4), pp.241-249.

[62] Resta, B., Dotti, S., Gaiardelli, P. and Boffelli, A., 2016, September. Lean manufacturing and sustainability: an integrated view. In IFIP International conference on advances in production management systems (pp. 659-666). Cham: Springer International Publishing.

[63] Saenagri, A., Usman, O. and Ishak, G., 2023. Implementation of Total Productive Maintenance and Lean Manufacturing in the Pharmaceutical Industry: An Empirical Study. Journal of Business and Management Studies, 5(3), p.114.

[64] Yang, M.G.M., Hong, P. and Modi, S.B., 2011. Impact of lean manufacturing and environmental management on business performance: An empirical study of manufacturing firms. International Journal of production economics, 129(2), pp.251-261.

[65] Dieste, M., Panizzolo, R., Garza-Reyes, J.A. and Anosike, A., 2019. The relationship between lean and environmental performance: Practices and measures. Journal of Cleaner Production, 224, pp.120-131.

[66] Dieste, M., Panizzolo, R. and Garza-Reyes, J.A., 2021. A systematic literature review regarding the influence of lean manufacturing on firms' financial performance. Journal of Manufacturing Technology Management, 32(9), pp.101-121.

[67] Shi, Y., Wang, X. and Zhu, X., 2020. Lean manufacturing and productivity changes: the moderating role of R&D. International Journal of Productivity and Performance Management, 69(1), pp.169-191.

[68] Belekoukias, I., Garza-Reyes, J.A. and Kumar, V., 2014. The impact of lean methods and tools on the operational performance of manufacturing organisations. International Journal of production research, 52(18), pp.5346-5366.

[69] Carney, M., Zhao, J. and Zhu, L., 2019. Lean innovation: Family firm succession and patenting strategy in a dynamic institutional landscape. Journal of Family Business Strategy, 10(4), p.100247.

[70] Nallusamy, S., 2016. Lean manufacturing implementation in a gear shaft manufacturing company using value stream mapping. International Journal of Engineering Research in Africa, 21, pp.231-237.

[71] Negrão, L.L.L., Lopes de Sousa Jabbour, A.B., Latan, H., Godinho Filho, M., Chiappetta Jabbour, C.J. and Ganga, G.M.D., 2020. Lean manufacturing and business performance: testing the S-curve theory. Production Planning & Control, 31(10), pp.771-785.

[72] Ardiansyah, S., Prabowo, R. and Hadi, S., 2026. Analysis of Lean Manufacturing and Agile Manufacturing Implementation to Reduce Waste and Improve Productivity in Crankshaft Repair Production (Case Study: PT. Intidaya Dinamika Sejati–Jember). Jurnal Teknologi dan Manajemen, 7(1), pp.22-30.

[73] Arumugam, V., Antony, J. and Kumar, M., 2013. Linking learning and knowledge creation to project success in Six Sigma projects: An empirical investigation. International Journal of Production Economics, 141(1), pp.388-402.

[74] Trimarjoko, A., Hardi Purba, H. and Nindiani, A., 2020. Consistency of DMAIC phases implementation on Six Sigma method in manufacturingand service industry: a literature review. Management and Production Engineering Review.

[75] Desai, D.A., Antony, J. and Patel, M.B., 2012. An assessment of the critical success factors for Six Sigma implementation in Indian industries. International Journal of productivity and performance management, 61(4), pp.426-444.

[76] Gupta, V., Jain, R., Meena, M.L. and Dangayach, G.S., 2018. Six-sigma application in tire-manufacturing company: a case study. Journal of Industrial Engineering International, 14(3), pp.511-520.

[77] Jirasukprasert, P., Arturo Garza-Reyes, J., Kumar, V. and K. Lim, M., 2014. A Six Sigma and DMAIC application for the reduction of defects in a rubber gloves manufacturing process. International journal of lean six sigma, 5(1), pp.2-21.

[78] Patel, M. and Desai, D.A., 2018. Critical review and analysis of measuring the success of Six Sigma implementation in manufacturing sector. International Journal of Quality & Reliability Management, 35(8), pp.1519-1545.

[79] Zhang, M., Wang, W., Goh, T.N. and He, Z., 2015. Comprehensive Six Sigma application: a case study. Production Planning & Control, 26(3), pp.219-234.

[80] Sutphin, P.D., Reis, S.P., McKune, A., Ravanzo, M., Kalva, S.P. and Pillai, A.K., 2015. Improving inferior vena cava filter retrieval rates with the define, measure, analyze, improve, control methodology. Journal of Vascular and Interventional Radiology, 26(4), pp.491-498.

[81] Gaikwad, L.M., Teli, S.N., Majali, V.S. and Bhushi, U.M., 2016. An application of Six Sigma to reduce supplier quality cost. Journal of The Institution of Engineers (India): Series C, 97(1), pp.93-107.

[82] He, Z., Deng, Y., Zhang, M., Zu, X. and Antony, J., 2017. An empirical investigation of the relationship between Six Sigma practices and organisational innovation. Total Quality Management & Business Excellence, 28(5-6), pp.459-480.

[83] Furlan, A., Dal Pont, G. and Vinelli, A., 2011. On the complementarity between internal and external just-in-time bundles to build and sustain high performance manufacturing. International Journal of Production Economics, 133(2), pp.489-495.

[84] Antony, J., Swarnakar, V., Cudney, E. and Pepper, M., 2022. A meta-analytic investigation of lean practices and their impact on organisational performance. Total Quality Management & Business Excellence, 33(15-16), pp.1799-1825.

[85] Subramaniyam, P., Srinivasan, K. and Prabaharan, M., 2011. An innovative lean six sigma approach for engineering design. International Journal of Innovation, Management and Technology, 2(2), p.166.

[86] Stoiljkovic, V., Milosavljevic, P., Mladenovic, S., Pavlovic, D. and Todorovic, M., 2014. Improving the Efficiency of the Center for Medical Biochemistry, Clinical Center NiS, by Applying Lean Six Sigma Methodology. Journal of medical biochemistry, 33(3), p.299.

[87] Assarlind, M., Gremyr, I. and Bäckman, K., 2012. Multi-faceted views on a Lean Six Sigma application. International Journal of Quality & Reliability Management, 29(1), pp.21-30.

[88] Albliwi, S.A., Antony, J. and Lim, S.A.H., 2015. A systematic review of Lean Six Sigma for the manufacturing industry. Business process management journal, 21(3), pp.665-691.

[89] Alkunsol, W.H., Sharabati, A.A.A., AlSalhi, N.A. and El-Tamimi, H.S., 2019. Lean Six Sigma effect on Jordanian pharmaceutical industry’s performance. International Journal of Lean Six Sigma, 10(1), pp.23-43.

[90] Furterer, S. and Elshennawy, A.K., 2005. Implementation of TQM and lean Six Sigma tools in local government: a framework and a case study. Total Quality Management & Business Excellence, 16(10), pp.1179-1191.

[91] Patel, A.S. and Patel, K.M., 2021. Critical review of literature on Lean Six Sigma methodology. International Journal of Lean Six Sigma, 12(3), pp.627-674.

[92] Costa, L.B.M., Godinho Filho, M., Fredendall, L.D. and Ganga, G.M.D., 2020. The effect of Lean Six Sigma practices on food industry performance: Implications of the Sector's experience and typical characteristics. Food Control, 112, p.107110.

[93] Swarnakar, V., Singh, A.R. and Tiwari, A.K., 2021. Effect of lean six sigma on firm performance: A case of Indian automotive component manufacturing organization. Materials Today: Proceedings, 46, pp.9617-9622.

[94] Oprime, P.C., Pimenta, M.L., Jugend, D. and Andersson, R., 2021. Financial impacts of innovation in Six Sigma projects. Total Quality Management & Business Excellence, 32(7-8), pp.829-851.

[95] Dorval, M., Jobin, M.H. and Benomar, N., 2019. Lean culture: a comprehensive systematic literature review. International Journal of Productivity and Performance Management, 68(5), pp.920-937.

[96] Angelis, J., Conti, R., Cooper, C. and Gill, C., 2011. Building a high-commitment lean culture. Journal of Manufacturing Technology Management, 22(5), pp.569-586.

[97] Ha, C., McCoy, D.A., Taylor, C.B., Kirk, K.D., Fry, R.S. and Modi, J.R., 2016. Using lean six sigma methodology to improve a mass immunizations process at the United States naval academy. Military medicine, 181(6), pp.582-588.

[98] Zhu, X. and Lin, Y., 2017. Does lean manufacturing improve firm value?. Journal of Manufacturing Technology Management, 28(4), pp.422-437.

[99] Parast, M.M., 2011. The effect of Six Sigma projects on innovation and firm performance. International Journal of Project Management, 29(1), pp.45-55.

[100] Duggan, J., Cormican, K. and McDermott, O., 2023. Lean implementation: analysis of individual-level factors in a biopharmaceutical organisation. International Journal of Lean Six Sigma, 14(2), pp.309-334.

[101] O'Connor , D. and Cormican, K., 2022. Leading from the middle: how team leaders implement lean success factors. International Journal of Lean six sigma, 13(2), pp.253-275.

[102] Hoerl, R.W. and Gardner, M.M., 2010. Lean Six Sigma, creativity, and innovation. International Journal of Lean Six Sigma, 1(1), pp.30-38.

[103] Lertwattanapongchai, S. and William Swierczek, F., 2014. Assessing the change process of Lean Six Sigma: a case analysis. International Journal of Lean Six Sigma, 5(4), pp.423-443.

[104] Hanoosh, J.A.A. and Kowang, T.O., 2023. The fundamental concept of integrates lean six sigma and dmadv methodologies. International Journal of Academic Research in Business and Social Sciences, 13(10), pp.1027-1040.

[105] Ghobakhloo, M. and Hong, T.S., 2014. IT investments and business performance improvement: the mediating role of lean manufacturing implementation. International Journal of Production Research, 52(18), pp.5367-5384.

[106] Sarwar, J., Khan, A.A., Khan, A., Hasnain, A., Arafat, S.M., Ali, H.U., Uddin, G.M., Sosnowski, M. and Krzywanski, J., 2022. Impact of stakeholders on Lean Six Sigma project costs and outcomes during implementation in an air-conditioner manufacturing industry. Processes, 10(12), p.2591.

[107] Sarkis, J., Zhu, Q. and Lai, K.H., 2011. An organizational theoretic review of green supply chain management literature. International journal of production economics, 130(1), pp.1-15.

[108] Stoiljkovic, V., Milosavljevic, P., Mladenovic, S., Pavlovic, D. and Todorovic, M., 2014. Improving the Efficiency of the Center for Medical Biochemistry, Clinical Center NiS, by Applying Lean Six Sigma Methodology. Journal of medical biochemistry, 33(3), p.299.

[109] Thakur, V., Akerele, O.A., Brake, N., Wiscombe, M., Broderick, S., Campbell, E. and Randell, E., 2023. Use of a Lean Six Sigma approach to investigate excessive quality control (QC) material use and resulting costs. Clinical Biochemistry, 112, pp.53-60.

[110] Widiwati, I.T.B., Liman, S.D. and Nurprihatin, F., 2025. The implementation of Lean Six Sigma approach to minimize waste at a food manufacturing industry. Journal of Engineering Research, 13(2), pp.611-626

[111] Setyabudhi, A.L. and Sipahutar, I., 2019, May. Application Of Six Sigma Methodology To Improve the Product Quality Of Moldings Plastic (Case Study: PT Mega Technology Batam). In IOP Conference Series: Materials Science and Engineering (Vol. 505, No. 1, p. 012067). IOP Publishing.

[112] Yamamoto, J., Abraham, D. and Malatestinic, B., 2010. Improving insulin distribution and administration safety using lean six sigma methodologies. Hospital Pharmacy, 45(3), pp.212-224.

[113] Daly, A., Teeling, S.P., Ward, M., McNamara, M. and Robinson, C., 2021. The use of lean six sigma for improving availability of and access to emergency department data to facilitate patient flow. International Journal of Environmental Research and Public Health, 18(21), p.11030.

[114] Delgado, C., Ferreira, M. and Castelo Branco, M., 2010. The implementation of lean Six Sigma in financial services organizations. Journal of Manufacturing Technology Management, 21(4), pp.512-523.

[115] Ashok Sarkar, S., Ranjan Mukhopadhyay, A. and Ghosh, S.K., 2013. Improvement of claim processing cycle time through Lean Six Sigma methodology. International journal of lean six sigma, 4(2), pp.171-183.

[116] Mamoojee-Khatib, H., Antony, J., Teeroovengadum, V., Garza-Reyes, J.A., Tortorella, G.L., Foster, M. and Cudney, E.A., 2025. A systematic review of lean implementation frameworks and roadmaps: lessons learned and the way forward. The TQM Journal, 37(1), pp.264-287.

[117] Alsadi, J., Antony, J., Goonetilleke, R., Romero, D., Chiarini, A., Tortorella, G. and Maalouf, M., 2025. A qualitative global study on the digitalization of Lean Six Sigma: insights from scholars and practitioners. Production Planning & Control, pp.1-31.

[118] Pongboonchai-Empl, T., Antony, J., Garza-Reyes, J.A., Tortorella, G.L., Komkowski, T. and Stemann, D., 2025. DMAIC 4.0-innovating the Lean Six Sigma methodology with Industry 4.0 technologies. Production Planning & Control, pp.1-22.

[119] Jalal, S.S. and Rosli, M.H., 2025, July. Lean Six Sigma Implementation and its Challenges in Malaysian Plantation Company. In 9th Terengganu International Business and Economics Conference 2025 (TiBEC IX 2025) (pp. 37-49). Atlantis Press.

[120] Gomaa, A.H., 2026. Supply Chain Risk Management for Sustainable and Resilient Operations: A Comprehensive Review and Strategic Framework in the Era of Industry 4.0-5.0. Transnational Supply Chain Research, 2(1), pp.1-23.

[121] Wu, S.J., Melnyk, S.A. and Flynn, B.B., 2010. Operational capabilities: The secret ingredient. Decision Sciences, 41(4), pp.721-754.

[122] Antony, J., Sony, M., McDermott, O., Swarnakar, V., Galli, B., Doulatabadi, M. and Kaul, R., 2023. An empirical study into the reasons for failure of sustaining operational excellence initiatives in organizations. The TQM Journal, 35(7), pp.1569-1587.

[123] Gomaa, A.H., 2026. Green Lean Six Sigma for Smart and Sustainable Manufacturing: A Comprehensive Review and Strategic Framework in the Industry 4.0–5.0 Era. Interdisciplinary Systems for Global Management, 2(1), pp.25-39.